Module

for

Certification of Energy Manager

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SREDA
Sustainable and Renewable
Energy Development Authority

Prepared by
Sustainable and Renewable Energy Development Authority (SREDA)

Preamble

SREDA (Sustainable & Renewable Energy Development Authority) has prepared this module as reading material for Energy Manager's certification scheme in cooperation with various National and Foreign partner organizations. This module covers necessary basic aspects for Energy Managers to run any Industry efficiently ensuring optimum quality production with minimum possible energy use.

In order to ensure energy efficiency and conservation and to determine the future course of action, Sustainable and Renewable Energy Development Authority (SREDA) has developed the Energy Efficiency & Conservation Master Plan up to 2030 in 2016. According to this plan, the target of energy saving has been set 20% per GDP by 2030 which will be achieved by the use of energy efficient machinery and equipment as well as by improving energy management system.

In order to achieve the above-mentioned target & to ensure the energy efficiency and conservation in industrial & commercial sector, SREDA has formulated the Energy Audit Regulation'2018. Based on this regulation, SREDA has introduced the Energy Manager Certification Scheme to create Energy Managers in Bangladesh.

Establishments having a minimum sector wise threshold value of TOE/Year annual consumption will be treated as Designated Consumer (DC) according to the EE&C rules 2016. It is mandatory for DC Consumers to go for energy efficiency and conservation activities. They will have to engage required number of Energy Managers as per their energy consumption and determined by SREDA.

We hope that these modules will also act as valuable resource for practicing engineers and other concerned stakeholders in comprehending and implementing energy efficiency measures in the facilities.

It is the first iteration of these modules. It will be a living document, which can be reviewed and revised time to time according to the evolution of the technology and industry. Any suggestion and comments (please email to *ad.eaa@sreda.gov.bd*) on the contents of this module will be highly appreciated.

ACRONYMS

AC	Air Conditioner
AC	Alternating Current
BTU	British Thermal Unit
CFL	Compact Fluorescent Lamp
CHP	Combined Heat and Power
CPM	Critical Path Method
DC	Direct Current
DSEE	Demand Side Energy Efficiency
EE&C	Energy Efficiency and Conservation
EECMP	Energy Efficiency and Conservation Master Plan
EnMS	Energy Management System
ESCO	Energy Service Company
EU	European Union
GCV	Gross Calorific Value
GDP	Gross Domestic Product
GHG	Green House Gas
Hz	Frequency in Hertz
I	Current in Ampere
IRR	Internal Rate of Return
kJ	Kilo Joule = 1000 Joule
Ktoe or ktoe	Kilo Tonnes of Oil Equivalent
kVA	Kilo Volt Ampere
kVAR	Kilo Volt Ampere Reactive
kW	Kilo Watt
LED	Light Emitting Diode
MCR	Maximum Continuous Rating
Mtoe or MTOE	Million tonnes oil equivalent
NCV	Net Calorific Value
O&M	Operation and Maintenance
P	Power in watts
Pa	Atmospheric Pressure
PDC	Project Development Cycle
PDC	Project Development Cycle
PERT	Program Evaluation and Review Technique
PF	Power Factor
Q_L	Quantity of Latent heat in kilojoules
R	Resistance in Ohms Ω
RE	Renewable Energy
RH	Relative Humidity
RMS	Root Mean Square
RPM	Revolution Per Minute

SOx	Sulphur Oxides
SPP	Simple Payback Period
SREDA	Sustainable and Renewable Energy Development Authority
SSEE	Supply-side energy efficiency
TDS	Total Dissolved Solids
toe or TOE	Ton of Oil Equivalent
V	Volt
WBS	Work Breakdown Structure

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CHAPTER 01: ENERGY EFFICIENCY AND CONSERVATION (EE&C): TRENDS & ISSUES

1.1 Global Energy Trend

Fossil fuels such as oil, natural gas, and coal have been the world's primary energy source for several decades. Currently, conventional fossil fuels supply about 83% of the global primary energy consumption for industrial, transportation, commercial and residential uses. Total primary energy consumption comprising commercially–traded fuels including renewable energy was 13389.3 million tonnes oil equivalent (MTOE) in 2020. The world primary energy consumption by fuel type/source is shown in Figure 1.1.

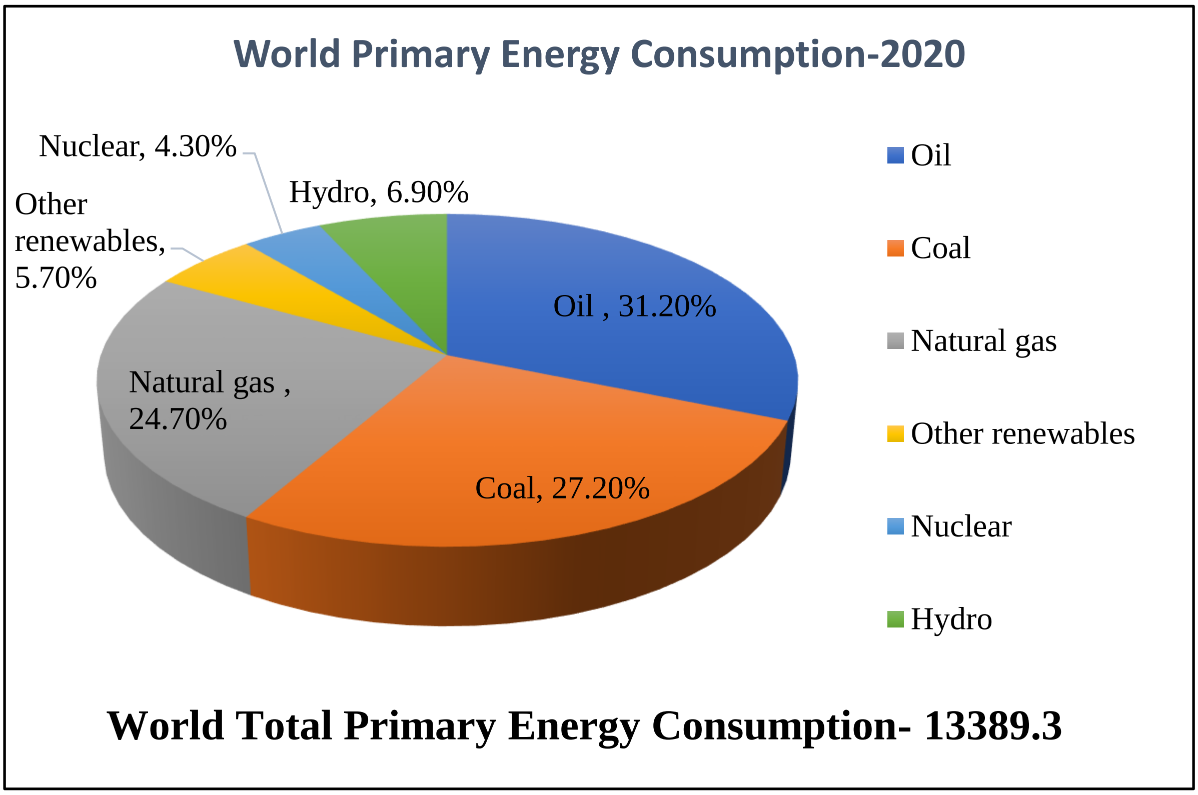


Figure 1.1: Breakup of World Primary Energy Consumption by Fuel / Source

(Source: BP Statistical Review of World Energy 2021 | 70th edition)

The world is facing the reality that fossil fuels will be exhausted soon as the global consumption rate is outpacing the discovery and exploitation of new reserves, and that the global environment is worsening due to increasing greenhouse gas (GHG) emissions caused by fossil fuels. The world primary energy consumption trend is shown in Figure 1.2.

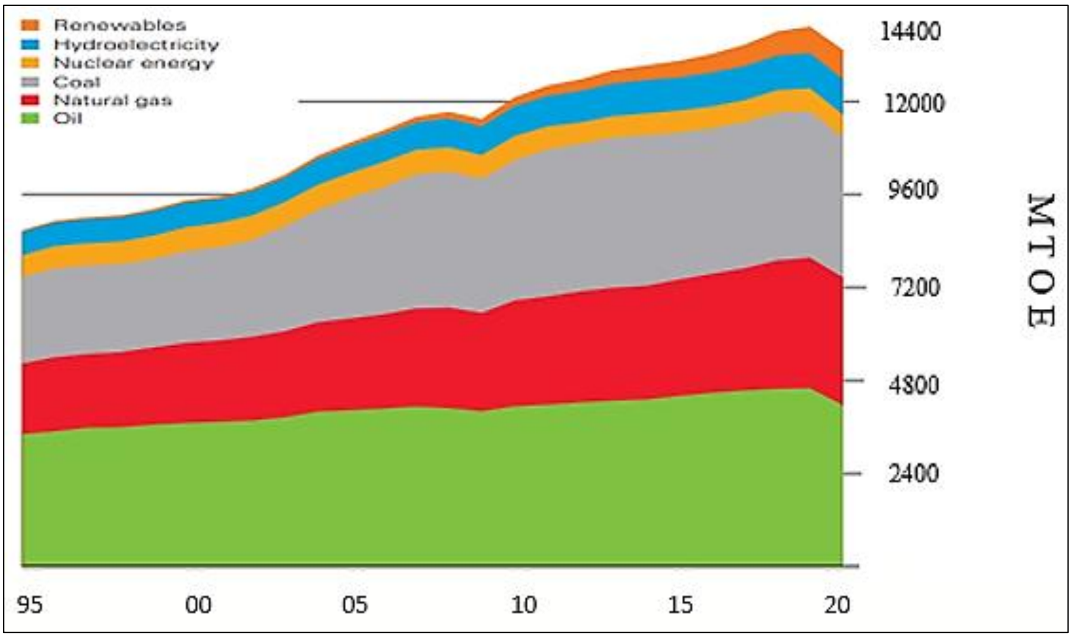


Figure 1.2: World Primary Energy Consumption Trend

(Source: BP Statistical Review of World Energy 2021 | 70th edition)

1.2 Energy and Climate Nexus

The global climate is changing and that is posing increasingly severe risks for ecosystems, human health and the economy. Many parts of the world are already facing impacts of a changing climate, including rising sea levels, more extreme weather, flooding, droughts and storms. Bangladesh is one of the worst affected countries though its contribution in GHG emission is negligible compared to global standard.

These changes are happening because large amounts of greenhouse gases are released into the atmosphere as a result of many human activities worldwide, including, most importantly, burning fossil fuels for electricity generation, heating and transport. Combustion of fossil fuels also releases air pollutants that harm the environment and human health.

Globally, the use of energy represents by far the largest source of greenhouse gas emissions from human activities. About two thirds of global greenhouse gas emissions are linked to burning fossil fuels for energy to be used for heating, electricity, transport and industry. The energy processes are the largest emitter of greenhouse gases; according to European environment agency, it was responsible for 78 % of total (European Union) EU emissions in 2015.

Our use and production of energy have a massive impact on the climate and the converse is also increasingly true. Climate change can alter our energy generation potential and energy needs. For example, changes to the water cycle have an impact on hydropower, and warmer temperatures increase the energy demand for cooling in the summer, while decreasing the demand for heating in the winter.

Human influence has warmed the climate at a rate that is unprecedented in at least the last 2000 years

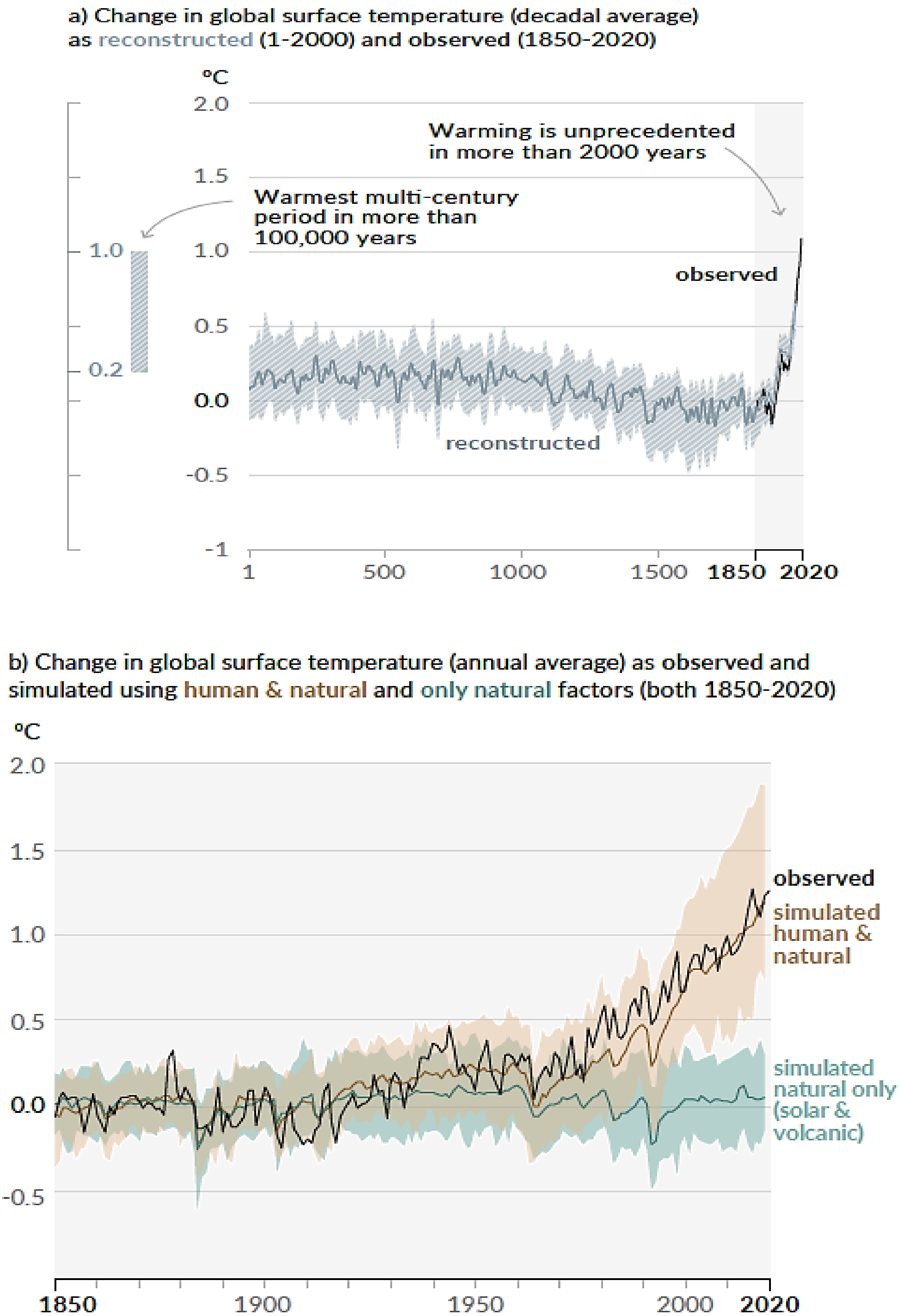


Figure 1.3: History of Global Temperature Change & Causes of Recent Warming

(Source: IPCC, 2021: Summary for Policymakers. In Climate Change 2021: The Physical Science Basis. Contribution of Working Group 1 to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press.)

Global trends of population growth, rising living standards and the rapidly increasing urbanized world are increasing the demand on water, food and energy. Added to this is the growing threat of climate change which will have huge impacts on water and food availability. It is increasingly clear that there is no place in an interlinked world for isolated solutions aimed at just one sector. In recent years the "nexus" has emerged as a powerful concept to capture these inter-linkages of resources and is now a key feature of policy-making.

This book is one of the first to provide a broad overview of both the science behind the nexus and the implications for policies and sustainable development. It brings together contributions by leading intergovernmental and governmental officials, industry, scientists and other stakeholder thinkers who are working to develop the approaches to the Nexus of water-food-energy and climate. It represents a major synthesis and state-of-the-art assessment of the Nexus by major players, in light of the adoption by the United Nations of the new Sustainable Development Goals and Targets in 2015.

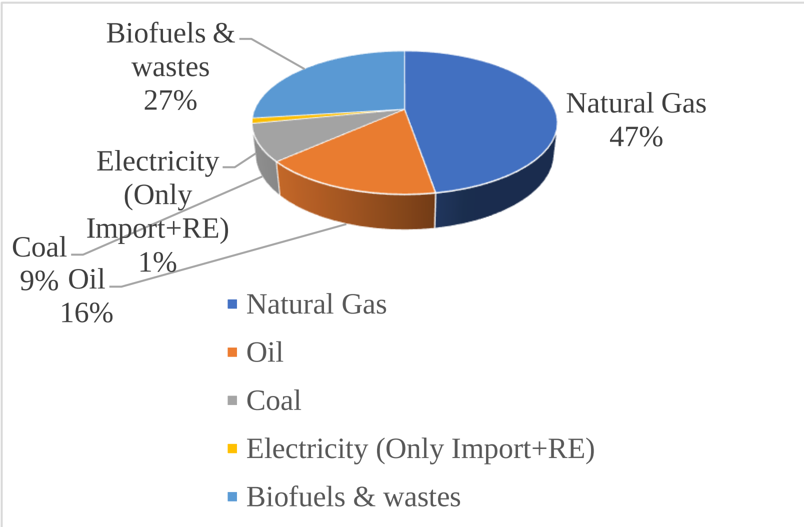
A water-food-energy and climate nexus will help to address these complex and interlinked challenges by exploiting available synergies across all policy areas, maximise coherence and promote positive trade-offs between different policies of a country.

1.3 Energy Scenario in Bangladesh

1.3.1 Primary Energy Supply by Fuel source in Bangladesh

The primary energy supply (PES) for Bangladesh during FY 2019-20 was 55.542 Mtoe. One third of the supply to the country is from its indigenous natural gas. Import of natural gas started from FY2018-19, and is rapidly increasing. The proportion of imported natural gas, in its second fiscal year, has already surpassed 20% of all gas supply. Oil, and oil products also comprises an important portion in the energy supply. For both oil and coal, the proportion of domestically-available supply is limited, with the import comprising a significant portion. Biofuels and wastes, which amounts to more than a quarter of the primary energy supply, are mostly firewood for domestic cooking purposes in rural and some urban households.

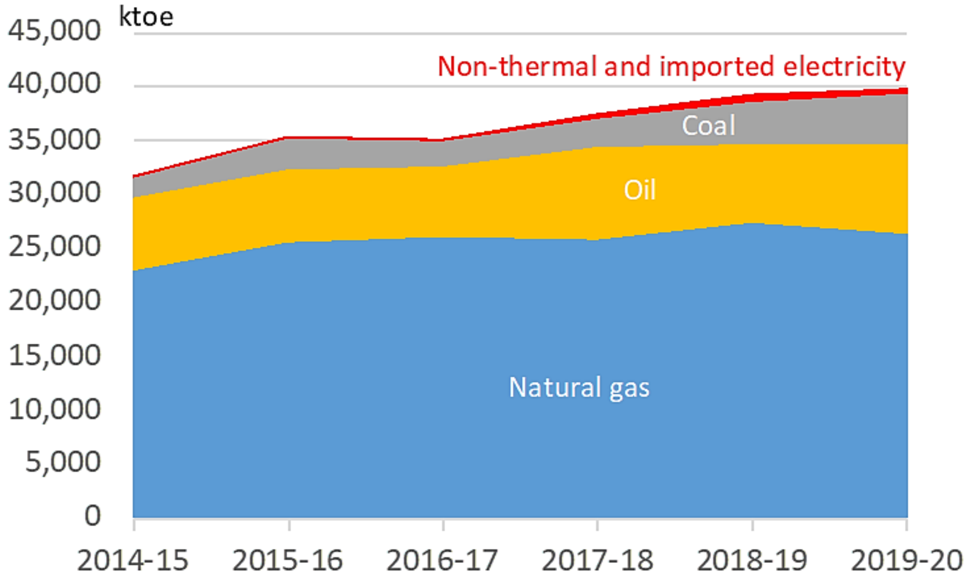
Fuel Source	***Ktoe***
Natural Gas	26273
Oil	8968
Coal	4661
Electricity (Only Import+RE)	650
Biofuels & wastes	14990
Total	***55542***



Note: Domestic sales data is used to represent supply, for natural gas and coal, instead of actual domestic production (or import) minus stock change and bunkers due to limited availability of published data.

Figure 1.4: Composition of Primary Energy Supply

(Source: National Energy Balance 2019-20)



Unit: Ktoe

FY	Natural gas	Oil	Coal	Non-thermal*
2014-15	23,104	6,729	1,617	339
2015-16	25,491	6,796	2,887	411
2016-17	26,028	6,486	2,318	485
2017-18	25,916	8,429	2,722	500
2018-19	27,494	7,107	4,019	649
2019-20	26,273	8,413	4,661	650

*: Non-thermal and imported electricity includes PV, hydro and imported.
Note: The following major changes were made from FY 2018-19 issue:
(1) Imported coal and imported petroleum products data have been added.
(2) Production and import data combined are being used for natural gas supply.
Note: Biofuels and waste are excluded from the primary energy supply.
Note: Figures may not add up due to rounding.

Figure 1.5: Composition of Primary Energy Supply

(Source: National Energy Balance 2019-20)

1.3.2 Renewable Energy Scenario in Bangladesh

Renewable Energy does not refer to any particular type of Energy- rather a general name for all continuously renewable, sustainable inexhaustible energy sources in the nature. It includes any form of energy that can be produced sustainably from a source that is replenished through natural process on a human time scale. Solar energy, Wind Energy, Bio Energy, Ocean energy, geo thermal energy are examples of renewable energy. Following is the present scenario of renewable energy in Bangladesh (up to date: 5 May 2022).

Techlology	Off-grid (MW)	On-grid (MW)	Total (MW)
Solar	350.18	203.49	553.68
Wind	2	0.9	2.9
Hydro	0	230	230
Biogas to Electricity	0.69	0	0.69
Biomass to Electricity	0.4	0	0.4
Total	**353.27**	**434.39**	**787.67**

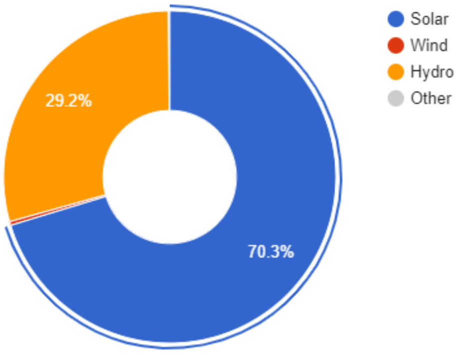


Figure 1.6: Renewable Energy Share

(Source: http://www.renewableenergy.gov.bd/)

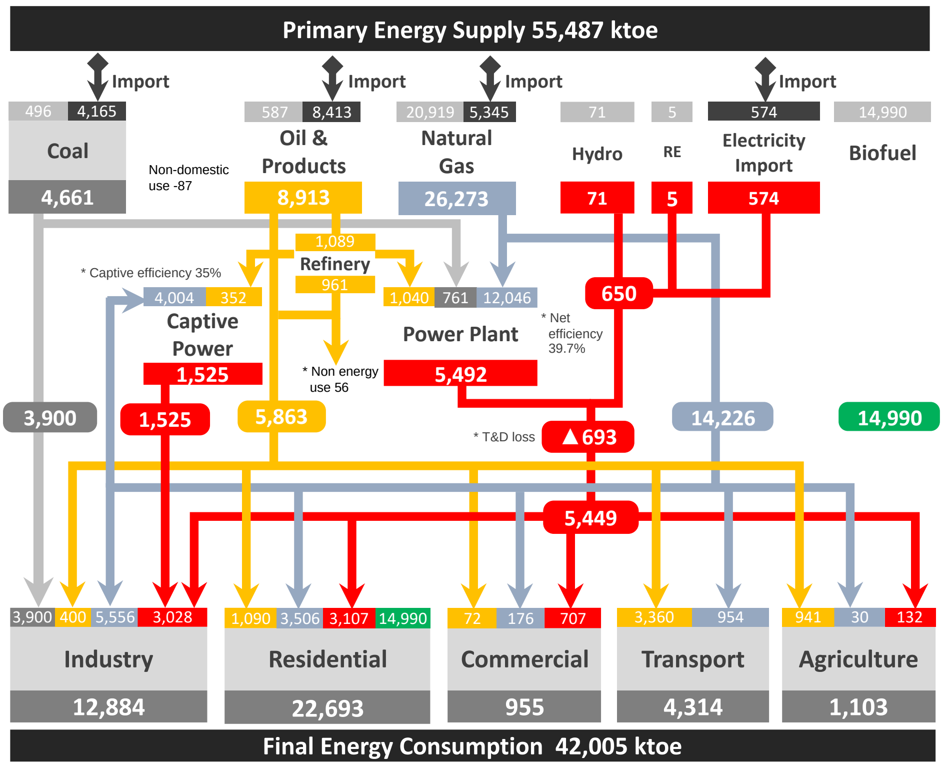
1.4 Energy Balance

The national energy balance is a presentation of a set of energy data to exhibit the overall pattern of energy supply, transformation and consumption pattern among the major sector and by source of energy. It can also be described as the input-output data, or a balance sheet table of energy supply to consumption within the country.

Based on readily available national energy supply, transformation efficiency and consumption data, an updated energy balance calculation was conducted at SREDA. The visual presentation focusing of the flow of energy by sector and source in Figure 1.7. It should be noted here that the energy consumption in national energy balance is on the basis of the final consumption and not on primary energy basis. It should also be noted the visual presentation contains ambiguity, which require to be solved once comprehensive official data become available from the data sources.

The striking characteristics of the national energy balance structure of Bangladesh is that the captive power generation comprises a significant portion of energy transformation. It also shows that approximately a half of the natural gas is being fed into power generation (including captive power generation). A captive power plant is a facility that provides a localised source of power to an energy user. These are typically industrial facilities, large offices or data centres. The plants may operate in grid parallel mode with the ability to export surplus power to the local electricity distribution network. Captive power generation is contributing a significant portion of electricity supply to the industry sector (approximately 40%).

Further, looking at fuel source-wise consumption, natural gas is the major source for industry and residential sectors. It should also be noted that the imported coal, imported petroleum products also comprise an important portion of the primary energy supply. Electricity is the most consumed form of energy in industry, residential and commercial & public service (building) sectors.



Note: Unit = ktoe

Seven boxes on the top (in five colours) are Primary Energy Supply by fuel source.

Middle **three** boxes (power plant, refinery, captive) are energy transformation means.

Bottom five boxes are final consumption by sector.

Figure 1.7: Energy Balance in Bangladesh (FY 2019-20)

(Source: Visualized Flow of National Energy Balance FY2019-20)

1.5 EE&C Concept, Application & Target

Energy conservation is basically using less energy and is usually associated with behavioural change that results in not using energy at a time when one might normally do or some sort of cut down in utility level of the consumer; for example, turning the lights off or setting air-conditioning system at higher temperature (say 28°C in Japan). Energy efficiency, however, refers to the reduction of energy use for a given service or level of activity by enhancing energy productivity and squeezing the maximum out of every unit of primary energy. Conversion of simple cycle power plants to combined cycle, replacement of incandescent bulbs with (Light Emitting Diode) LED bulbs are examples of energy efficiency improvement measures, which consumes less energy than (Compact Fluorescent Lamp) CFL but gives same illumination.

Approaches for improving energy efficiency include supply-side energy efficiency [SSEE] and demand-side energy efficiency [DSEE]. SSEE is achieved by decreasing energy losses in the supply chain while DSEE is aimed at consuming less energy for the same level of service. To achieve SSEE, conversion of simple cycle power plants to combined cycle is an example. Rehabilitation of old and inefficient power plants, setting up online interface meters at the energy dispatch point from the power station to the grid to monitor energy generation, train up O&M personnel of the power plant as per standard practice have been undertaken in the power generation sector. Even in efforts to increase power generation with coal-fired power plant, Bangladesh is opting for ultra-supercritical technology with strict pollution control measures. To attain efficiency in power transmission sector, Power Grid Company of Bangladesh has been implementing projects namely "Capacitor Bank Installation in 132 KV Transmission Line" for improvement of reactive power management and "Transmission Efficiency

Improvement Project" for optimization of voltage drop. Upgradation of line and transformer capacity, automation in generation control, smart grids and system metering are under active consideration for implementation. Important interventions undertaken in power distribution sector include up gradation of distribution lines and substations, power factor improvement, scaling up prepaid metering etc.

To realize DSEE & improve energy access situation, the government has adopted a comprehensive energy development strategy to explore demand side energy management that conserves energy and discourages inefficient use. Reducing the amount of energy required to deliver various goods or services is also essential in this regard. Energy efficiency in the demand-side is one of the main pillars for offering sustainable energy.

Efficient use of energy contributes to sustainable transport, affordable energy, competitiveness, ensure energy security and environmental sustainability. Improving energy efficiency is widely recognised as the easiest and most cost-effective means of reducing carbon emissions. Being more energy efficient offers tremendous financial benefits - industry and society can achieve more with less energy, public services are delivered at lower cost, and fuel poverty is reduced. Reducing demand also put less pressure on energy supplies. However, this can only be achieved with significant changes to the behaviour of individuals, communities, businesses, and the public sector. Energy Balance calculation for energy efficiency and conservation reaffirms the government's commitment on efficient use of energy. The Energy Balance calculation helps to set a framework for energy efficiency and conservation that furthers help the government to combat climate change, tackle economic and social agendas. It sets a target of energy saving and identify some actions to meet the target.

Energy efficiency is the first and foremost matter of controlling and reducing energy demand, and targeted actions are required for both energy consumption and energy supply. As the energy efficiency and conservation is a cross-cutting issue, tapping most potential energy values calls for initiatives to be taken in industrial, residential, commercial, transportation and agricultural sectors.

To identify the core actions to achieve energy efficiency & conservation national target SREDA has prepared the "Energy Efficiency and Conservation Master Plan (EECMP) up to 2030", in May 2016. According to EECMP, the target is to reduce 20% primary energy consumption per Gross domestic product or GDP (= national energy intensity) by 2030 (Note: the targets are set against the actual figure observed in FY 2013/14 as the base year).

In the EECMP, altogether five core actions are identified as the means to achieve the aforementioned target, which are, (i) energy management program, (ii) EE&C labelling program, (iii) EE&C building program. (iv) EE&C finance program, and (v) awareness raising program.

1.5.1 EE&C Potential

EE&C Potential in Industrial Sector

With regard to EE&C potential in the industrial sub-sectors, through energy intensity comparison and actual on-site energy audits, it was found that our country has a large EE&C potential as shown in Figure 1.8. The EE&C potential is estimated to be around 21% of the entire sector consumption, excluding non-feasible EE&C potential. Considering that about 50% of the national primary energy is consumed in industrial sector, the potential impact of EE&C measures on the economy is massive and it is expected that the national primary energy consumption can be reduced by almost 10%.

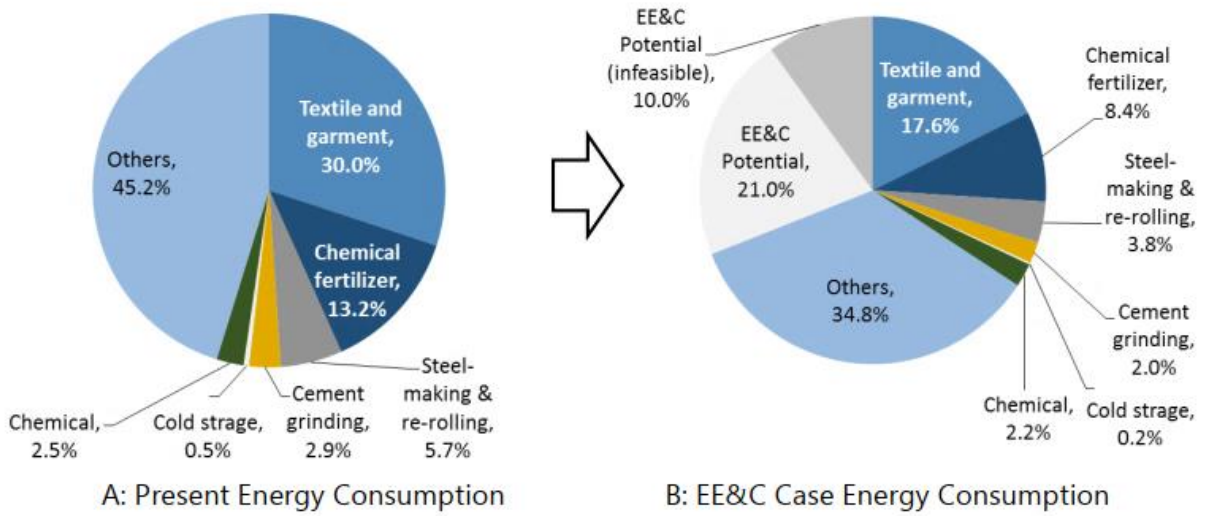


Figure 1.8: EE&C Potential in Industrial Sector

(Source: EECMP up to 2030)

EE&C Potential in Residential Sector

Energy efficient home appliances are available in the market; however, their sales shares are still minor compared to inefficient and cheap similar product in the present market. If all existing home electric appliances in residences are replaced with the most efficient products of that kind, a huge scale of energy consumption reduction can be achieved. Figure 1.9 shows the present electricity consumption by home appliance (A) and EE case electricity consumption (B) using the EE rates given in Table 2.1-5. The total EE&C potential in the residential sector is estimated to be around 28.8%, excluding non-feasible potential. Considering that about 30% of the national primary energy is consumed in residential sector, the potential impact of EE&C measures on the economy is massive: it is expected that the national primary energy consumption can be reduced by almost 9%.

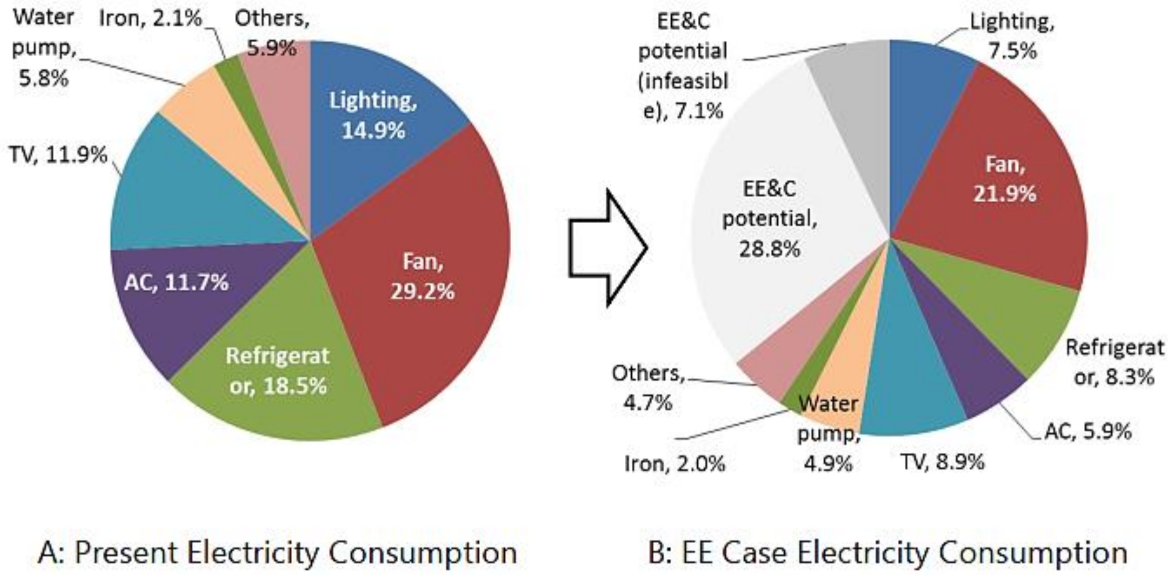


Figure 1.9: EE&C Potential in Industrial Sector

(Source: EECMP up to 2030)

EE&C Potential in Commercial Sector (Buildings)

Simple replacement of (air conditioner) **ACs** and **lighting systems** with high-energy efficiency ones can save up to 50% of total electricity consumptions in the building sector.

CHAPTER 02: FUNDAMENTALS OF ENERGY MANAGEMENT

2.1 Basics of Energy

Energy is described as the ability to do work or as the ability to carry a heat transfer. Energy is required for doing work or involving in a heat transfer. In practical terms, energy is what we use to manipulate the world around us, whether by exciting our muscles, by using electricity or by using mechanical devices such as automobiles.

Broadly, energy can be classified as Potential energy and Kinetic energy.

2.1.1 Potential Energy

Potential energy is the stored energy within a body because of its position or configuration. For example, raising a weight up high and release it to do work.

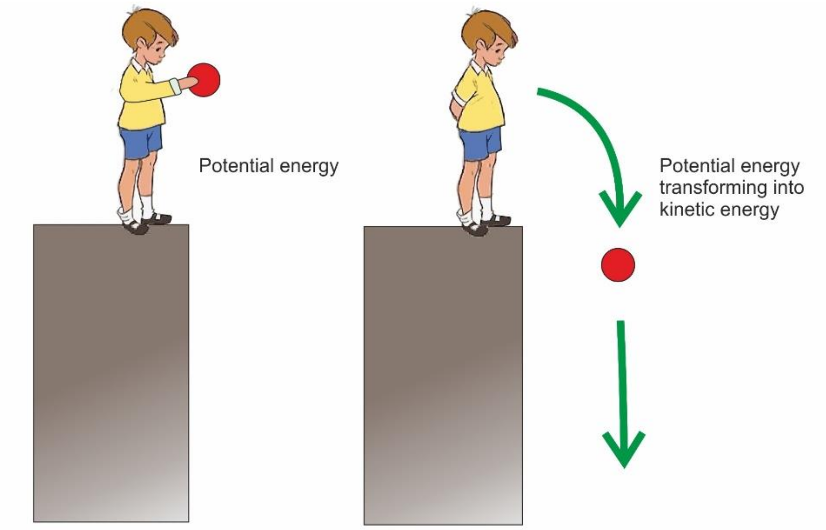


Figure 2.1: Potential Energy transforming into Kinetic Energy

Potential energy stored in a body due to its height above a datum level is expressed by:

$$Potential\ energy\ (E_P) = mass\ x\ gravitational\ acceleration\ x\ height = m\ g\ h.$$

Where $g = 9.81\ m/sec^2$

2.1.2 Chemical Energy

Chemical energy is the energy stored in the bonds of atoms and molecules and released as heat in a chemical reaction. This is specific to each reaction and is usually given as energy per unit mass (e.g. kJ/ kg) or number of molecules (e.g. kJ/mol). Biomass, petroleum, natural gas, propane and coal are examples of stored chemical energy.

2.1.3 Nuclear Energy

Nuclear energy is the energy stored in the nucleus of an atom - the energy that holds the nucleus together. The nucleus of a Uranium atom releases nuclear energy when its' fission (split in two parts) results in a loss of mass and the corresponding loss of mass(m) is converted to nuclear energy by the following famous equation of Einstein:

$Nuclear\ energy\ (EJ\ =\ mass\ x\ speed\ of\ light\ squared\ =\ mc^2$ (where c = 3 x 10^8 m/s)

2.1.4 Stored Mechanical Energy

Stored mechanical energy is energy stored in objects by the application of a force. Compressed springs and stretched rubber bands are examples of stored mechanical energy.

2.1.5 Gravitational Energy

Gravitational energy is the energy of place or position. Water in a reservoir behind a hydropower dam is an example of gravitational energy. When the water is released to spin the turbines, it becomes motion energy in the form of mechanical power-which drives the Generators/Alternators to produce electrical energy.

2.1.6 Kinetic Energy

It is the energy a body possesses by virtue of motion or velocity. For example, a moving vehicle, a flowing fluid and moving parts of machinery all have kinetic energy because of their motion.

Kinetic energy $\mathrm{E_k} = \frac{1}{2}\mathrm{mv}^2 = \mathrm{half} * \mathrm{mass} * \mathrm{velocity\ squared}$

2.1.7 Radiant Energy

Radiant energy is electromagnetic energy that travels in transverse waves. Radiant energy includes visible light, x-rays, gamma rays and radio waves. Solar energy is an example of radiant energy.

2.1.8 Thermal Energy

Thermal energy is the internal energy in substances - the vibration and movement of atoms and molecules within substances. Geothermal energy is an example of thermal energy.

2.1.9 Motion energy

The movement of objects or substances from one place to another is motion. Wind and hydropower are manifestations of motion energy.

2.1.10 Sound energy

Sound is the movement of energy through substances in longitudinal (compression/rarefaction) waves.

2.1.11 Electrical Energy

Electrical energy is the movement of electrons. Lightning and electricity are examples of electrical Energy.

2.1.12 Work

The unit of work or energy is the joule (J).

Work done is expressed as,

$$W = F \times s \cdots\cdots\cdots\cdots (2.1)$$

Where, $F = Force\ in\ Newtons\ and$
$s = distance\ in\ meters\ in\ the\ direction\ of\ force$

For rotating body work done is expressed as

$$W = \tau * \theta \ \cdots\cdots\cdots\cdots (2.2)$$

Where, $\tau = Torque\ in\ Newton - Meter\ and$
$\theta = angle\ in\ radian\ the\ body\ rotated.$

Kilojoule (1 kJ = 1000J) is more common unit among engineers. Even kilojoule is too small a unit when considering national or global amounts of energy. In such cases Mega joule (10^6 J), Gigajoule (10^9 J), Terra joule (10^{12} J) and Petajoule (10^{15} J) are used.

2.1.13 Energy and Power

Energy represents the ability to do work. To do the work, one has to use energy of one form at a given rate and convert it to another form. Power is defined as the rate of doing work or rate at which energy is used and converted.

Power can be expressed as,

$$P = \frac{W}{t} \cdots\cdots\cdots\cdots (2.3)$$

Where, $W = work\ done\ or\ energy\ transferred\ in\ Joules$ and
$t = time\ in\ seconds.$

The unit of power is Watt (W). Technically Energy and Work done is always equal. When work is done equal amount of energy is being converted from one form to another form.

Thus, energy, in joules can be expressed as from equation (2.3),

$$W = P \times t \cdots\cdots\cdots\cdots (2.4)$$

Now, $1\ kWh = 1 \frac{kJ}{s} \times 3600s$
$= 1000\frac{J}{s} \times 3600s$
$= 3600000\,J$
$= 3600\ KJ$
$= 3.6MJ$

In case of rotating body, power in Watts,

$$P = \tau * \omega \cdots\cdots\cdots\cdots (2.5)$$

Where, $\tau = Torque\ applied\ in\ Newton - Meter,$
$w = Angular\ velocity\ in\ Radian/\sec = \frac{2\pi rN}{60}$
$N = revolution\ per\ minute\ (RPM).$
$r = radius\ of\ rotating\ body$

Example 2.1
A portable machine requires a force of 200 N to move it. How much work is done if the machine is moved 20 m and what average power is utilized if the movement takes 25 s?

Solution:

Work done, $W = F \times s$
$= 200$ N × 20 m
= 4000 Nm = 4 kJ
Power, $P = \frac{W}{t}$
$= \frac{4000J}{25s} = 160\frac{J}{s} = 160\ W$

2.2 Electricity Basics

2.2.1 Direct Current (DC)

A current which is a non-varying, unidirectional current, e.g. current produced by batteries.

2.2.2 Alternating Current (AC)

A current which reverses in regularly recurring intervals of time and which has alternate positive and negative values occurring specified number of times, e.g. current from utilities. In 50 Cycle (Hertz) AC, current reverses direction 100 times per second i.e. two times in one cycle.

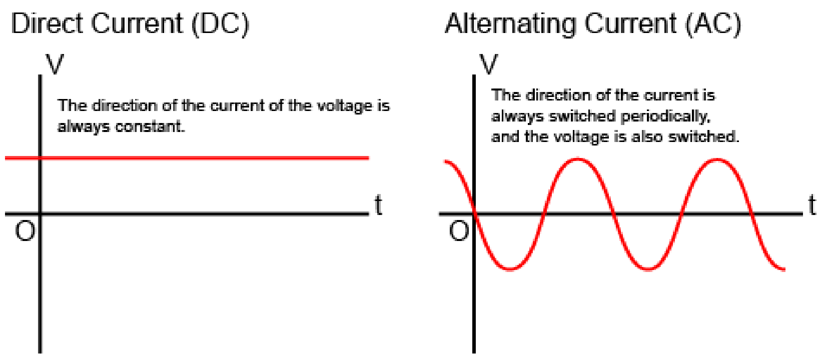


Figure 2.2: Direct Current and Alternating Current Visualization

2.2.3 Amps or Ampere (A)
Current is the rate of flow of charge. Ampere is the basic unit of electric current.

2.2.4 Voltage or Volts (V)

It is a measure of electric potential or electromotive force. A potential of one Volt (V) appears across a resistance of one Ohm when a current of one Ampere flows through the resistance.

2.2.5 Resistance and Conductance

Resistance is a measure of the opposition to current flow in an electrical circuit. The unit of electric resistance is the ohm (Ω) where one ohm is equal to one volt per ampere.

Resistance, in ohms $R = \frac{V}{I} = \frac{1\ Volts}{1\ Amps} = 1\ \Omega \cdots\cdots\cdots\cdots (2.6)$

Where, $V = potential\ difference\ across\ the\ two\ points\ in\ volts$ and
$I = current$ flowing $between\ the\ two\ points\ in\ amperes$

The reciprocal of resistance is called conductance and is measured in Siemens (S). Thus, conductance, in mho (reverse of ohm) or Siemens G = 1/R, where R is the resistance in ohms.

2.2.6 Frequency (Hertz)

The supply frequency is the number of cycles at which alternating current changes. The unit of frequency is cycles / second or Hz. In Bangladesh the normal supply frequency by utilities is at 50 Hz.

2.2.7 Electrical Energy

When a direct current (DC) of I amperes is flowing in an electric circuit and the voltage across the circuit is V volts, then,

Power, in Watts, $P = V \times I \cdots\cdots\cdots\cdots$ (2.7)

Again, $Electrical\ energy, E = Power \times time$

Or, $Electrical\ energy, E = P \times t \cdots\cdots\cdots\cdots$ (2.8)$[in\ watts]$

Or, $Electrical\ Energy, E = V \times I \times t$ Joules [from equation (2.7)]

The same formulae can be used in AC applications as well (since voltage and current are normally expressed in RMS values for AC applications)

Example 2.2
An electric heater consumes 1.8 MJ when connected to a 220 V supply for 30 minutes. Find the power rating of the heater and the current taken from the supply?

Solution:
We Know, from equation 2.8, $Electrical\ energy,$

$$E = P \times t$$

$$\Rightarrow P = \frac{E}{t}$$

$$= \frac{\mathbf{1.8 \times 10^6 J}}{\mathbf{30 \times 60 s}} = \mathbf{1000\, Js^{-1}}$$
$$= 1000W\ (Ans)$$

So, Power of the Heater is 1000W or 1KW

From Equation 2.7, Power,
$P = V \times I$
$\Rightarrow I = \frac{P}{V}$

$= \frac{1000\, W}{220\, V} = 4.54\, A$ (Ans)

Hence, the current taken from the supply is 4.54 A.

Example 2.3
A 100 W electric light bulb is connected to a 220 V supply. Determine (a) the current flowing in the bulb, and (b) the resistance of the bulb

Solution:
Here, Power P = 100W

Voltage V= 220V
Find, (a) Current I = ?
(b) Resistance R = ?

Now, From Equation 2.7, Power,
$P = V \times I$
$\Rightarrow I = \frac{P}{V} = \frac{100W}{200V} = 0.45A\ (Ans)$

From Equation 2.6, Resistance,

$$R = \frac{V}{I} = \frac{220V}{0.45A} = 489\ \Omega\ \text{(Ans)}$$

Example 2.4
An electric kettle has a resistance of 30 Ω. What current will flow when it is connected to a 240 V supply? Find also the power rating of the kettle.

Solution:
Here, Resistance, R= 30 Ω
Voltage, V= 240 V
Find, Current, I = ?
Power, P= ?

Now, From Equation 2.6, Resistance,
$R = \frac{V}{I}$
$\Rightarrow I = \frac{V}{R} = \frac{240V}{30\Omega} = 8A\ (Ans)$
From Equation 2.7, Power,
$P = V \times I$
$= 240V \times 8A$
$= 1920W = 1.92KW\ (Ans)$

Example 2.5
An electric heater of 230 V, 5 kW rating is used for hot water generation in an industry. Find electricity consumption per hour (a) at the rated voltage (b) at 200 V.

Solution
Here, Voltage, V= 240 V
Power, P= 5kW = 5000W
Time, t= 1hr
Find, Energy, E_{230V} = ?
Energy, E_{200V} = ?

(a) Now, from equation 2.8, $Electrical\ energy,$

$$E_{230V} = P \times t$$
$$\Rightarrow E_{230V} = 5\ KW \times 1\ h$$
$$\Rightarrow E_{230V} = 5\ KWh\ (Ans)$$

(b) We Electricity consumption other than rated voltage

$$E = \left(\frac{V_{200V}}{V_{230V}}\right)^2 \times P \times t \cdots\cdots\cdots\cdots (2.9)$$
$$\Rightarrow E = \left(\frac{200V}{230V}\right)^2 \times 5KW \times 1h$$
$$\Rightarrow E = 3.78\ KWh\ (Ans)$$

2.2.8 Power Factor (PF)

The total power requirement is comprised of two components, as illustrated in the power triangle (Figure 2.3). This triangle shows the resistive portion or kilowatt (kW), 90° out of phase with the reactive portion, kilovolt ampere reactive (kVAR). The reactive current is necessary to build up the flux for the magnetic field of inductive devices, but otherwise it is non-usable. The resistive portion is also known as the active power which is directly converted to useful work. The hypotenuse of the power triangle is referred to as the kilovolt ampere or apparent power (kVA). The angle between kW and kVA is the power factor angle.
From the Figure,

$Resistive\ Power, P_{Resistive} = Apparent\ Power,\ P_{Apparent} \times Cos\theta$

$\Rightarrow P_{Resistive} = P_{Apparent} \times Cos\theta \cdots\cdots\cdots\cdots (2.10)$
$\Rightarrow kW = kVA\ cos\theta$
$\Rightarrow kVA = kW/\ cos\ \theta$
$\Rightarrow kVAR = kVA\ sin\ \theta \cdots\cdots\cdots\cdots (2.11)$

$\mapsto PF = cos\ \theta = \frac{P_{Resistive}}{P_{Apparent}} = \frac{KW}{KVA} \cdots\cdots\cdots\cdots (2.12)$

$\mapsto tan\ \theta = \frac{P_{Reactive}}{P_{Resistive}} = \frac{KVAR}{KW} \cdots\cdots\cdots\cdots (2.13)$

PF is referred to as the power factor.
P is referred to as the Power

Only power portions in same phase with each other can be combined. For example: resistive portions of one load can be added to resistive portions of another. The same will hold for reactive loads also.

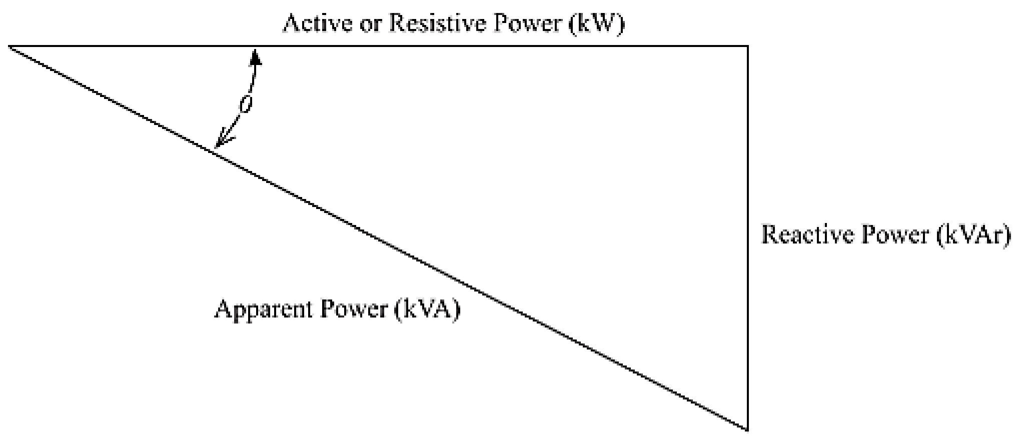


Figure 2.3: Illustration of Power Triangle

Relationships between Power, Voltage, and Current

For a balanced three-phase load,
Power, $P = \sqrt{3}\, V_L \times I_L Cos\theta \cdots\cdots\cdots\cdots\cdots$ (2.14)

For a balanced single-phase load,
Power, $P = V_L \times I_L\; Cos\theta \cdots\cdots\cdots\cdots\cdots$ (2.15)

Where,
$V_L \;=\; Line\; Voltage$
$I_L \;=\; Line\; current.$

Q 2.1: Which applications use single-phase power in an industry?

Single-phase power is mostly used for lighting, fractional HP motors and electric heater applications.

Example 2.6
A 400 Watt mercury vapor lamp was switched on for 10 hours per day. The supply volt is 230 V. Find the energy consumption per day? (Volt = 230 V, Current = 2 amps, PF = 0.8)

Solution:
Here, Time, t = 10h
Voltage, V = 230V
Current, I = 2 Amps
Power Factor, $PF \;= Cos\theta =\; 0.8$

Now,
From Equation 2.15 Power,
$P = V \times I\; Cos\theta$

From equation 2.8, $Electrical\; energy\; Consumption$*

$$E \;=\; P \times t$$

$\Rightarrow E =\; V \times\; I \times\; Cos\;\theta\; \times t$
$\Rightarrow E =\; 230\, V \times\; 2\, A \times\; 0.8\; \times 10h$
$\Rightarrow E =\; 3700$ Wh $= 3.7KWh$
[here 400w Power cannot be used as power factor and Current rating and voltage has been given. Calculating from voltage amperage is most accurate rather from rated power]

*Here, $E \;= \frac{P*t}{1000}\; can\; also\; be\; used. Where, E\; in\; KWh, P\; in\; KW, t\; in\; Hour$

2.2.9 Motor Loads

Each electrical load in a system has an inherent power factor. Motor loads are usually specified by horse power [*HP*] ratings. These can be converted to Apparent Power (kVA), by use of Equation

$$Apparent\; Power, kVA \;= \frac{HP\; \times\; 0.746}{\eta\; \times\; PF} \cdots\cdots\cdots\cdots\cdots (2.16)$$

Where,
$\eta \;=\; Motor\; efficiency$
$PF =\; Motor\; power\; factor$
$HP \;=\; Motor\; horsepower\; (i.e. Rated\; Output\; power).$

Most motor manufacturers can supply information on motor efficiencies and power factors. Smaller motors running partly loaded are the least efficient and have the lowest power factor.

Example 2.7
A 3-phase AC induction motor (20 kW capacity) is used for pumping operation. Electrical parameters such as current, volt and power factor were measured with power analyzer. Find the energy consumption of motor in one hour? (Volts. = 440 V, current = 25 amps and PF = 0.90).

Solution:
Here,
Voltage, V= 440V
Current, I= 25 amps
PF, $Cos\,\theta = 0.90$
From Equation 2014, for a balanced three-phase load,
Power, $P = \sqrt{3}\, V_L \times I_L Cos\theta$
$\Rightarrow P = \sqrt{3} \times 440 \times 25 \times 0.9 = 17150\, W$
$\Rightarrow P = 17.15\, KW$

Measured Energy consumption = $E = Pt = 17.15\text{kW} \times 1\text{h} = 17.15\ kWh\ (Answer)$

Motor loading calculation
The name plate details of motor, KW or HP indicates the output of the motor at full load the other Parameters such as volt, amps, PF are the input condition of motor at full load. Motor Loading Can be found by below equation,

$$Motor\ loading\ (\%) = \frac{Measured\ Power}{Rated\ Input\ Power} \cdots\cdots\cdots\ (2.17)$$

Example 2.8
A 3-phase 10 kW motor has the name plate details as 415 V, 18.2 amps and 0.9 PF. Actual input measurement shows 415 V, 12 A and 0.7 PF which was measured with power analyzer during motor running. Find out the motor loading and actual input power of the motor.

Solution:
Here
Rated output power at full load, $P_{output} = 10\ KW$
Rated voltage, $V_{rated} = 415\, V$
Rated current, $I_{rated} = 18.2\ amps$
Rated Power Factor, $PF_{rated} = 0.9$
Measured voltage, $V_{calculated} = 415\, V$
Measured current, $I_{measured} = 12\ amps$
Measured Power Factor, $PF_{measured} = 12\ amps$

Now,
Rated input at full load, $P_{input,rated} = \sqrt{3}\, V_L \times I_L Cos\theta$
$\Rightarrow P_{input,rated} = 1.732 \times 0.415 \times 18.2 \times 0.9 = 11.8\, kW$

The rated efficiency of motor, $\eta = \frac{P_{Output}}{P_{input,rated}} = \frac{10}{11.8} = 85\%$
Measured (Actual) input, $P_{input,measured} = \sqrt{3}\, V_L \times I_L Cos\theta$
$\Rightarrow P_{input,measured} = 1.732 \times 0.415 \times 12 \times 0.7 = 6.0\, kW\ (Ans)$

Again, We know from equation 2.17,

$$Motor\ loading\ (\%) = \frac{Measured\ Power}{Rated\ Input\ Power} = \frac{P_{input,measured}}{P_{input,rated}}$$

$$\Rightarrow Motor\ loading\ (\%) = \frac{6\ kw}{11.8\ kw} \times 100 = 51.2\%\ (Ans)$$

2.3 Thermal Energy Basics

2.3.1 Temperature

Temperature is a physical property that quantitatively expresses the common notions of hot and cold. Objects of low temperature are cold, while various degrees of higher temperatures are referred to as warm or hot.

Temperature is measured with thermometers, which may be calibrated to a variety of temperature scales. Much of the world uses the Celsius scale for most temperature measurements. In Fahrenheit scale (British system), the freezing point of water is 32°F and the boiling point of water is 212°F at atmospheric pressure.

The Kelvin scale is the temperature standard for scientific or engineering purposes. It has the same incremental scaling (1°) as the Celsius scale, but fixes its origin, or null point, at absolute zero (‘K = -273.15°C)

Conversion of the degree Celsius (C) into Fahrenheit (F),

$$F = C \times 1.8 + 32 \cdots\cdots\cdots\cdots\cdots (2.18)$$

Conversion of the Fahrenheit(F) into degree Celsius (C)

$$C = (F - 32) / 1.8 \cdots\cdots\cdots\cdots\cdots (2.19)$$

Degrees Celsius (C) to degrees Kelvin (K),

$$K = C + 273 \cdots\cdots\cdots\cdots\cdots\ \cdots\cdots (2.20)$$

Relationship between the temperature scales

$$\frac{C}{5} = \frac{F - 32}{9} = \frac{K - 273}{5} \cdots\cdots\cdots\ \cdots\cdots (2.21)$$

2.3.2 Pressure

It is the force per unit area applied to outside of a body.

$$P = \frac{F}{A} = \frac{ma}{A} = \frac{mg}{A} \cdots\cdots\cdots (2.22)$$

Where,
$P = pressure\ in\ N/m^2\ or\ Pascals$
$F = force\ in\ Newtons\ (N)$
$a = acceleration\ in\ m/s^2$
$g = Gravitational\ cceleration\ in\ m/s^2$
$A = Area, where\ force\ is\ exerted\ in\ m^2$

2.3.3 Absolute pressure

The absolute pressure (P_s) is total or true pressure. It is measured relative to the absolute zero pressure - the pressure that would occur at absolute vacuum. All calculation involving the gas laws requires pressure to be in absolute units and temperature in Kelvin.

2.3.4 Gauge Pressure

Gauge pressure (P_g) is the pressure indicated by a gauge. All gauges are calibrated to read zero at atmospheric pressure. Gauges indicated the pressure difference between a system and the surrounding atmosphere. The gauge pressure can be expressed as

$$P_g = P_s - P_a \cdots\cdots\cdots \cdots\cdots (2.23)$$

Where,
$P_g = gauge\ pressure$
$P_s = system\ pressure\ (absolute)$
$P_a = atmospheric\ pressure$

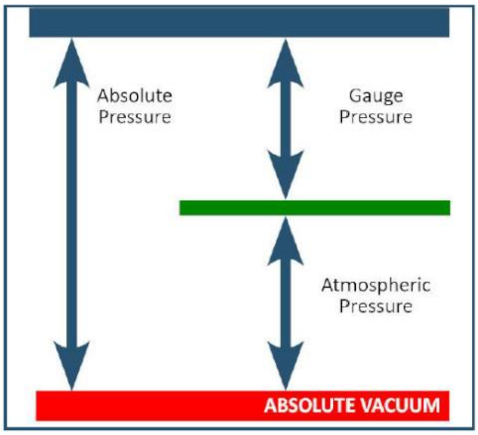


Figure 2.4: Relationship between Absolute, Gauge and Atmospheric pressure

2.3.5 Atmospheric Pressure

Atmospheric pressure (P_a) is pressure in the surrounding air at the surface of the earth. The atmospheric pressure varies with temperature and altitude above sea level.

2.3.6 Standard Atmospheric Pressure

Standard Atmospheric Pressure (atm) is used as a reference for gas densities and volumes. The Standard Atmospheric Pressure is defined at sea-level at 273°K (0°C) and is 1.01325 bar or 101325 Pascal (absolute). The temperature of 293°K (20°C) is also used.

$1\ \text{atm} = 1.01325\ \text{bar}$
$= 101.3\ \text{kPa}$
$= 760\ \text{mmHg}$
$= 10.33\ \text{meter}\ \text{H}_2 0$
$= 1.013\ \text{mbar}$
$= 1.0332\ \text{kgf/cm}^2$

2.3.7 Heat

Heat is transferred from one body to another body at a lower temperature by virtue of temperature difference i.e., Heat is energy in transition or transitory energy.

The quantity of heat depends on the quantity and type of substance involved.

Calorie is the unit for measuring the quantity of heat. It is the quantity of heat, which can raise the temperature of 1gram of water by 1°C.

Calorie is too small a unit for many purposes. Therefore, a bigger unit Kilocalorie (1 Kilocalorie = 1000 calories) is used to measure heat. 1 kilocalorie can raise the temperature of 1000g (i.e. 1kg) of water by 1°C.

However, nowadays generally Joule as the unit of heat energy is used. It is the internationally accepted unit. Its relationship with calorie is as follows:

$$\begin{aligned} 1 \text{ Calorie } &= 4.187 \text{ J} \\ &\sim 4.2 \text{ J} \end{aligned}$$

2.3.8 Specific Heat

If the same amount of heat energy is supplied to equal quantities of water and milk, their temperature goes up by different amounts. This is due to different specific heats of different substances.

Specific heat is defined as the quantity of heat required to raise the temperature of 1kg of a substance through 1°C or 1 K. Specific heat is expressed in terms of kcal/kg^{0}C or J/kg K. Specific heat varies with temperature. In case of gases-there are an infinite number of processes in which heat may be added to raise gas temperature by a fixed amount and hence a gas could have an infinite numbers of specific heat capacities. However-only two specific heats are defined for gases i.e. specific heat at constant pressure, cp and specific heat at constant volume, cv. For solids and liquids, however, the specific heat does not depend on the process.

The specific heat of water is very high as compared to other common substances; it takes a lot of heat to raise the temperature of water. Also, when water is cooled, it gives out a large quantity of heat. The specific heats of common substances are given in Table 1.1.

Table 2.1: Specific Heat of Some Common Substances

Substance	Specific Heat(Jkg^{-1} °C)	Specific Heat (Kcal/kg °C) $= \frac{J\,kg^{-1}°C}{4.2\times1000}$
Lead	130	0.031
Mercury	140	0.033
Copper	390	0.093
Aluminium	910	0.22
Water	4200	1
Alcohol	2400	0.571
Iron	470	0.112

2.3.9 Sensible Heat

The amount of heat which when added to any substance causes a change in temperature. The changes in temperature that do not alter the moisture content of air. It is expressed in calories or Joules.

$Q = m\, C_p\, \Delta T \cdots\cdots\cdots \cdots\cdots (2.24)$
Where,
$Q = Sensible\ Heat$
$m = mass\ of\ substances\ or\ fluid$
$C_p = specific\ heat\ at\ constant\ pressure$

2.3.10 Phase Change

The change of state from the solid state to a liquid state is called fusion. The fixed temperature at which a solid changes into a liquid is called its melting point.

The change of a state from a liquid state to a gaseous is called vaporization. The fixed temperature at which a liquid changes into a vapour is called its boiling point. The change of a state from gaseous state to a liquid state is called condensation.

2.3.11 Latent heat

It is the change in heat content of a substance, when its physical state is changed without a change in temperature.

2.3.12 Latent heat of fusion

The latent heat of fusion of a substance is the quantity of heat required to convert 1 kg solid into liquid state without change of temperature. It is represented by the symbol h_{lf}. Its unit is Joule per kilogram (J/Kg) Thus, Q_L (ice) = 335 KJ/kg. The change in phase occurs in either direction at the fusion temperature i.e. liquid to solid and solid to liquid. The temperature and quantity of heat to bring about the change will be the same in either case and can be determined from the following equation:

$Q_L = m \times h_{lf} \cdots\cdots\cdots \cdots\cdots (2.25)$

Where
$Q_L = The\ quantity\ of\ latent\ heat\ in\ kilojoules$
$m = The\ mass\ in\ kg$
$h_{lf} = The\ latent\ heat\ of\ fusion\ in\ kJ/kg$

Example 2.10

If the latent heat of fusion of water is 335 kJ/kg, determine the quantity of latent heat given up by 10 kg of water at 0°C when it freezes into ice at 0°C.

Solution:
Here,
$h_{lf} = 335\ kJ/kg$
$m = 10kg$

From equation 2.25 we know,
$Q_L = m \times h_{lf}$

$$\Rightarrow Q_L = 10\ kg \times 335 \frac{kJ}{kg} = 3350\ kJ\ (ans)$$

Example 2.11

If 20 kJ of heat is supplied to 25 kg of ice at 0°C, how many kilograms of ice will be melted into water?

Solution:

Here,
Let, $h_{lf} = 335\ kJ/kg$
Given, $Q_L = 20KJ$

From equation 2.25 we know,
$Q_L = m \times h_{lf}$

$$\Rightarrow m = \frac{Q_L}{h_{lf}} = \frac{20\ KJ}{335\ kJ/kg} = 0.06\ kg$$

$So\ only\ 0.06kg\ of\ Ice\ will\ be\ melted\ (ans)$

2.3.13 Latent Heat of Vaporization

The quantity of heat that a 1 kg mass of liquid will absorb in going from the liquid phase to the vapour phase, or give up in going from the vapour phase to the liquid phase, without change in temperature, is called latent heat of vaporization.

It is also denoted by the symbol Q_L and its unit is J/kg. The latent heat of vaporization of water is 2257 KJ/kg. When 1 kg of water at 100°C vaporizes to form steam at 100°C, it absorbs 2257 kcal/kg (540 kcal/kg) of heat.

$$Q_L = m \times h_{fg} \cdots\cdots\cdots\cdots \cdots\cdots\cdots (2.26)$$

Where,
$Q_L = The\ quantity\ of\ latent\ heat\ in\ kilojoules$
$m = The\ mass\ in\ kg$
$h_{fg} = The\ latent\ heat\ of vaporization\ in\ kJ/kg$

2.3.14 Condensation

Condensation is the change by which any substance is converted from a gaseous state to liquid state without change in temperature. When 1 kg of steam at 100 condenses to form water at 100°C, it gives out 2260 kJ of heat.

Example 2.12
Determine the quantity of heat required to vaporize 2 m^3 of water at 100°C if the latent heat of vaporization of water at that temperature is 2257 kJ/kg

Solution:
Given,
Volume of water, $V = 2m^3$
Latent heat of Vaporization, $h_{fg} = 2257\ kJ/kg$
Let, Density of water, $\rho = 1000\ kg/m^3$

We know, $\rho = \frac{m}{V} \cdots\cdots\cdots\cdots \cdots\cdots\cdots (2.27)$
So, mass of water, $m = \rho V = 1000 \times 2 = 2000\ kg$
From Equation 2.26,
$Q_L = m \times h_{fg}$

$$Q_L = 2000\ kg\ X\ 2257\ kJ/kg = 4{,}514{,}000\ kJ$$

2.3.15 Super Heating

Super heating is the heating of vapour, particularly saturated steam to a temperature much higher than the boiling point (also called saturation temperature) at the existing pressure. This is done in power plants to improve efficiency and to avoid condensation in the turbine

2.3.16 Humidity

Moisture contained in air is expressed as Humidity. Saturated air holds all the moisture it can contain at that temperature and pressure.

The unit for humidity is kg of moisture / kg of dry air.

2.3.17 Dew Point

It is the temperature at which water vapor in the air becomes saturated with moisture and the moisture starts to condense into water droplets. It is equal to the saturation temperature at the partial pressure of the water vapour in the mixture.

2.3.18 Specific Humidity or Humidity Ratio

It is the mass (kg) of the water vapor in each kg of dry air (kg/kg).

2.3.19 Relative Humidity (RH)

It is the ratio of mass of water vapour actually held by the air in a given volume to that which air could hold at the same temperature if the air were saturated. It is expressed as a percentage. Warmer air will hold more water vapour and saturated air cannot hold any more water vapour.

Relative humidity affects comfort conditions. An air sample that is at 50% RH is holding half the moisture it is capable of holding at the same temperature (at dew point or saturated).

2.3.20 Dry bulb and Wet bulb Temperatures

Dry bulb measures sensible heat content in air-vapour mixtures. Dry bulb temperature is not influenced by RH. It is the temperature recorded by the thermometer with a dry bulb.

Wet bulb thermometer has wick saturated with distilled water enveloping the bulb of the thermometer. The evaporation of water lowers temperature, taking the latent heat from the water-soaked wick-thus decreasing the temperature recorded. Wet bulb temperature takes into account RH.

If relative humidity is 100%, dew point, wet bulb and dry bulb temperatures are all the same.

2.3.21 Enthalpy of air

It is the measure of total heat content of air and water vapour mixture measured from pre-determined base point. It is expressed as $kCal/kg$. Enthalpy of air stream can be determined by measuring dry and wet bulb temperature and referring the psychometric chart.

2.3.22 Fuel Density

Density is the ratio of the mass of the fuel to the volume of the fuel at a stated temperature. Density is expressed in kg/m^3.

2.3.23 Specific gravity of fuel

The specific gravity of fuel is the ratio of density of fuel to that of water. The specific gravity of water is defined as 1. As it is a ratio there are no units. Higher the specific gravity, higher will be the heating values. Specific gravity has no dimensions.

2.3.24 Viscosity

The viscosity of a fluid is a measure of its internal resistance to flow. All liquid fuels decrease in viscosity with increasing temperature. Higher viscosity of fuel required higher pumping power.

Viscosity is measured in $Stokes$ / $Centistokes$. Sometimes viscosity is quoted in Engler, Saybolt or Redwood.

2.3.25 Energy Content in Fuel

Energy content (**Calorific Value**) in an organic matter can be measured by burning it and measuring the heat released.

The heating value of fuel is the measure of the heat released during the complete combustion of unit weight of fuel. It is expressed as Gross Calorific Value (GCV) or Net Calorific Value (NCV). Relationship between GCV and NCV-

$$GCV = NCV + Heat\ of\ Vaporisation\ of\ Water \cdots\cdots\cdots\cdots \cdots\cdots\cdots (2.28)$$

Typical GCV and NCV for heavy fuel oil are 44100 J/kg (10,500 kcal/kg) and 41160 J/kg (9,800 kcal/kg).

Higher Heating Value (HHV) other-wise known as Gross Calorific Value (GCV)
Lower Heating Value (LHV) other-wise know as Net Calorific Value (NCV)

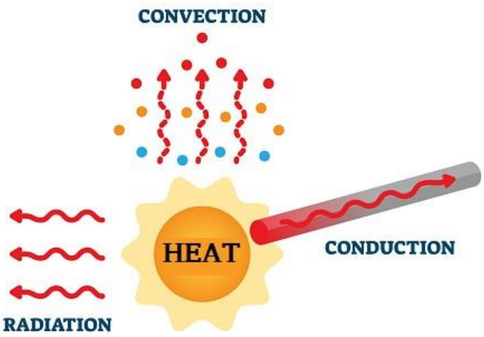
2.3.26 Heat transfer

Heat will always be transferred from hot to cold independent of the mode. The energy transferred is measured in Joules. The rate of energy transfer, more commonly called heat transfer, is measured in Watts (J/s)

Heat is transferred by three primary modes:

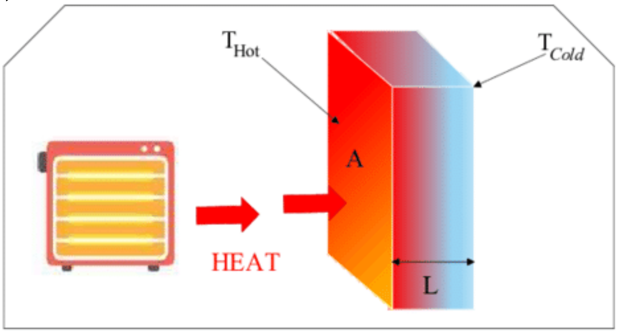
- Conduction (Energy transfer in a solid)
- Convection (Energy transfer in a fluid)
- Radiation (doesn't need a material to travel through)

Conduction is the primary mode of heat transfer through solid. Conduction occur by molecular vibration, whereas Convection occur by molecular movement. Radiation occur by electromagnetic radiation.



Equations of Heat transfer

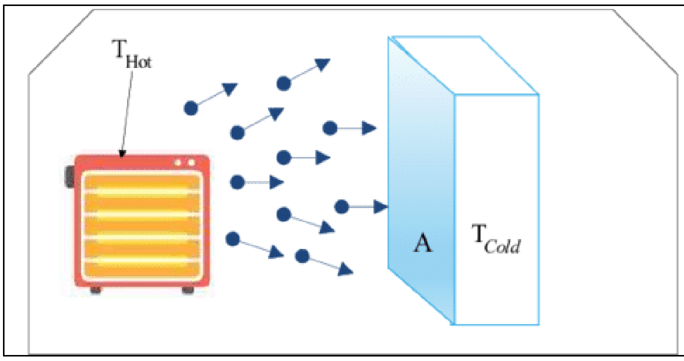
(a) Conduction



$$q = \frac{kA(T_{hot} - T_{cold})}{L} \cdots\cdots (2.29)$$

Where, T= Temperature,
A= Exposed area
L= depth of solid
K= thermal conductivity

(b) Convection



$$q = h(T_{hot} - T_{cold}) \cdots\cdots (2.30)$$

Where, T= Temperature,
A= Exposed area
L= depth of solid
h= Convection Coefficient

(c) Radiation

$$q = \varepsilon\sigma A(T_2^4 - T_1^4) \cdots\cdots\cdots\cdots (2.31)$$

Where,
$q = heat\ transfer$
$\varepsilon = Emmissivity\ of\ material$
$\sigma = stefan\ boltzman\ constant = 5.67 \times 10^{-8}\ W.m^{-2}/K^{-4}$
$T_2, T_1 = Temperatures$

Figure 2.5: Illustration of Conduction, Convection and Radiation Heat Transfer

2.3.27 Steam Properties Evaporation

When a liquid evaporates it goes through a process where

- ✓ The liquid heats up to the evaporation temperature
- ✓ The liquid evaporates at the evaporation temperature by changing state from fluid to gas
- ✓ The vapor heats above the evaporation temperature - superheating

The heat transferred to a substance when temperature changes is often referred to as sensible heat. The heat required for changing state as evaporation is referred to as latent heat of evaporation.

The most common vapour is evaporated water - steam.

2.3.28 Enthalpy of steam

Enthalpy means total amount of energy in a system. Enthalpy of a system is defined as the mass of the system (m) multiplied by the specific enthalpy (h) of the system and can be expressed as:

$$H = m\,h \cdots\cdots\cdots (2.32)$$

Where,

$H = enthalpy\ (kl)$

$m = mass\ (kg)$

$h = specific\ enthalpy\ (kJ/kg)$

Specific Enthalpy

Specific enthalpy is a property of the fluid and can be expressed as:

$$h = u + pv$$

Where,

$u = internal\ energy\ (kJ/kg)$

$p = absolute\ pressure\ (N/m^2)$

$V = specific\ volume\ (m^3/kg)$

2.3.29 The laws of thermodynamics

Thermodynamics is the study of heat and work, and the conversion of energy from one form into another. There are actually three laws of thermodynamics, although the majority of thermodynamics is based on the first two laws.

The first law of thermodynamics: The first law of thermodynamics is also known as the law of conservation of energy. It states that the energy in a system can neither be created nor destroyed. Instead, energy is either converted from one form to another, or transferred from one system to another.

The second law of thermodynamics: While the first law of thermodynamics refers to the quantity of energy that is in a system, it says nothing about the direction in which it flows.

It is the second law which deals with the natural direction of energy processes. For example, according to the second law of thermodynamics, heat will always flow only from a hot object to a colder object.

Another term arising from the second law of thermodynamics is the term ‘entropy’ which means disorder. Entropy can be used to quantify the amount of useful work that can be performed in a system. In simple terms, the more chaotic or disorderly a system, the more difficult it is to perform useful work.

It is the second law of thermodynamics that accounts for the fact that a heat engine can never be 100% efficient. Some of the heat energy from its fuel will be rejected to the surroundings, with the result that it will not be converted into mechanical energy.

The third law of thermodynamics: The third law of thermodynamics is concerned with absolute zero (i.e.$-273\ C$). It simply states that it is impossible to reduce the temperature of any system to absolute zero.

We will be using these fundamental basics (2.1, 2.2 & 2.3) throughout this book. Please carefully memorize or find a way to use these basics in the practical applications.

2.4 Energy Management System: Demand & Supply Side

Energy such as electricity, oil, coal, and natural gas is being consumed in all facilities for its operations. If energy is not efficiently used and managed, it will increase operational and maintenance costs besides polluting the environment.

Energy management can be defined as:

"The judicious and effective use of energy to maximize profits (that is, minimize costs) and enhance competitive positions.""

Successful energy management need an effective strategy and involves all employees. Energy audit is the key to a systematic approach for decision making in the area of energy management.

The objectives of Energy Management include,

- To achieve and maintain optimum energy procurement and utilisation, throughout the organisation
- To minimize energy costs/waste without affecting production and quality
- To minimise environmental effects

Energy Audit

An energy audit is an investigation of a facility's historical and current energy use with an objective of identifying and quantifying areas of energy wastage in its activities.

The outcome is the identification of viable and cost-effective energy saving measures to reduce energy consumption per unit of product output thereby lowering the operating costs.

Energy audit serves as the 'foundation' on which successful energy management programme can be built in an organisation. Energy audit also provides a 'benchmark' for managing energy and planning a more effective use of energy throughout the facility.

Energy Management can be broadly classified based on policy into two category Supply side Energy Management and Demand Side Energy Management

Supply Side Energy Management: The Supply Side Energy Management (SSEM) refers to the actions taken to ensure the generation, transmission and distribution of energy efficiently. The SSM enables the installed generating capacity to provide electricity at lower cost and reduces environmental emissions per unit of end-use electricity provided.

Demand Side Energy Management: Demand-Side Energy Management (DSEM) refers to the action taken for the energy customer to lower energy demand, which in turn avoids the cost of building new infrastructure like generators, transmission lines etc. and saves customers money, lowers pollution from electric generators. These actions are Energy Audit Program, Awareness program, Labelling Program, Financial Incentive program, EE building program etc.

2.4.1 ISO 50001:2018

In order to manage energy well, an organization requires an effective Energy Management System (EnMS) to be established, implemented, maintained and continually improved. There are two ways to doing it; they can develop and implement their own Energy Management System or they can implement Energy Management System conforming to ISO 50001.

It is in the interest of the organizations to go for ISO 50001 since it is based on the management system model that is already understood and implemented by organizations worldwide. It can make a positive difference for organizations of all types immediately even without any investment, while supporting longer term efforts for capital intensive energy-efficient technologies.

In order to spur interest in energy efficiency and help organisation take appropriate actions to overcome barriers in implementing practical energy saving measures, International Organisation for Standardisation (ISO) had released the first version of 'ISO 50001 Energy Management Systems (EnMS)–Requirements with guidance for use' in June 2011 and revised version of ISO 50001:2018 in August, 2018.

The implementation of ISO 50001 will provide following benefits:

a) provide organizations with a well-recognized framework for integrating energy efficiency into their management/business practices,
b) provide a logical and consistent methodology for identifying and implementing improvements that can contribute to a continual increase in energy efficiency across the facilities,
c) assist organizations to better utilize existing energy consuming assets, thus reducing costs and/or expanding capacity,
d) offer guidance on benchmarking, measuring, documenting, and reporting energy efficiency improvements,
e) lead the organizations to meet overall climate change mitigations goals by reducing their energy related greenhouse gas emissions,
f) assist facilities in evaluating and prioritizing implementation of state-of-the-art energy-efficient technologies,
g) provide an approach for organizations to encourage suppliers to better manage their energy, thus promoting energy efficiency throughout the supply chain.

Role of Energy Manager for implementation of ISO 50001:2018: Energy Manager can play a significant role in implementing ISO 50001:2018. In this standard, all requirements of Energy Management System have been clearly stated. First of all, Energy Manager should read or get trained for basic implementation methods of ISO 500001. Role of Energy Manger for this implementation is tentatively listed below-

1. Determine the external and internal issues that are relevant to organisation's purpose and that affect its ability (positive or negative) to achieve the intended outcome(s) of its Energy Management System.
2. Determine the needs and expectation of interested parties (like government policy, legal requirement, international laws, buyers' requirements etc.). List all applicable legal and other requirement and create a resister.
3. Determine and document the scope and boundaries to be covered under Energy Management System (EnMS). While determining EnMS Scope, external and internal issues need to be considered.
4. Implement and maintain the Energy Management System
5. Identify Energy Baseline, Energy Performance Indicator, Energy Review of the organisation
6. Energy Manager should also assist the firm who is working for ISO 500001: 2018 certification of that organisation.

2.5 Fundamentals of Energy Audit: Role of Energy Manager

Energy Manager of an organization should always seek the opportunities to save energy and aim to influence all projects in which energy is a significant factor. Energy Manager is the person who should seek the opportunity/necessity to appoint the energy auditor in the premise. He/she can assist the Energy Audit with his depth of knowledge. Some of them are-

1. Energy Manager can look for the ways to match energy equipment capacity to end use needs. For Example, Pump capacity (flow) more than required and throttled: Energy manager can eliminate throttling of a pump by impeller trimming, installing variable frequency drive, replacing existing pump with a smaller pump.
2. He/she can look for opportunities to maximize the system efficiency. Once the energy source and usage is matched, next step is to operate the equipment efficiently using best operation and maintenance practices.
3. Energy Manager should continue his day-to-day energy efficiency maintenance works.

To equip the energy manager organisation should procure most handy, portable, durable, easy to operate and relatively inexpensive instruments and metering equipment. The operating instructions for all instruments must be understood and staff should familiarize themselves with the instruments.

When an Energy Audit is being implemented Energy Manager can play a vital role to assist the Energy Auditors. He/she will be one of the team members of the energy audit team. He can assist with-

1. Providing relevant information regarding the organisation being audited
2. Suggest priority area of investigation needed
3. Identify major energy consuming areas/process to be audited
4. Provide major energy consumption and production data

2.6 Scope of Energy Audit

Typically, the scope of an energy audit includes an examination of the following areas:

- Energy conversions in equipment such as boilers, furnaces, transformers, pumps, fans, compressors etc.
- Energy distribution (electricity, steam, condensate, compressed air, water etc.)
- Energy utilisation efficiency of equipment
- Production planning, operation, maintenance, and housekeeping
- Management aspects (information flow, data collection and analysis, feedback, achievements, training of employees, motivation, etc.)

2.7 Project Management

On completion of energy audit, the management team reviews the report and decides on the course of action. At this point, the facility is ready to prioritise and implement various energy conservation measures and tool such as ISO 50001 is highly useful. Management can think for a project to implement the energy management recommendation provided by the Energy Auditor.

At this position, it is worth mentioning that Energy Service Company (ESCO) can be engaged to conduct detailed energy audit from the beginning or can be involved later in implementation of detailed energy audit measures. The ESCO evaluates the detailed energy audit in order to offer a comprehensive efficiency solution that captures all energy efficiency opportunities and not just the obvious ones. This is carried out by preparing a detailed project report (DPR).

A typical DPR includes the following:

▪ Examination of technological parameters
▪ Description of the technology to be used
▪ Broad technical specification
▪ Evaluation of existing resources
▪ Project schedule/execution plan
▪ General layout
▪ Volume of work

A project is a "temporary endeavour undertaken to create a unique product or service". Projects are temporary because they have a definite beginning and a definite end. They are unique because the product or service they create is different in some distinguishing way from similar products or services.

Designing, installation and commissioning of a cogeneration system in an industry is an example of a project. The unique work is defined by the cogeneration system and has a specific beginning and end.

2.7.1 Project Development Cycle (PDC)

The various steps in the PDC are:

1. Project Identification and Screening

In this step, different components of future project are identified by both internally and externally. Energy Manger/facility manager can act as internal personnel and detailed energy audits and respective energy auditor can act as external personnel. Afterward screening is done based on below criteria-

- ✓ Economic feasibility of energy savings measures (Internal rate of return, net present value, cash flow, average payback)
- ✓ Sustainability of the savings over the life of the equipment.
- ✓ Ease of quantifying, monitoring, and verifying energy savings.
- ✓ Availability of technology, and ease of adaptability of the technology to Bangladeshi conditions.
- ✓ Other environmental and social cost benefits (such as reduction in GHG emissions and local pollutants such as SOx emissions)

2. Technical Design

For a project to be considered a viable investment, the project proponent must present a sound technical feasibility study that identifies the following elements in detail:

- ✓ The proposed new technologies, process modifications, equipment replacements and other measures included in the project.
- ✓ Product/technology/material supply chain (e.g., locally available, imported, reliability of supply)
- ✓ Any special technical difficulties (installation, maintenance, repair), associated skills required.
- ✓ Preliminary designs, including schematics, for all major equipment needed, along with design requirements, manufacturer's name and contact details, and capital cost estimate.
- ✓ Organizational and management plan for implementation, including timetable, personnel requirements, staff training, project engineering, and other logistical issues.

3. Financing

When considering a new project, it should be remembered that other departments in the organization would be competing for capital for their projects. However, it is also important to realize that energy efficiency is a major consideration in all types of projects, whether they are:

- ✓ Projects designed to improve energy efficiency
- ✓ Projects where energy efficiency is not the main objective, but still plays a vital role.

Most organization reaches the point when all the obvious measures to save energy have been taken and capital investment is needed to make further savings. Low cost measures for saving energy, which can be treated as mini projects in their own rights, should be given top priority. It is necessary to ensure that the present system is operating efficiently before spending any money.

4. Contracting

Since a substantial portion of a project is typically executed through contracts, the proper management of contracts is critical to the successful implementation of the project. In this context, the following should be taken care.

- ✓ The competence and capability of all the contractors
- ✓ Proper discipline must be inculcated among contractors and suppliers by insisting that they should develop realistic and detailed resource and time plans that are matching with the project plan.
- ✓ Penalties-which may be graduated-must be imposed for failure to meet contractual obligations. Likewise, incentives may be offered for good performance.
- ✓ Help should be extended to contractors and suppliers when they have genuine problems-they should be regarded as partners in a common pursuit.
- ✓ Project authorities must retain independence to off-load contracts (partially or wholly) to other parties well in time where delays are anticipated.

5. Implementation

A great deal of the emphasis in the planning stage of any project is on understanding where and when problems may occur. Many projects introduced by energy managers end up as some other manager's responsibility, e.g., a production manager or a works engineer. The following needs to be thought ahead and anticipated.

- ✓ Type and extent of measurements needed to control and measure the success of the project
- ✓ Winning the confidence and cooperation of key personnel involved.
- ✓ Timely and frequent communication between participants.

With proper techniques, changes and modifications in project can be understood and incorporated without loss of control.

Before considering the components of a plan, its purpose must be defined. A plan turns a proposed project into reality. As reality often differs from theory, the plan should consider as many technical, financial and other 'what ifs' as possible.

6. Performance Monitoring

In order to track the progress of the project, a system of monitoring must be established. This helps in:

- ✓ Anticipating deviations from the implementation plan
- ✓ Analysing emerging problems
- ✓ Taking corrective action

In developing a system of monitoring, the following points must be borne in mind:

- ✓ It should focus sharply on the critical aspects of project implementation.
- ✓ It must lay more emphasis on physical milestones and not on financial targets.
- ✓ Monitoring must be kept simple.

2.7.2 Project Planning Techniques:

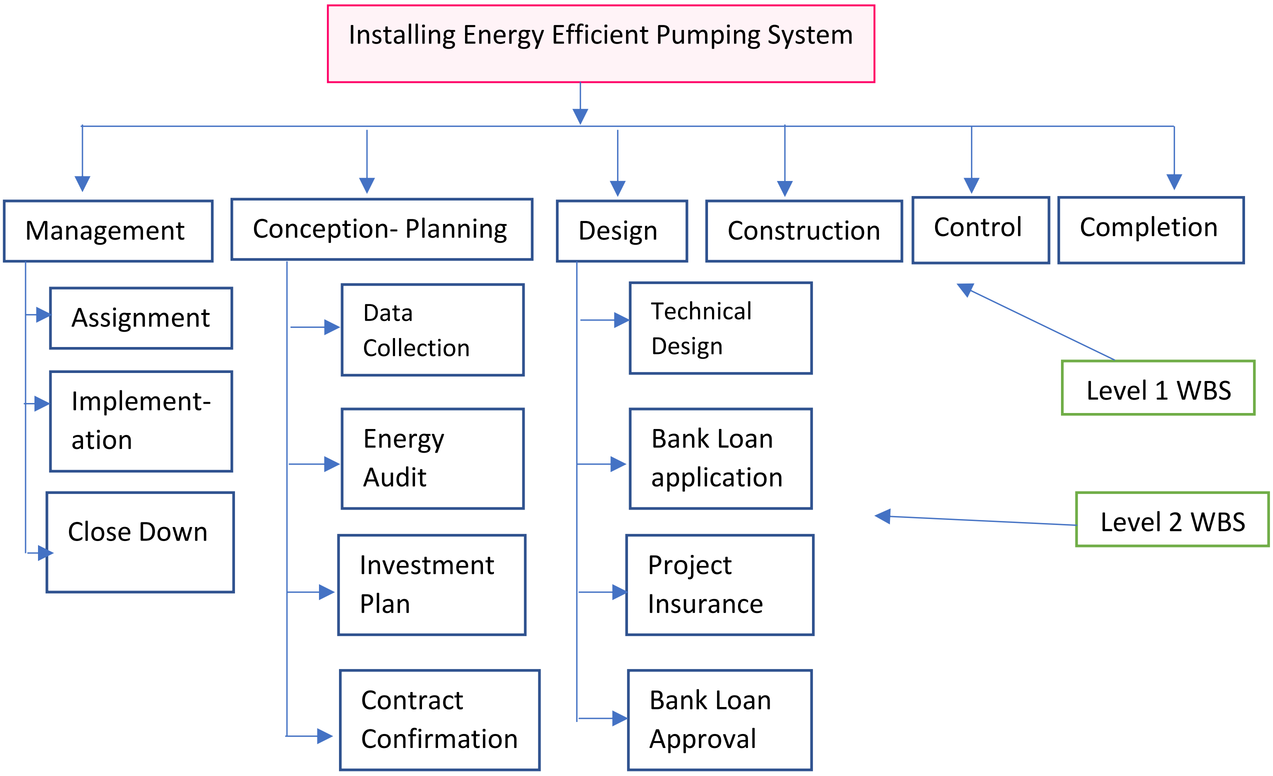
To achieve control of a project, it is necessary to plan. For more complex projects, the more advanced planning methods are needed. Some major project planning techniques are:

1. Work Breakdown Structure (WBS)
2. Gantt chart
3. Project Networking Techniques
4. Critical Path Method (CPM)
5. Program Evaluation and Review Technique (PERT)

1. Work Breakdown Structure (WBS)

   Work Breakdown Structure (WBS) is the process of dividing complex projects to simpler and manageable tasks. The project managers use this method for simplifying the project execution. WBS can be displayed using tree structure or list or tables. An example of energy efficiency project of an industry is given for reference. WBS is developed before dependencies are identified and activity durations are estimated.

   The WBS can be used to identify the tasks before constructing Gantt chart and networks such as Critical Path Method -CPM and Program Evaluation and Review Technique— PERT.



2. Gantt chart

During the era of scientific management, Henry Gantt developed a tool for displaying the progress of a project in the form of a specialized chart. An early application was the tracking of the progress of ship building projects. Today, Gantt's scheduling tool takes the form of a horizontal bar graph and is known as a Gantt chart.

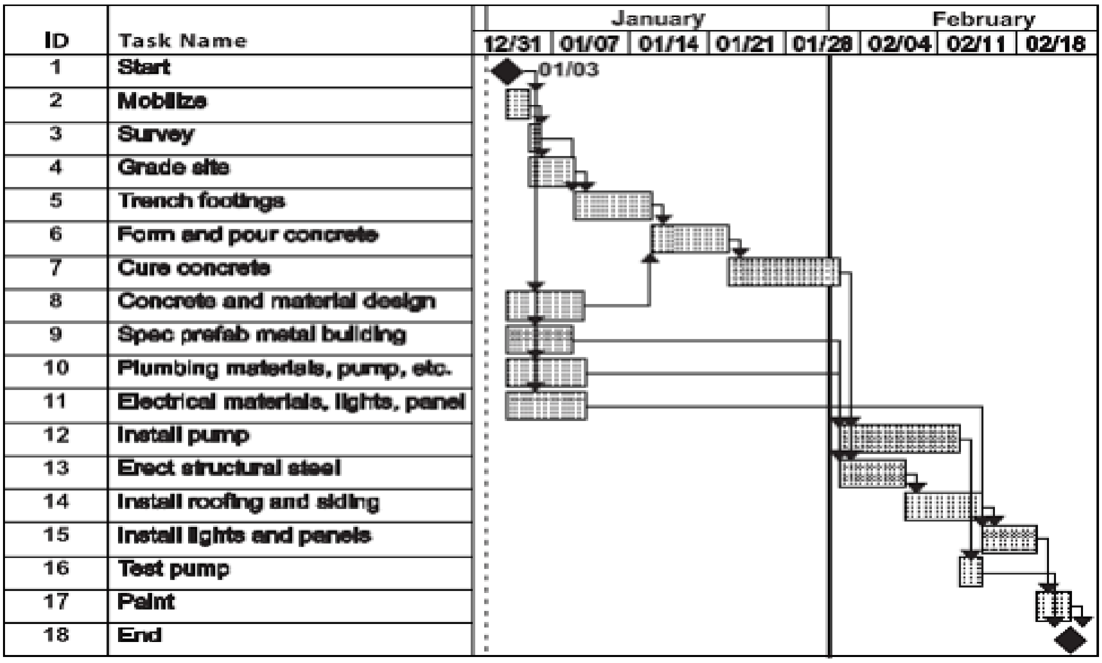


Figure 2.6: Gantt chart for a pumping station

Limitation of Gantt chart

The Gantt chart does not normally show the logical interdependencies between the predecessor and successor activities very well. Such requirements are best served by the network diagram, which shows logic clearly but does not have a time scale axis like the Gantt chart.

3. Project Networking Techniques:

Project network shows dependency relationships between tasks/activities in a project in a graphical View. It shows clearly tasks that must precede or succeed other tasks in a logical manner. It is a powerful tool for planning and controlling project. Some Definitions are-

Activity: Any portions of project (tasks) which required by project, uses up resource and consumes time.

Event: Beginning or ending points of one or more activities are called 'nodes'

Network: Combination of all project activities and the events

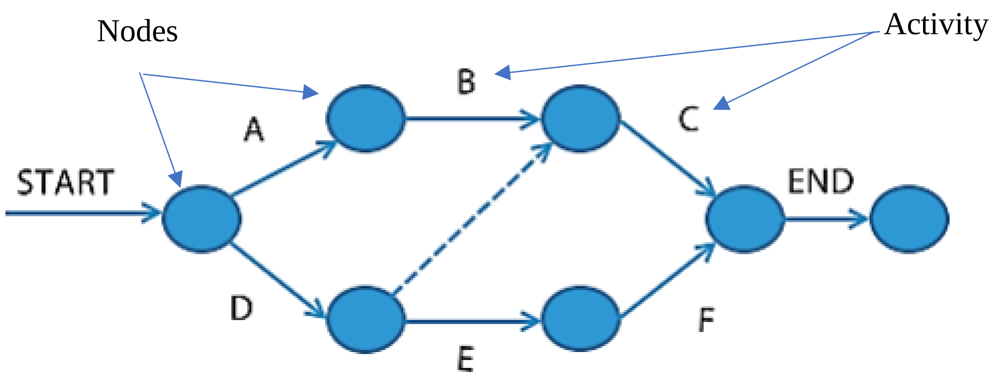


Figure 2.7: Project Network

4. Critical Path Method (CPM)

The critical path is the longest-duration path through a project network. The significance of the critical path is that the activities that lie on it, cannot be delayed without delaying the project. Because of its impact on the entire project, critical path analysis is an important aspect of project planning.

Steps in CPM Project Planning-

a) Specify the individual activities (Work Breakdown Structure method)
b) Determine the sequence of those activities. (Project Network Technique)
c) Draw a network diagram.
d) Estimate the completion time for each activity.
e) Identify the critical path (longest path through the network)
f) Update the CPM diagram as the project progresses.

5. Program Evaluation and Review Technique (PERT)

The Program Evaluation and Review Technique (PERT) is a probabilistic network model that allows for randomness in activity completion times. PERT was developed in the late 1950's for the US. Navy's Polaris project having thousands of contractors. It has the potential to reduce both the time and cost required to complete a project.

2.7.3 Evaluation of Critical Path Method (CPM)

The critical path can be identified by determining the following four parameters for each activity:

- ES - Earliest start time: the earliest time at which the activity can start given that its precedent activities must be completed first.
- EF - Earliest finish time: equal to the earliest start time for the activity plus the time required to complete the activity.
- LF - Latest finish time: the latest time at which the activity can be completed Without delaying the project.
- LS - Latest start time, equal to the latest finish time minus the time required to complete the activity.

The total float (slack time) for an activity is the time between its earliest and latest start time, or between its earliest and latest finish time. Slack is the amount of time that an activity can be delayed past its earliest start or earliest finish without delaying the project.

The critical path is the path through the project network in which none of the activities have slack, that is, the path for which ES=LS and EF=LF for all activities in the path. A delay in the critical path delays the project

Example 2.13

WBS of a project is given below

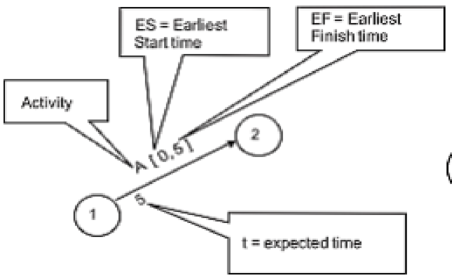
Activity	Immediate Predecessor	Completion time (weeks)
A	-	5
B	-	6
C	A	4
D	A	3
E	A	1
F	E	4
G	D, F	14
H	B, C	12
I	G, H	2

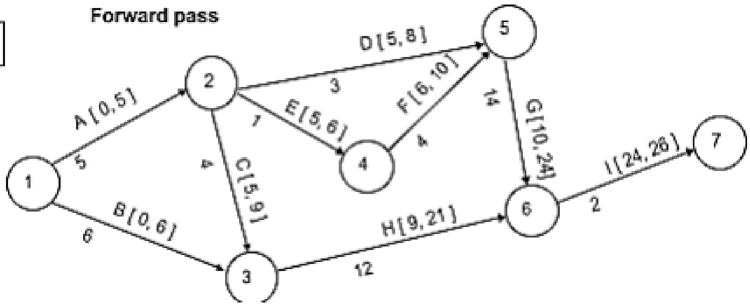
Find out Critical path of the network.

Solution:

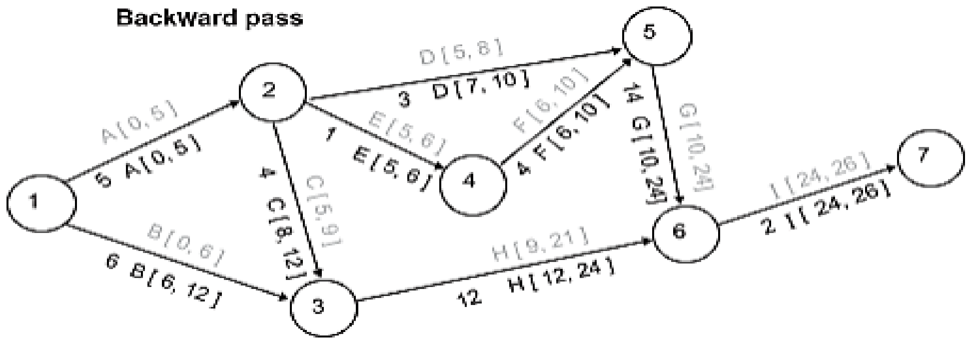
Forward Pass: The expression EF = ES + t can be used to find the earliest finish time for a given activity. The completion time or the duration of an activity is represented as t.

For activity A, ES = 0 and t = 5; thus, the earliest finish time for activity A is EF = 0 + 5 = 5.





Backward Pass: The expression LS = LF — t can be used to calculate latest start time for each activity. For example, for activity I, LF = 26 and t = 2, thus the latest start time for activity I is LS = 26 -2 = 24.



Float or Slack or Free Time:

slack for C = 3 weeks, i.e. Activity C can be delayed up to 3 weeks {LS (8 weeks) — ES (5 weeks) or LF (12 weeks) — EF (9 weeks) = 3 weeks}

Summary

Activity	Duration (weeks)	Earliest Start ES	Earliest Finish EF	Latest Start LS	Latest Finish LF	Float or Slack LS-ES or LF-EF	Critical Path
A	5	0	5	0	5	0	Yes
B	6	0	6	6	12	6	
C	4	5	9	8	12	3	
D	3	5	8	7	10	2	
E	1	5	6	5	6	0	Yes
F	4	6	10	6	10	0	Yes
G	14	10	24	10	24	0	Yes
H	12	9	21	12	24	3	
I	2	24	26	24	26	0	Yes

Critical Path- A-E-F-G-I= 5+1+4+14+2= 26 weeks

The total time to complete the activities is 26 weeks.

2.8 Financial Management

Businesses are increasingly realizing that prices of energy like coal, oil and natural gas are going to be expensive and there is a need to reduce energy use. Energy savings can be achieved by

- improving organizational procedures,
- adopting best operation and maintenance (O & M) practices, and/or
- Modifying or replacing existing equipment with energy efficient equipment.

These energy efficiency measure implementations would definitely require some investment. The investment requirements for different options need to be prioritized to derive maximum benefit at least cost. The investment criteria is also governed by the level of investments required, funding options available, ease of obtaining finance, demand for their products (increasing/decreasing/static), interest & currency rate scenarios, taxation, cost of production etc.

2.8.1 Investment Need and Appraisal Criteria

To consider investment in energy efficiency an organization need to be convinced that the energy project is profitable and comparable to other profit enhancement projects like increasing production. An investment proposal highlighting the following aspects should be presented to the management for active consideration of energy projects.

- The size of the energy problem it currently faces (e.g. Cost of energy in terms of overall production costs, regulatory requirements etc.)
- Best operational and maintenance practices available to reduce energy use or improve energy efficiency at low costs (e.g. by providing appropriate training to employees).
- Proven and implemented energy saving projects that are technically and economically feasible.
- Incentives available that make the project financially viable.
- Add on benefits from the energy project in terms of faster production, improved product quality, safety, human comfort in quantitative terms to the extent possible.
- The predicted return on investment.
- The need for investments in energy conservation can arise under following circumstances

- To retrofit existing technology & equipment and with new energy efficient one owing to normal replacement of equipment at end of life or due to substantial savings foreseen by replacing existing equipment,
- To modify or improve existing process by new technology owing to regulations or substantial savings foreseen.
- To provide staff training
- To implement or upgrade the energy information system

Investment Appraisal criteria
Energy manager has to

- Identify how cost savings arising from energy management contribute to profits,
- How energy projects are comparable to other profit enhancing projects and
- How energy projects are integral to manufacturing and not standalone projects.

To do this, he/she has to work out how benefits of increased energy efficiency can be best sold to top management as:

- Reducing operating /production costs
- Increasing employee comfort and well-being and thereby scope of worker productivity.
- Improving cost-effectiveness and/or profits
- Protecting under-funded core activities
- Enhancing the quality of service or customer care delivered.
- Protecting the environment

To conduct the investment appraisal it needs to be appreciated that investment in energy efficiency is no different from any other investments. So one should apply the same criteria to energy saving investments as it applies to all its other investments.

2.8.2 Financial Analysis Approach and Techniques

Business's prime goal is to maximize profits. So, in assessing the financial viability of any project the proposal should answer the following questions.

- How much will the proposal cost?
- How much money will be saved by the proposal?
- Whether alternate proposals cost less and save more?

It is therefore important that the financial appraisal process allows for all these factors, with the aim of determining which investments should be undertaken, and of optimizing the benefits achieved. The appraisal process involves understanding of types of costs and their impacts on the project. This appraisal process is divided into three parts.

- The first part of this analysis will cover types of costs and their impacts.
- The second part will cover techniques for appraisal of investment.
- The third part will cover sensitivity analysis to assess risks associated in financial appraisal of projects.

Profit, Revenue and Costs

Business's prime goal is to maximize profits which occurs when difference between total revenue and total cost is the highest.

$$Profit = Total\ Revenue - Total\ Costs \ \cdots\cdots\cdots \ (2.33)$$

Energy specialists have no control on factors impacting revenue. However, energy specialists can aid in cost minimization by

- identifying and evaluating energy conservation ways in existing systems to reduce energy consumption costs
- modifying, replacing equipment or system which involve purchasing and costs money

Understanding fixed and variable costs

Example 2.14

The capital cost of the DG set is BDT 9,00,000, the annual output is 219 MWh, and the maintenance cost is BDT 30,000 per annum. The cost of producing each unit of electricity is 3.50 BDT/kWh. The total cost of a diesel generator operating over a 5-year period, taking into consideration both fixed and variable cost is:

Item	Type of Cost	Calculation	Cost (BDT)	percentage
Capital cost of generator	Fixed	-	9,00,000	21.5%
Annual Maintenance	Fixed	30,000 x 5 (years)	1,50,000	
Fuel cost	Variable	219,000 x 3.50 x 5	38,32,500	
		Total Cost	48,82,500	

It can be seen that the fixed costs represent 21.5% of the total cost. In fact, the annual electricity output of 219 MWh assumes that the plant is operating with an average output of 50 kW.

If this output were increased to an average of 70 kW, then the fuel cost would become BDT 53, 65,500, with the result that the fixed costs would drop to 16.37% of the total.

Thus, the average unit cost of production decreases as output increases. This phenomenon is better explained using the concept of marginal analysis.

Marginal analysis

Marginal analysis is used to determine how much amount should be spent on energy saving projects. Marginal refers to the last increment of a variable, like last LED bulb or solar panel installed in a building. The criteria applied for the project is till the marginal savings exceed the marginal cost, it is economical to add another unit. The example below illustrates the application and concept.

Example 2.15

The marginal cost and cost savings of insulating a home with different thicknesses of insulation are as follows:

Amount of insulation (in inches)	(BDT)	
	Marginal cost per sq. ft of last inch	Savings per sq. ft of last inch
1	5.83	125.01
2	1.67	41.67
3	1.67	16.67
4	1.67	8.33
5	1.67	5.83

6	1.67	4.17
7	1.67	2.50
8	1.67	2.08
9	1.67	1.25

Find out Marginal thickness of insulation?

The proper amount is where marginal cost is equal to marginal cost savings. This occurs between the eighth and ninth inch of insulation. Therefore, if the home owner installs the eighth inch, the cost savings are greater than the costs. However, if the ninth inch is installed, the cost of that inch is greater than the cost savings it generates. Since insulation cannot be bought by the half-inch the least profitable inch to install in this case is the eighth inch.

Therefore, eighth inches of insulation should be installed.

Break-even Analysis

The concept of fixed and variable costs can be used to determine the break-even point for a proposed project. The break-even point can be determined by using the following equation.

$$\mathrm{UC_{util}} \times \mathrm{W_{av}} \times \mathrm{n} = \mathrm{FC} + \left(\mathrm{UC_{prod}} \times \mathrm{W_{av}} \times \mathrm{n}\right) \cdots\cdots\cdots (2.34)$$

Where,

$\mathrm{UC_{util}}$ = unit cost per kWh of energy bought from utility (BDT/kWh)
$\mathrm{UC_{prod}}$ = unit cost per kWh of produced energy(BDT/kWh)
FC = fixed costs(BDT)
$\mathrm{W_{av}}$ = average power output (or consumption) (kW)
n = number of hours of operation(hours)

Example 2.16

If the electricity bought from a utility company costs an average of BDT 4.5/kWh, the breakeven point for the generator described in Example 1, when the average output is 50 kW is given by:

$$4.5 \times 50 \times \mathrm{n} = (900000 + 150000) + (3.5 \times 50 \times \mathrm{n})$$

n = 21000 hours

If the average output is 70 kW, the break-even point is given by:

$$4.5 \times 70 \times n = (9{,}00{,}000 + 1{,}50{,}000) + (3.50 \times 70 \times n)$$

n = 15000 hours

Thus, increasing the average output of the generator significantly reduces the break-even time for the project. This is because the capital investment (i.e., the generator) is being better utilized.

Time Value of Money

Financial organizations like banks offer interest on money deposited and charge interest on money lent. Business organizations borrow for projects if the earnings anticipated are more than the interest charged for borrowing.

The interest charges change the value of money with time creating the problem of equating cash flows which occur at different times. To account for the time value of money and to equate cash flows it is therefore important to understand interest charge calculation and equating cash flow.

Table: 2.2 Calculation and Concept of Simple and Compound interest

Simple Interest (SI) $$SI = \frac{r}{100} \times P \times n \cdots\cdots\cdots (2.35)$$	Compound interest (CI) $$\boldsymbol{CI} = \boldsymbol{P} \times (\mathbf{1} + \frac{\boldsymbol{r}}{\mathbf{100}})^{\boldsymbol{n}} \cdots\cdots\cdots\cdots (2.36)$$
Total Repayment value based on SI (TRV) $$TRV_{SI} = \frac{P \times n \times r}{100} + P \cdots\cdots\cdots\cdots (2.37)$$	Total Repayment value based on CI (TRV) $$\mathrm{TRV_{CI}} = P \times (1 + \frac{r}{100})^{n} + P \cdots\cdots\cdots\cdots (2.38)$$
P= Principle value R= interest rate n = repayment period (years) SI= Simple Interest CI= Compound interest TRV= Total repayment value which represent the future value of principal borrowed	

Example 2.17: Calculating Simple and Compound Interest

A company borrows BDT 30,00,000/- to finance a new boiler installation. If the interest rate is 10% per annum and the repayment period is 5 years. Calculate the value of the total repayment and the monthly repayment value, assuming (i) simple interest and (ii) compound interest.

Solution: Given,
P = 30,00,000 BDT
n= 5 years
r = 10%

Assuming simple interest:

From equation 2.37

$$TRV_{SI} = \frac{P \times n \times r}{100} + P$$
$$\Rightarrow TRV_{SI} = \frac{30{,}00{,}000 \times 5 \times 10}{100} + 30{,}00{,}000$$
$$\Rightarrow TRV_{SI} = 45{,}00{,}000\ BDT$$

Monthly Repayment = $\frac{45{,}00{,}000}{5\times12} = 75{,}000\ BDT$

Assuming compound interest:
From equation 2.38,

$$\mathrm{TRV_{CI}} = P \times (1 + \frac{r}{100})^{n} + P$$

$$= 30{,}00{,}000 \times (1 + \frac{10}{100})^{5} + 30{,}00{,}000$$
$$= 48{,}31{,}530\ \mathrm{BDT}$$

Monthly Repayment = $\frac{48{,}31{,}530}{5\times12} = 80{,}525\ BDT$

It can be seen that by using compound interest, the lender recoups an additional BDT 33, 1530 ($= 48{,}31{,}530 - 45{,}00{,}000$). Lenders usually charge compound interest on loans.

Equating Cash flow:
The method by which various cash flows are related is called future, or the present value concept.

If money deposited in the bank at 10% interest, then a BDT 100 deposit will be worth BDT 110 in one year's time. Thus the BDT 110 in one year, is a future value equivalent to the BDT 100 present value. In the same manner, BDT 100 received one year from now is only worth BDT 90.91 in today's money. Thus BDT 90.91 represents the present value of BDT 100 cash flow occurring one year in the future

$$\text{Future Value} = \text{NPV}\,(1+\text{i})^{n} \;\cdots\cdots\cdots\cdots (2.39)$$

$$\text{NPV} = \frac{\text{FV}}{(1+\text{i})^{\text{n}}} \cdots\cdots\cdots\cdots (2.40)$$

Where
FV = Future value of the cash flow
NPV= Net Present Value of the cash flow
i = Interest or discount rate
n = Number of years in the future

Example 2.18 Future Value of a Fixed Amount Greater than BDT1

A house decides to buy two 1 m^2 solar collector panels at BDT 20000/ each and has the option of paying BDT 20000/ now or BDT 30000/ 5 years from now. The relevant interest rate is 10%.
Find the payment plan that will minimize the cost the house owner must pay using future value method.

Solution:

From Equation 2.39,

The future value of BDT 20000, 5 years from now, is calculated as follows

$$\text{FV} = \text{NPV}\,(1+\text{i})^{\text{n}}$$

$$\Rightarrow \text{FV} = 2000\,(1+\frac{10}{100})^{5} = \;32210\ \text{BDT}$$

So, Future value of 20000 BDT is higher than 30,000 BDT 5 years from now. So it is wise to wait for 5 year and pay 30000 BDT instead of paying 20000 BDT now.

Annuity
Most projects yield series of cost savings contrary to one-time amount as per the present/future value equation. These series of cash-flows are to be standardized, because savings occur at different times. The standardization can be done by assessing the present/future value of these flow of savings. This method of standardization of series of cash flows is called annuity.

The future value of annuity can be calculated using the following formulas.

$$\text{FVA}_{\text{n}}(\text{M}) = \;\text{M} \times \;\{(1+\text{r})^{\text{n}-1} + \;(1+\text{r})^{\text{n}-2} + \cdots \ldots. + (1+\text{r})^{1} + 1\} \cdots\cdots\cdots\cdots (2.41)$$

$$\text{FVA}_{\text{n}}(1\ \text{BDT}) = \;\;(1+\text{r})^{\text{n}-1} + \;(1+\text{r})^{\text{n}-2} + \cdots \ldots. + (1+\text{r})^{1} + 1 \cdots\cdots\cdots\cdots (2.41.a)$$

Where,
$\text{FVA}_{\text{n}}(\text{M})$ = Future value (sum) of an annuity of M after paying for n time periods at ‘r’ rate of interest.
$M = annuity\ per\ year/\ annual\ or\ periodic\ payment\ or\ savings$ or
Where,
$\text{FVA}_{\text{n}}(\text{M})$ = Future value (sum) of an annuity of M after paying for n time periods at ‘r’ rate of interest.

The Present value of annuity can be calculated using the following formulas.

$$\mathrm{PVA_n(M)} = \mathrm{M} \times \{(1+\mathrm{r})^{-1} + (1+\mathrm{r})^{-2} + (1+\mathrm{r})^{-3} + \cdots \ldots + (1+\mathrm{r})^{-\mathrm{n}}\} \quad \cdots (2.42)$$

Where,
$\mathrm{PVA_n(M)}$ = Present value (sum) of an annuity of M for n time periods at 'r' rate of interest
$M = annual\ or\ periodic\ payment\ or\ savings$

Example 2.19 Sum of an annuity of more than BDT 1 per year

An intermediate raw material store room in a factory building is equipped with 300 watts (W) of fluorescent lighting, although only 30W are needed. The lights burn 24 hours per day, 365 days per year (d/yr).

Find: the cost savings per year resulting from the reduction in watts in the store room and the future value of these cost savings after 4 years if cost of electricity is BDT 5 per kilowatt hour (kWh), and the interest rate is 8%.

Solution:

Given that, r = 8%
n = 4 Years
Find, Cost Saving per year M = ?
Future Value of cost saving = Future value annuity, $FVA_n(M) =$?

Now, finding per year cost saving M,

Replacing of 300W with 30W bulb will save P = 300W – 30W = 270W

Energy Saving per year , from equation 2.8

$$E = P \times t$$

Where, total hours in a year t = 24*365 = 8760 hour

So, Energy Saved E = 270* 8760 = 2365200 Wh = 2365.2 kWh
Cost Saving per year = 2365.2 * price of Electricity
= 2365.2 * 5 = 11823 BDT = Annuity per year (M) (Ans)

Now, from equation 2.41,

Future value of annuity at end of 4 years,

$$\Rightarrow \mathrm{FVA_n(M)} = \mathrm{M} \times \{(1+\mathrm{r})^{\mathrm{n}-1} + (1+\mathrm{r})^{\mathrm{n}-2} + \cdots + (1+\mathrm{r})^1 + 1\}$$

$$= 11826 \times \{(1+0.08)^{4-1} + (1+0.08)^{4-2} + (1+0.08)^{4-3} + 1\}$$

= 53289 BDT

Future value of annuity at end of 4 years ($\mathrm{FVA_n(M)}$) = 53289 BDT

Example 2.20 The present value of an annuity

A star hotel to reduce electricity costs considered replacing CFL bulbs of a certain wattage with LED bulbs of a lower wattage in every hallway of a hotel. These bulbs have an expected life of 8 years, and will save BDT 1300 per year for the 8-year period. The interest rate is 6%.
Find: The present value of the cost savings.

Solution:

Given, Annuity per year M = 1300 BDT
n= 8 years
r = 6%
find sum of present value of annuity or present value of cost savings $PVA_n(M) \ = ?$

Now from the equation 2.42,
$\mathrm{PVA_n(M)} = \mathrm{M} \times \{(1+\mathrm{r})^{-1} + (1+\mathrm{r})^{-2} + (1+\mathrm{r})^{-3} + \cdots \ldots + (1+\mathrm{r})^{-\mathrm{n}}\ \}$
$= 1300 \times \{(1+0.06)^{-1} + (1+0.06)^{-2} + (1+0.06)^{-3} + \cdots \ldots + (1+0.06)^{-8}\ \}$
$= 8072.73$ (ans)

Financial Analysis Techniques

For management to consider any energy project the overall costs of all possible alternatives should be known and the project should save at least as much as it costs. Depending on the complexity and level of investment the following techniques can be used.

1. Simple Payback Period (SPP):

SPP represents the time (number of years) required to recover the initial investment (First Cost), considering only the Net Annual Saving.

$$\text{SPP (years)} = \frac{\text{Capital cost of the project (in BDT)}}{\text{Net Annual Savings (in BDT)}} \ldots.(2.43)$$

Example 2.21 Payback Period when savings each year are equal

A SME (Small and Medium scale enterprise) considered a desktop computer with energy monitoring and management software to pursue energy conservation opportunities. The system has an original cost of BDT 3, 20,000 and will generate net after tax savings of BDT 40,000 per year.
Find: The payback period of this investment
Solution:
From equation 2.43,

$$SPP = \frac{BDT\ 320000}{BDT\ 40000} = 8\ years$$

If savings each year are not constant then the above equation is not applicable. In such case savings from each year are added until their sum equals the original investment. An example is shown below.

Example 2.22 Payback Period when savings each year are not constant

In the above example (example 2.21), suppose the annual net cost savings is BDT40,000 for the first year will increase 12% each year thereafter, whereas, the original price of the system remains at BDT 3,20,000. Find the payback period of this investment.
Solution: Consider the following table.

Year	Original Savings (first year) (BDT)	Escalation FVIP r = 12% eq^n. (2.39)	Actual savings for year (BDT)	Cumulative savings at end of year (BDT)
0	40000	1 $[= (1+r)^0]$	40000	40000
1	40000	1.12 $[= (1+r)^1]$	44800	84800
2	40000	1.2544 $[= (1+r)^2]$	50176	134976
3	40000	1.4049 $[= (1+r)^3]$	56196	191172
4	40000	1.5735 $[= (1+r)^4]$	62940	254112

5	40000	1.7623 [$= (1+r)^5$]	70492	324604

The Table above shows, the total cost savings of the project become equal to its cost at the end of the fifth year. Thus, a rough estimate of the payback period if 5 years.

Limitation: SPP fails to consider time value of money. In the 2.21 example the net cost savings of 5th year are counted equally with those of the first year. This violates the most basic principle of financial analysis, which stipulates that cash flows occurring at different points of time can be added or subtracted only after suitable compounding/discounting

The payback method does not consider savings that are accrued after the payback period has finished. This leads to discrimination against projects that generate substantial cash inflows in later years.

2. Return on Investment (ROI):

ROI expresses the "annual return" from the project as a percentage of capital cost

$$\text{ROI} = \frac{\text{Annual Net Cash Flow}}{\text{Capital Cost}} \times 100$$

Limitation: This ROI does not take into account the time value of money. Also, It does not account for the variable nature of annual net cash inflows.

3. Benefit-Cost Analysis

The net cost savings of an energy project are often called the benefits of the project.
The formula for this ratio is as follows:

$$\frac{\text{Benefit}}{\text{Cost}} = \frac{\text{Actual net cost savings/yr}}{\text{Net cost savings/yr needed to recover original investment}}$$

If the benefit-cost ratio is larger than one, then the net cost savings of a project (or its benefits) exceed its cost and the investment is profitable.

4. Profitability index

Another technique, which can be used to evaluate the financial viability of projects, is the profitability index. The profitability index can be defined as:

$$\text{Profitability Index} = \frac{\text{Sum of the discounted net savings}}{\text{Capital Costs}}$$

The higher the profitability index, the more attractive the project.

5. Discounted Cash Flow Methods

In order to overcome the weakness of simple pay-back assessment method a number of discounted cash flow techniques have been developed, which are based on the fact that money invested in a bank will accrue annual interest. The two most commonly used techniques are the 'net present value' and the 'internal rate of return' methods.

a) Net Present value

Because an amount of money in the present is worth more than the same amount at any point in the future due to time value of money, all amounts should be converted to the same period to arrive at net present value. The net present value method achieves this by quantifying the impact of time on any particular future cash flow. The present value (PV) is determined by using an assumed interest rate, usually referred to as a discount rate. Discounting is the opposite process to compounding. The formulae-

$$NPV = \frac{CF_0}{(1+k)^0} + \frac{CF_1}{(1+k)^1} + \ldots. \ . + \frac{CF_n}{(1+k)^n} = \sum_{t=0}^{n} \frac{CF_t}{(1+k)^t}$$

Where
NPV = Net Present Value
CF_t = Cash flow occurring at the end of year 't' (t=0,1,….n)
n = life of the project
k = Discount rate

b) Internal Rate of Return (IRR)

This method calculates the rate of return that the investment is expected to yield. The internal rate of return (IRR) method expresses each investment alternative in terms of a rate of return. The expected rate of return is the interest rate for which total discounted benefits become just equal to total discounted costs (i.e. net present benefits or net annual benefits are equal to zero, or for which the benefit / cost ratio equals one). The criterion for selection among alternatives is to choose the investment with the highest rate of return.
The discount rate which achieves a net present value of zero is known as the internal rate of return (IRR) The higher the internal rate of return, the more attractive the project.

The rate of return is usually calculated by a process of trial and error, whereby the net cash flow is computed for various discount rates until its value is reduced to zero and is calculated using the equation given below.

$$0 = \frac{CF_0}{(1+k)^0} + \frac{CF_1}{(1+k)^1} + \cdots \ldots \ldots \ldots + \frac{CF_n}{(1+k)^n} = \sum_{t=0}^{n} \frac{CF_t}{(1+k)^t}$$

Where,
CF_t cash flow at the end of year "t"
k discount rate
n life of the project

- CF_t is negative if expenditure> savings
- CF_t is positive if expenditure < savings.

In the net present value calculation we assume that the discount rate (cost of capital) is known and determine the net present value of the project. In the internal rate of return calculation, we set the net present value equal to zero and determine the discount rate (internal rate of return), which satisfies this condition.

Table 2.3 Comparison of Project Evaluation Methods

Method	Needed Information	Result
Capital recovery factor and benefit-cost	Original cost; Life of investment; Relevant interest rate	Needed cost savings per year to recover original investment; Ratio that shows how cost savings relate to cost
Net Present value	Original cost; Life of investment; Relevant interest rate; Net cost savings per year	How much total present value of net cost savings exceeds (or less than) original cost
Internal Rate of Return	Original cost; Life of net cost savings per year	Interest rate which shows how net cost savings relate to original cost

Payback period	Original cost; Net cost savings per year	Rough estimate of time needed to recover original cost.

CHAPTER 03: UNITS OF ENERGY, TARIFF STRUCTURE AND COST OF ENERGY

3.1 Various units of energy & conversion.

SI system has 6 base units on which other units are derived. The base units are:

Base quantity	Name	Symbol
Length	meter	m
Time	Second	S
Electric current	Ampere	A
Temperature	Kelvin	K
Amount of substance	Mole	mol
Luminous intensity	Candela	cd

The examples of derived units from base units are:

Derived quantity	Name	Symbol
Area	Square meter	m^2
Volume	Cubic meter	m^3
Acceleration	Meter per second Squared	m/s^2
Mass density	Kilogram per cubic meter	kg/m^3
Specific volume	Cubic meter per kilogram	m^3/kg
Luminance	Candela per square meter	Cd/m^2

SI derived units are given special names and symbols for better understanding. Some derived SI units relevant to Energy Management & Audit are listed below:

Derived quantity	Name	Symbol	Expression in terms of other units	Expression in terms of base unit
Frequency	Hertz	Hz	-	s^{-1}
Force	Newton	N	-	$m \cdot kg \cdot s^{-2}$
Pressure	Pascal	Pa	N/m^2	$m^{-1} \cdot kg \cdot s^{-2}$
Energy, work, quantity of heat	Joule	J	N-m	$m^2 \cdot kg \cdot s^{-2}$
Power	Watt	W	J/s	$m^2 \cdot kg \cdot s^{-3}$
Electric potential difference, electromotive force	Volt	V	W/A	$m^2 \cdot kg \cdot s^{-3} \cdot A^{-1}$
Capacitance	Farad	F	C/V	$m^{-2} \cdot kg^{-1} \cdot s^4 \cdot A^2$
electric resistance	Ohm		V/A	$m^2 \cdot kg \cdot s^{-3} \cdot A^{-2}$
electric conductance	Siemens	S	A/V	$m^{-2} \cdot kg^{-1} \cdot s^3 \cdot A^2$
Celsius temperature	degree Celsius	°C	-	K
luminous flux	lumen	lm	$cd \cdot sr$ (c)	$m^2 \cdot m^{-2} \cdot cd = cd$
Illuminance	lux	lx	lm/m^2	$m^2 \cdot m^{-4} \cdot cd = m^{-2} \cdot cd$

3.2 Temperature Units

Conversion of the degree Celsius into Fahrenheit = degrees C X 1.8 + 32
Conversion of the Fahrenheit into degree Celsius = (degrees F - 32.) / 1.8
Degrees Celsius (C) to degrees Kelvin (K) = (C) + 273.15 = (K)

3.3 Pressure Units

1 atm	760 mm Hg	atmosphere (standard)
1 atm	101325 Pa	atmosphere (standard)
1 bar	100000 Pa	bar
1 cmHg (0 °C)	1333.22 Pa	centimetre of mercury (0 °C)
1cm H_2O	98.0638 Pa	centimeter of water (4 °C)
1 kgf/cm^2	98066,5 Pa	kilogram force per square centimetre
1 kgf/m^2	9,80665 Pa	kilogram force per square meter
1 kPa	1000 Pa	kilopascal
1 MPa	1000000 Pa	megapascal
1 mbar	100 Pa	millibar
1 N/m^2	1 Pa	pascal
1 lbf/ft^2	6894,76 Pa	pound force per square inch

3.4 Energy Units and Conversions

1 Joule	= 1 Watt/s
1 kW	= 1000 W
1 kWh	= 3.6 x 10^6 J = 3.6 million Joules
1 Mega-joule	= 278 Wh
1 Watt-hour (Wh)	= 3600 Joules
1 British thermal unit (BTU)	= 252 Cal
1 BTU	= 1055 J
1 Btu/h	= 0.293071 Wh
1 Kilocalorie/hour (kcal/h)	= 1163 Wh
1 HP	= 745.7 Watts

1 BTU	= 2.52 x 10^{-8} toe
1 MJ	= 2.39 x 10^{-5} toe
1 kWh	= 8.60 x 10^{-5} toe (consumption basis)
1 cft	= 0.283168 m^3
1 BBL	= 0.159 m^3

Source: National Energy balance 2019-20

3.5 Tariff Structure: Electricity, Gas & Water Supply

Energy Managers should have a clear picture of Tariff structure. He can then plan about financial savings for his project or industry. This saving in bill will not only help the project to get optimum output through minimum financial input, but will also help country to attain load management. The emission saving is additional benefit. It will have financial value if carbon tax is fully implemented. From business point of view, today's market is competitive. A slight decrease in operating cost matters in overall competition.

Electricity tariff management

The electricity tariff is approved by Bangladesh Energy Regulatory Commission (BERC).
Electricity tariff constitutes the following where there is scope of individual consumers saving

Demand charge

Electricity Demand and Electricity consumption: The Energy managers need to have a clear understanding of the difference between electricity demand and electricity consumption. Knowing how your utility provider measures and bills electricity is crucial to reducing costs without negatively impacting operations or occupant comfort.

Electricity demand is measured in kilowatts (kW) and represents the rate at which electricity is used. Electricity consumption, on the other hand, is measured in kilowatt-hours (kWh) and represents the amount of electricity used over a certain time. For billing purpose by Utilities, it is one month.

Let's start with the familiar analogy of driving a car to explain further. The rate at which a building or installation consumes energy, or the facility's demand (kW), equates to the car's speed (kmph). And the energy consumption (kWh) is like the total distance driven (km) by the car during a specified time interval.

Total driving distance and total energy consumption are calculated the same way: in the car, multiply the average speed by the number of hours driven to determine distance driven; for energy usage, multiply average demand by time in use and you get total electricity consumption.

Why knowing the difference between demand and consumption is important?

Utility rates for commercial and Industrial consumers are frequently based on the highest average demand (peak demand) during a specific period in the utility cycle, usually tracked in 15-minute intervals. This means if your establishment's demand profile holds steady around 120 kW but surges to 180 kW for one 15-minute period, the utility bills are based on the consumer's demand of 180 kW, though average demand may be 120 kW in this case..

Why? Because the utility has to ensure that they can meet Consumer's peak electricity demands without compromising grid reliability. They're charging higher rates to encourage reduced demand. Consumption billing formulas also change depending on peak usage.

The demand charge is a monthly fee that you pay as part of the cost of maintaining the electric utility's infrastructure required to deliver required electricity to your establishment. On each month's bill, the demand charge amount is based on how high your energy use measured in kilowatts (kW) peaked during the month.

Each consumer at the time of connection has to declare its required Peak Demand (also called sanctioned load) of electricity. The Utility is bound to keep this electricity reserve to the Consumer. For that it takes monthly demand charge. The Demand charge of various consumer categories as approved by BERC on 27 Feb, 2020 is given below. BERC can change the Demand charge any time.

Consumer category-wise demand charge

Sl	Consumer category	Demand charge/ kW/month	Remarks
1	Domestic/Residential 440 v/230 v	Tk 30/	
2	Domestic/Residential, 11 kV	Tk 60/	
3	Commercial & Office	Tk 60/	

4	Small Industry	Tk 30/	
5	Irrigation	Tk 30/	
6	Battery charging stations	Tk 100/	
7	Educational, religious institutions and hospitals	Tk 35/	
8	Construction site & temporary connections	Tk 100/	

Ref. BERC approved Tariff dated 27 Feb 2020.

Consumer must maintain its Peak demand within approved Demand. In case of excess use over Contract demand, Demand charge @ **200%** is charged.

Demand cannot exceed 110% of contract demand. In case it exceeds 110% of contract demand for 3 consecutive months, then a notice with 15 days' time will be served to the consumer and connection will be disconnected.

Contract demand may be increased/decreased on consumers written request. However, contract demand cannot be changed alone by the respective utility.

As Energy Manager, you should plan together with Production Engineer, how to keep Peak demand minimum. But simultaneously the contract Peak demand with Utility may be amended.

Service Charge

For providing electricity, a service charge for providing electricity is imposed on monthly basis. The service includes providing electricity up to Consumer meter, Operation and maintenance, billing, administrative charges etc.

Meter rent

Digital Electric meters are costly items. It is provided by the Utility at their cost, but a meter rent is taken from the Consumers.

Prepaid Meters Billing

Utilities are installing Prepaid meters. This enables accurate meter reading on monthly basis. There is no scope of overbilling in a particular month. Consumer will get 1% rebate of net bill (excluding VAT) on advance payment.

There is provision of Emergency balance to facilitate the consumer use electricity with no balance up to a certain amount. This is adjusted from the next recharge of prepaid meter cards. No interest is charged for emergency balance.

Tariff

Tariff refers to the amount of money the consumer has to pay for making the power available to them at their installation, which may be residence, Industry, Commercial establishment, educational institution etc. Tariff system takes into account various factors to calculate the total cost of the electricity.

Tariff - Peak

Peak hour is the time when electricity demand is more than usual. As a result, the cost of electricity generation is more. The electricity tariff is also high during this time.
Normal Peak hour: 5.00 PM to 11.00 PM (6 hours).

Tariff - Off-Peak.

Time other than Peak hour is Off-Peak hour. The tariff is normally less.
Normal Off-Peak hour: 11.00 PM to 5.00 PM (18 hours)

Tariff during Peak and Off-Peak hours
As per latest BERC approved Tariff dated 27 February 2020, normally Peak hour Tariff is around 39% more than Off-Peak hour rate. Which means, same electricity consumption during Peak hour will cost around 39% more than Off-Peak hour use.

Consumer Category wise Tariff Details

Consumer category	Tariff Type/ Slab	Rate/kWh Tk	Peak more than Off Peak Slab difference
Small Industry	Off-Peak hour	7.68	
	Peak hour	10.24	33% more than Off-Peak tariff.
11 kV Industry	Off-Peak hour	7.70	
	Peak hour	10.69	39% more than Off-Peak tariff.
33 kV Industry	Off-Peak hour	7.61	
	Peak hour	10.56	39% more than Off-Peak tariff.
Commercial	Off-Peak hour	9.27	
	Peak hour	12.36	33% more than Off-Peak tariff.
Domestic/Residential	00 – 75 kWh 1st slab	4.19	
	76 - 200 kWh 2nd slab	5.72	36% more than 1st slab
	201 - 300 kWh 3rd slab	6.00	5% more than 2nd slab. 43% more than 1st slab.
	301 - 400 kWh 4th slab	6.34	6% more than 3rd slab. 11% more than 2nd slab. 51% more than 1st slab.
	401 - 600 kWh 5th slab	9.94	57% more than 4th slab. 66% more than 3rd slab. 74% more than 2nd slab. 237% more than 1st slab.
	Above 600 kWh 6th slab	11.49	16% more than 5th slab. 81% more than 4th slab. 91% more than 3rd slab. 201% more than 2nd slab. 274% more than 1st slab.

The Domestic/Residential tariff various slabs and its comparison with other slabs is given to make the occupants aware of excess use of electricity leads to higher bill. “The more you consume, the more you pay”. There are Industries with residential accommodation and dormitories. Often Bill is paid by the industries. In that case each unit should have a separate Billing meter to keep residential consumption in lower slabs.

Super Off-Peak hour
This Tariff is offered only to Battery charging stations. They are encouraged to consume electricity when the demand is lowest.

Time	Rate	Tariff for 230/400 v, 0 -7.5 kW/0-80kW	Tariff for 50 - 5000kW
11.00 PM – 5.00 AM	Off-Peak	6.88	6.80
5.00 AM – 9.00 AM	**Super Off-Peak**	**6.11**	**6.05**

9.00 AM – 5.00 PM	Off-Peak	6.88	6.80
5. 00 PM – 11.00 PM	**Peak**	**9.66**	**9.45**

There is also Flat rate (same electricity rate for 24 hours), but with digital electric programmable meters, flat rate Tariff is not imposed by Utilities. For better load management, Utilities also prefer variable rates tariff.

Example of

A 33 kV Industry savings through Tariff Management
Production: 12 hour/day. Average: 4000 kWh/hr. (excluding PF)

Item	Off-Peak	Peak	Total
Production 9 AM -10 PM, 1 hr. break	08 hrs.	04 hrs.	12 hrs.
Average per day consumption (kWh)	32,000	16,000	48,000
Demand charge 5000 kW @ Tk 60/ per kW			3,00000
Off-Peak 7.61/, Peak 10.56/kWh per day	Tk 243520	Tk 168960	Tk 4,12,480/
Total Per Month Bill (26 days) use including Demand charge	Tk 6331520 /	Tk 4392960 /	Tk 1,10,24,480 /
If Peak shifted to Off -Peak 5AM- 5PM			12 hours
Per day Bill amount	Tk 365,280/	0.00	Tk 365,280/
Per month Bill	Tk 94,07,280/	0.00	Tk 94,07,280/
If by Demand management, it is reduced from 5000kW to 4600 kW @ Tk 60/kW			Tk 276,000/
Total Bill including Demand charge with management			Tk 97,73,280 /
PM saving-Off Peak shift & Demand management			Tk 12,51,200/
Per year saving considering holiday/ maintenance (10 month)			Tk 1,25,12,000 / 11.34%
Share 50% of savings as Bonus with employees for odd hour works			Tk 62,56,000 /

Power Factor (PF)

Power factor is a measure of how effectively Consumer facility is using electricity. It is the ratio of the real power used to do work and the apparent power supplied to the circuit. The power factor, which can be found on a utility bill, will be between 0 and 1.

Does power factor affect electricity bill?

The power factor indicates how much power is actually being used to perform useful work by a load and how much power it is "wasting". As trivial as its name sounds, it is one of the major factors behind high electricity bills, power failures and sometimes the imbalance in electrical networks.

Effects of Low Power factor:

A lower power factor causes a higher current flow for a given load. As the line current increases, the voltage drop in the conductor increases, resulting in a lower voltage at the equipment and increase in losses (I^2R). With an improved power factor, the voltage drop in the conductor is reduced, improving the voltage at the equipment with less current flow and as a result less losses (I^2R).

Disadvantages of low power factor:

a. Higher kVA rating of the equipment for same load.

b. Higher conductor size due to higher current flow .
c. Higher copper losses.
d. Poor voltage regulation.
e. Optimum capacity of the system cannot be utilized.
f. More cost required for station and distribution equipment for the given load.

As per BERC approved Tariff, PF is to be maintained for all Consumers having contract load 20 kW or above.

In order to maintain quality electricity with minimum losses, Consumer is expected to maintain desired Power Factor, failing which a penalty is imposed by the Utility on the Consumer.

Similarly, the Utilities like BREB, DESCO, NESCO, DPDC etc. have to pay penalty in case their Power Factor is less than predetermined PF.

Approved Power factor = 0.95 or 95% or more for all category of consumers.

Consumers having PF less than 95% (0.95), will be penalized @ 0.75% for each percent less than 95% (0.95).

Minimum allowable PF = 0.75 (75%) with penalty.

For Consumers having PF less than 0.75 (75%) will be given written notice. If PF< 0.75 (75%) for consecutive 3 (three) months, then the connection will be disconnected with written notice after 3 months.

Power factor penalty example.
Consumer A PF for a month = 0.75
PF less than approved PF = 0.95 - 0.75 = 0.20
PF Penalty = 0.20 x 0.75 = 0.15 (15%)
Consumer will be penalized additional 15% bill for PF compensation (20% less than approved PF).

PF Penalty analysis of 33 kV Industry
Production: 12 hour/day. Average: 4000 kWh/hr.

Item	Total	Amount Tk
Average per day consumption	48,000 kWh	
Average consumption PM (26 days)	12,48,000 kWh	
For PF 90%, Penalty kWh, PM (@ 0.75%)	46,800 kWh	
For PF 90%, Penalty kWh & Tk, per year (10 month considering holidays & maintenance) @ Tk 7.61/kWh	4,68,000 kWh	35,61,480/
For PF 85%, Penalty kWh & Tk, per year (10 month considering holidays & maintenance) @ Tk 7.61/kWh	9,36,000 kWh	71,22,960/
For PF 92%, Penalty kWh & Tk, per year (10 month considering holidays & maintenance) @ Tk 7.61/kWh	2,80,800 kWh	21,36,888/

Effect of Power Factor on Transformer capacity

Power Factor has direct effect on Transformer capacity utilization.

Transformer capacity is in kVA (kilo Volt Ampere)

A kilo Watt (kW) is simply a measure of how much power an electric appliance consumes.

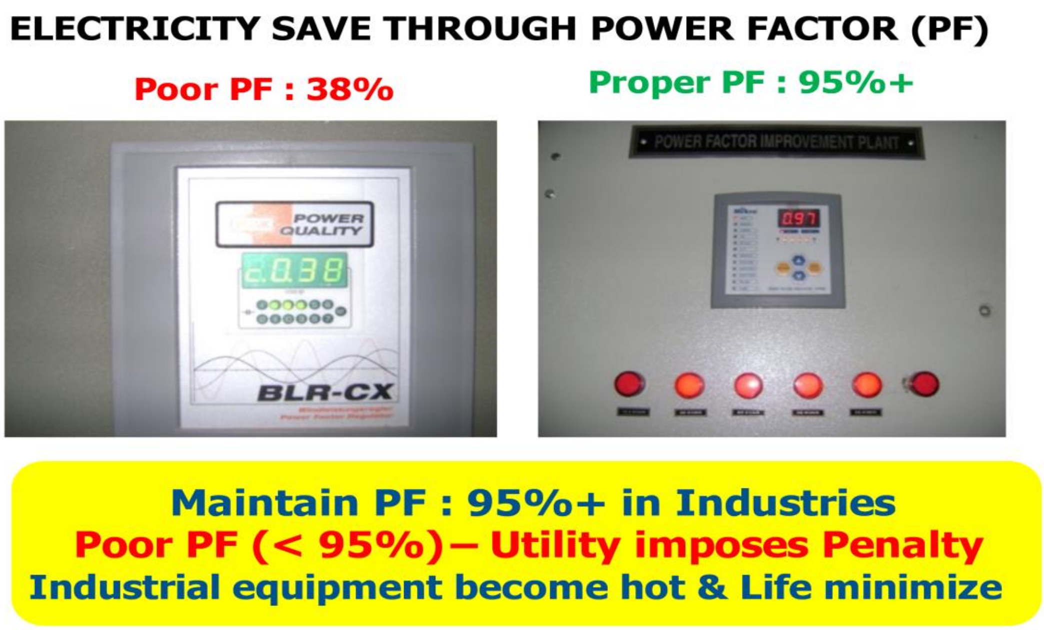
A kVA is simply 1,000-volt amperes. A volt is electrical pressure. An ampere is electrical current. A term called Apparent power is equal to the product of the volts and amperes. On the other hand, a watt (W) is a measurement of real power.

kW = kVA Cos θ

= kVA x **PF** (Standard PF=0.95)

Example:

An Industry calculated its Peak load and found it to be 900 kW
The Engineer procured a 1000 kVA Transformer
If the Industry PF=0.95, then Transformer capacity in kW = 1000 x 0.95 = 950 kW. Surplus 50 kW.
If the Industry PF=0.90, then Transformer capacity in kW = 1000 x 0.9 = 900 kW. Meets Demands of the Industry.
But, if the Industry PF=0.85, then Transformer capacity in kW = 1000 x 0.85 = 850 kW. Deficit 50 kW. Cannot meet its Peak demand.
If the Industry PF=0.80, then Transformer capacity in kW = 1000 x 0.80 = 800 kW. Deficit 100 kW. Cannot meet its Peak demand.
So, you see same transformer will have different output capacity with different PF.

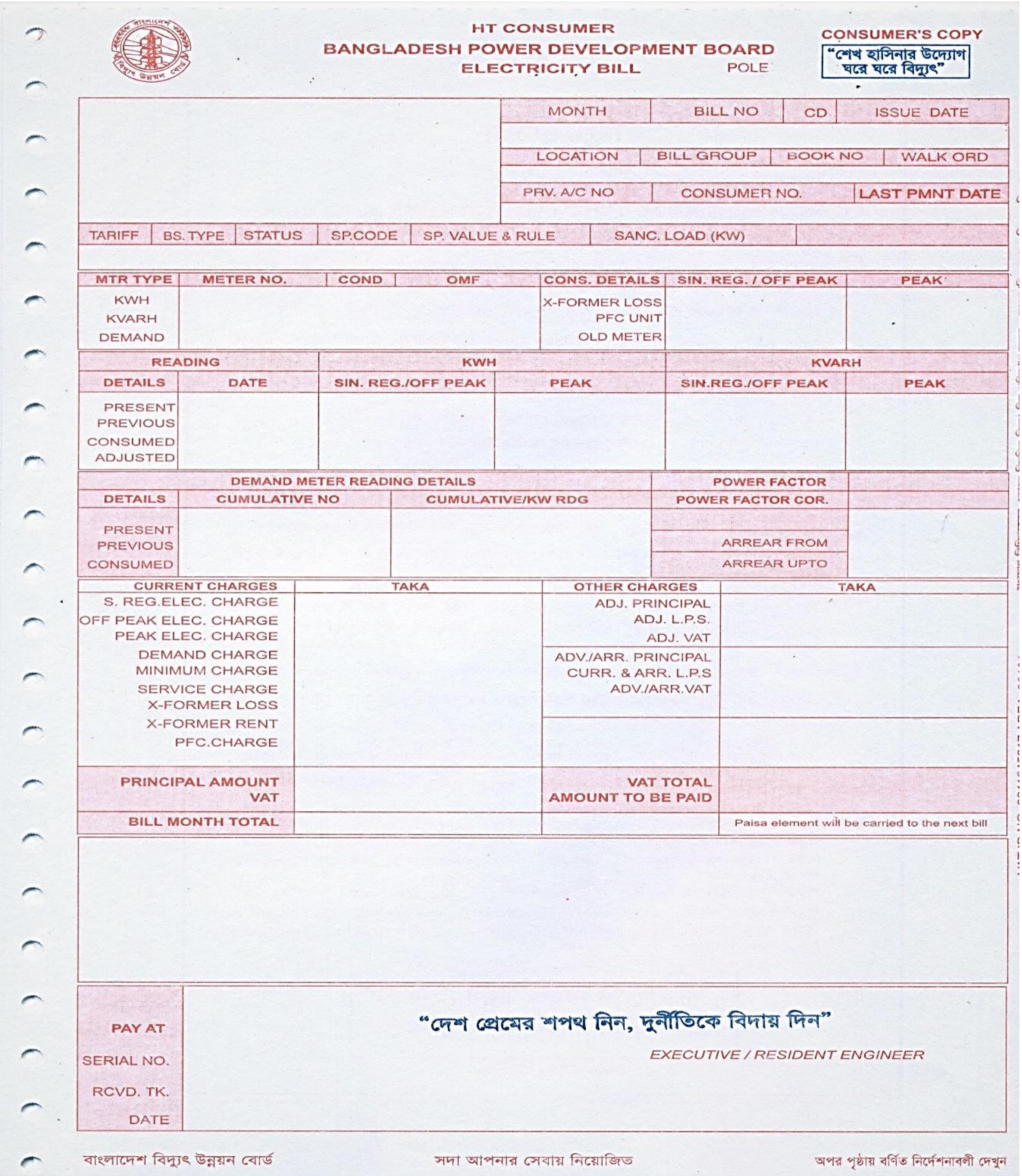


Power factor Correction
Power factor correction (PFC) aims to improve power factor, and therefore power quality. It reduces the load on the electrical distribution system, increases energy efficiency and reduces electricity costs. It also decreases the likelihood of instability and failure of equipment.

Late payment charge
In case the consumer fails to pay the electric bill within predetermined date, he has to pay 5% of Bill value as Late payment charge. It is same for all category of consumers.

Electric Bill Format

Each Utility has its own Billing format. Since Tariff is uniform so BERC is going to implement a uniform Bill format for all Utilities. The electricity bill format for BPDB



HT CONSUMER
BANGLADESH POWER DEVELOPMENT BOARD
ELECTRICITY BILL
POLE

CONSUMER'S COPY
"শেখ হাসিনার উদ্যোগ ঘরে ঘরে বিদ্যুৎ"

MONTH	BILL NO	CD	ISSUE DATE
LOCATION	BILL GROUP	BOOK NO	WALK ORD
PRV. A/C NO	CONSUMER NO.		LAST PMNT DATE

TARIFF	BS. TYPE	STATUS	SP.CODE	SP. VALUE & RULE	SANC. LOAD (KW)

MTR TYPE	METER NO.	COND	OMF	CONS. DETAILS	SIN. REG. / OFF PEAK	PEAK
KWH KVARH DEMAND				X-FORMER LOSS PFC UNIT OLD METER		

READING		KWH		KVARH	
DETAILS	DATE	SIN. REG./OFF PEAK	PEAK	SIN.REG./OFF PEAK	PEAK
PRESENT PREVIOUS CONSUMED ADJUSTED					

DEMAND METER READING DETAILS			POWER FACTOR	
DETAILS	CUMULATIVE NO	CUMULATIVE/KW RDG	POWER FACTOR COR.	
PRESENT PREVIOUS CONSUMED			ARREAR FROM ARREAR UPTO	

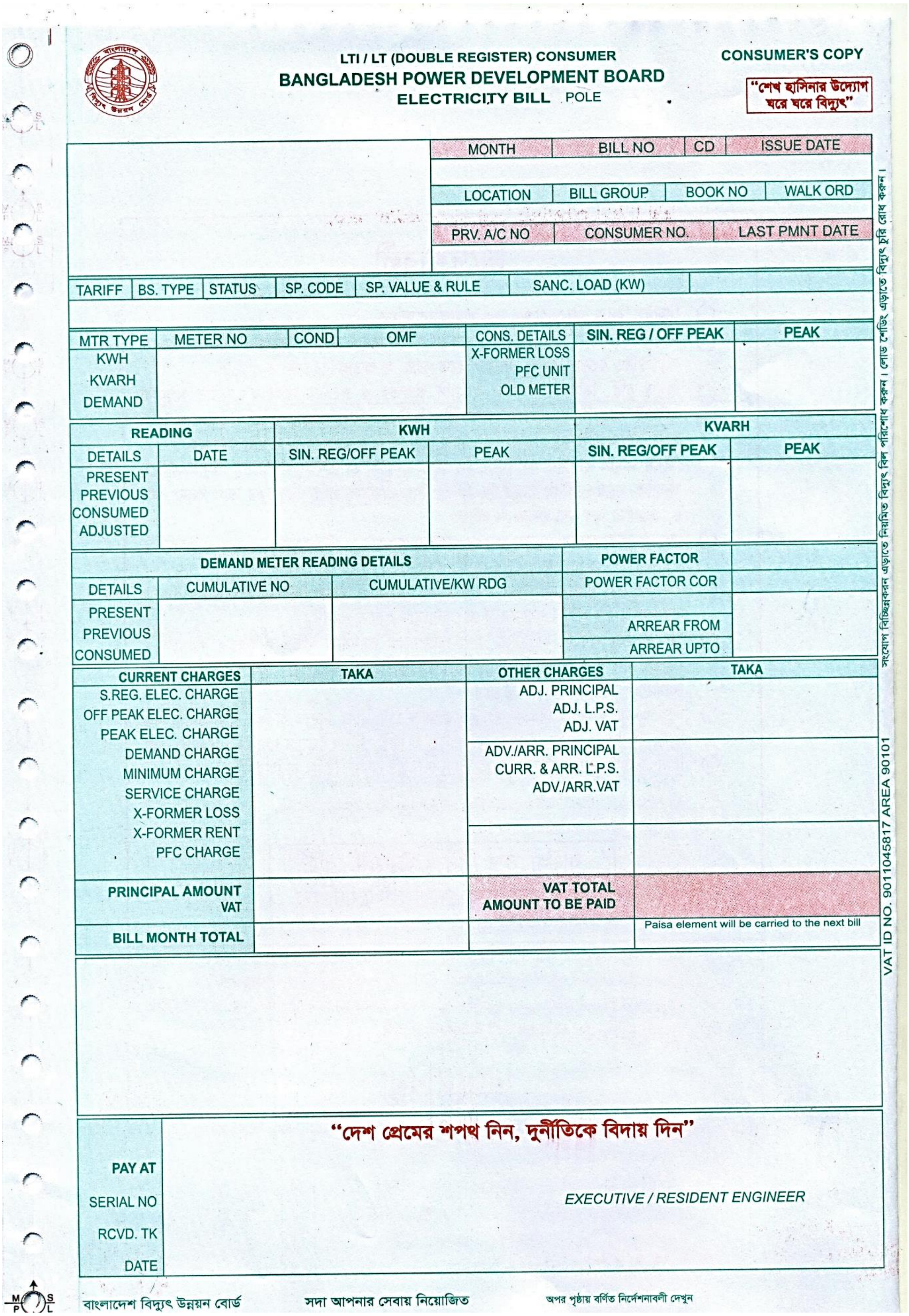
CURRENT CHARGES	TAKA	OTHER CHARGES	TAKA
S. REG.ELEC. CHARGE OFF PEAK ELEC. CHARGE PEAK ELEC. CHARGE DEMAND CHARGE MINIMUM CHARGE SERVICE CHARGE X-FORMER LOSS X-FORMER RENT PFC.CHARGE		ADJ. PRINCIPAL ADJ. L.P.S. ADJ. VAT ADV./ARR. PRINCIPAL CURR. & ARR. L.P.S ADV./ARR.VAT	
PRINCIPAL AMOUNT VAT		VAT TOTAL AMOUNT TO BE PAID	
BILL MONTH TOTAL			Paisa element will be carried to the next bill

PAY AT
SERIAL NO.
RCVD. TK.
DATE

"দেশ প্রেমের শপথ নিন, দুর্নীতিকে বিদায় দিন"

EXECUTIVE / RESIDENT ENGINEER

বাংলাদেশ বিদ্যুৎ উন্নয়ন বোর্ড
সদা আপনার সেবায় নিয়োজিত
অপর পৃষ্ঠায় বর্ণিত নির্দেশনাবলী দেখুন


LTI / LT (DOUBLE REGISTER) CONSUMER
BANGLADESH POWER DEVELOPMENT BOARD
ELECTRICITY BILL POLE
CONSUMER'S COPY
"শেখ হাসিনার উদ্যোগ ঘরে ঘরে বিদ্যুৎ"

MONTH	BILL NO	CD	ISSUE DATE

LOCATION	BILL GROUP	BOOK NO	WALK ORD

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TARIFF	BS. TYPE	STATUS	SP. CODE	SP. VALUE & RULE	SANC. LOAD (KW)

MTR TYPE	METER NO	COND	OMF	CONS. DETAILS	SIN. REG / OFF PEAK	PEAK
KWH				X-FORMER LOSS		
KVARH				PFC UNIT		
DEMAND				OLD METER		

READING		KWH		KVARH	
DETAILS	DATE	SIN. REG/OFF PEAK	PEAK	SIN. REG/OFF PEAK	PEAK
PRESENT					
PREVIOUS					
CONSUMED					
ADJUSTED					

DEMAND METER READING DETAILS			POWER FACTOR	
DETAILS	CUMULATIVE NO	CUMULATIVE/KW RDG	POWER FACTOR COR	
PRESENT				
PREVIOUS			ARREAR FROM	
CONSUMED			ARREAR UPTO	

CURRENT CHARGES	TAKA	OTHER CHARGES	TAKA
S.REG. ELEC. CHARGE		ADJ. PRINCIPAL	
OFF PEAK ELEC. CHARGE		ADJ. L.P.S.	
PEAK ELEC. CHARGE		ADJ. VAT	
DEMAND CHARGE		ADV./ARR. PRINCIPAL	
MINIMUM CHARGE		CURR. & ARR. L.P.S.	
SERVICE CHARGE		ADV./ARR.VAT	
X-FORMER LOSS			
X-FORMER RENT			
PFC CHARGE			
PRINCIPAL AMOUNT		VAT TOTAL	
VAT		AMOUNT TO BE PAID	
BILL MONTH TOTAL			Paisa element will be carried to the next bill

"দেশ প্রেমের শপথ নিন, দুর্নীতিকে বিদায় দিন"
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VAT ID NO. 9011045817 AREA 90101

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Gas

Gas tariff is how a Natural gas provider charges a customer for their gas use.

Bangladesh once had abundant natural gas. But its extensive use without any measure for energy conservation has now led us to import gas Liquified Natural Gas (LNG).

Liquefied natural gas (LNG) is natural gas that has been cooled to a liquid state, at about -160° C, for shipping and storage. The volume of natural gas in its liquid state is around 600 times smaller than its volume in its gaseous state.

Earlier with very less Tariff, high consuming, inefficient equipment was used. Now from power generation to domestic use, all are getting aware to use gas efficiently and economically.

Gas transmission is done by Gas Transmission Company Limited (GTCL). Gas distribution at Consumer level is done by various distribution companies. BERC is entrusted with fixation of tariff. Bangladesh has uniform tariff for all companies. Gas tariff effective from 01 July 2019 is given below.

The tariff is highest for CNG followed by Commercial - Hotel and Restaurants and then other commercial establishments including small and cottage industries.

Electricity generation by Government owned generation companies and Fertilizer have the lowest tariff.

Gas tariff is 24 hours flat rate for metered consumers.

GAS TARIFF EFFECTIVE 01 JULY 2019

Organization	**Category**	**Unit**	**Rate Tk**	**Demand/ Cum Contract**
Bakhrabad/	Electricity	Cum	4.45	0.10
Jalalabad/	Captive Power	Cum	13.85	0.10
Poshchimanchol/	Fertilizer	Cum	4.45	0.10
	Industry	Cum	10.70	0.10
	Tea Industry	Cum	10.70	0.10
	Commercial - Hotel & Restaurant	Cum	23.00	0.10
	Commercial – Small/cottage Industry	Cum	17.04	0.10
	CNG	Cum	**43.00**	0.10
	Residential - Metered	Cum	12.60	0.00
	Residential - Un Metered Single burner	P.M	925.00	0.00
	Residential - Un Metered Double burner	P.M	975.00	0.00
GTCL	Transmission charge	Cum	**0.4235**	

Water Tariff

Most Industries have their own water supply system those located outside City Corporation area. Their only concern should be to draw water during Off-Peak hour 11.00 PM to 5.00 PM (18 hours), Otherwise if water is drawn during Peak hour, then the industry has to pay 39% more for same electricity consumption.

The water tariff of major Water and Sewerage Authority (WASA) is given below.

WASA TARIFF

Organization	**Effective Date**	**Category**	**Unit**	**Rate**
Dhaka WASA	1-Jul-21	Residential	1000 L	15.18
	1-Jul-21	Commercial	1000 L	42.00
Chattogram WASA	1-Mar-20	Domestic	1000 L	12.40
	1-Mar-20	Non-Domestic	1000 L	30.30
Khulna WASA	1-Dec-19	Domestic	1000 L	6.91
	1-Dec-19	Non-Domestic	1000 L	10.00

CHAPTER 04: KEY POLICY LANDSCAPE OF EE&C

4.1 Electricity Act

Bangladesh power sector continued to be managed & regulated on the basis of the **Electricity Act 1910.** Since **1994** a number of policy statements have been issued and considerable progress has been made with sector **unbundling**, IPPs were introduced & corporatization of sector entities took place. In **2003**, **BERC Act** came into effect to create conducive investment climate, determine tariff & promote competitive market. Consequently, many provisions of the Electricity Act 1910 lost their relevance and have become redundant. Moreover, reforming the power sector for better service delivery to consumers and cater to increasing demand for electricity called for re-enacting the old legislation.

Contents of the Electricity Act are as follows;

Preamble: Development & reform power sector for better service and meet increasing demand.

No of Chapters: 8
1. Preliminary [Section 1-3]
2. Power sector development & ISO [Section 4 & 5]
3. Civil works, etc. [Section 6-14]
4. Power supply, meter installation, etc. [Section 15-26]
5. Protection and safety measures [Section 27-30]
6. Chief Electricity Inspector and Electricity Inspector [Section 31]
7. Offences and punishments [Section 32-52]
8. Miscellaneous [Section 53-61]

No of Sections: 61
Section 21 of the Electricity Act authorizes the power utilities for suggesting consumers to use power saving equipment and appliances.

4.2 SREDA Act 2012

Sustainable and Renewable Energy Development Authority (SREDA) has been established in 2012 by the Sustainable and Renewable Energy Development Authority Act, 2012 to promote renewable energy and energy efficiency & conservation in Bangladesh

SREDA act contains 29 sections. Section 2(8) defines energy manager and outlines his/her responsibilities. Section 6(6) authorizes SREDA to set requisite qualification and competency to be eligible as Energy Managers by making regulation.

4.3 EE&C Master Plan up to 2030

The Energy Efficiency & Conservation Master Plan (EECMP) is the supreme plan of Bangladesh's initiative on energy efficiency and conservation. The EE&CMP clearly indicate Roadmap up to 2030 with Action Plan, consisting of the outlines of legal, institutional and operational frameworks for the effective implementation of EE&C initiatives.

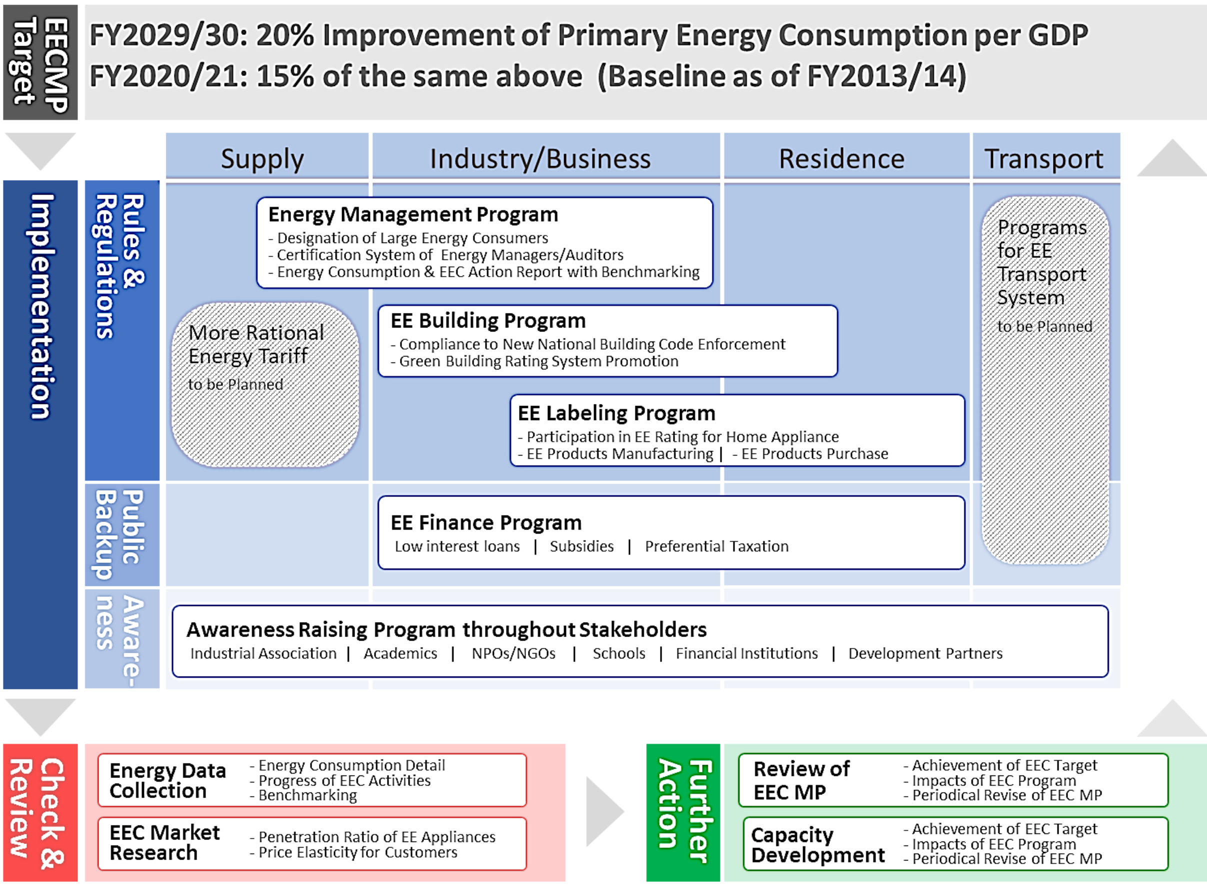


Figure 4.1: Energy Efficiency & Conservation (EE&C) initiatives in Bangladesh

2.9 4.4 EE&C Rules 2016

Pursuant to section 26 of SREDA Act 2012, Government formulated EE&C Rules 2016. Salient features of the rule concerning energy manager are as follows;

a) Rule 6 provides for Standardization and Labelling of Equipment and Appliances;
b) Rule 9 authorizes SREDA to declare Designated Consumers;
c) Rule 10 is about Designated Consumers & its responsibilities;
d) Rule 13 entrusted SREDA with the responsibility of Information Management where Energy Managers are tasked with providing information of respective Designated Consumers.

4.5 Energy Audit Regulation 2018

Pursuant to section 27 of SREDA Act 2012 read with section 6(6), Government formulated Energy Audit Regulation 2018. Regulation 10, among others, sets out the responsibilities of the Energy Manager.

4.6 Bangladesh National Building Code (BNBC) 2020

Government has enacted BNBC in 2021 to establish minimum standards for design, construction, quality of materials, use and occupancy, location and maintenance of all buildings within Bangladesh in order to safeguard, within achievable limits, life, limb, health, property and public welfare. Energy Efficiency and Conservation options are included in the BNBC. List of relevant sections, which are related to EE&C, is given below in the following table.

Sections related to EE&C in BNBC 2020

Page Number of pdf document	***Page Number mentioned in the header portion of the gazette document***	***Topic/ Chapter***	***Comments***
16	2598	(c) streamline and improve transparency through dissemination of information related to build environment including detail land use plan, regulations on safety, water and environmental conservation, health, energy efficiency and urban planning requirements through print and digital media including its website;	
182	2764	**PART III** **Chapter 4** **Energy Efficiency and Sustainability**	A full chapter on energy efficiency and sustainability
191	2773	4.5 Energy Efficient Building systems	
1933	4511	**PART VIII** **Chapter 1** **Electrical and Electronic Engineering Services for Buildings**	Lighting illuminance, fan related information are mentioned
1939	4517	1.2 Lighting and Illumination	
1943	4521	Table 8.1.5: Recommended Values of Illumination for Residential Buildings	
1944	4522	Table 8.1.6: Recommended Values of Illumination for Educational Buildings	
1944	4522	Table 8.1.6: Recommended Values of Illumination for Educational Buildings	
1946	4524	Table 8.1.9: Recommended Values of Illumination for Business and Commercial Buildings	
1963	4541	(iv) LED Lights:	
1969	4547	Table 8.1.17: Minimum Load Densities	
1975	4553	1.3.3.5 Fans	
2046	4624	**PART VIII** **Chapter 2** **Air-Conditioning, Heating And Ventilation**	AC related information are mentioned
2049	4627	ENERGY EFFICIENCY RATIO	
2118	4696	2.12 Energy Conservation	
2122	4700	Table 8.2.10: Minimum Performance of Unitary Air Conditioning Equipment	

CHAPTER 05: BASICS OF FUELS AND COMBUSTION

5.1 Introduction to Fuels

Various type of fuels like liquid, solid and gaseous fuels are available for firing in combustion equipment like boilers, furnaces etc. The selection of right type of fuel depends on the various factors such as availability, storage, handling, pollution and landed cost of fuel.

The knowledge of the fuel properties helps in selecting the right fuel for the right purpose and efficient use of the fuel. The following characteristics, determined by laboratory tests, are generally used for assessing the nature and quality of fuels.

5.2 Properties of Liquid Fuels

Liquid fuels like furnace oil, Diesel, LDO, HFO etc. are predominantly used in industrial application. The various properties of liquid fuels are given below.

5.2.1 Density

Density is the ratio of the mass of the fuel to the volume of the fuel at a reference temperature typically 15°C. The knowledge of density is useful for quantity calculations and assessing ignition quality. The unit of density is kg/m^3.

5.2.2 Specific gravity

This is defined as the ratio of the weight of a given volume of oil to the weight of the same volume of water at a given temperature. The measurement of specific gravity is generally made by a hydrometer. The density of fuel, relative to water, is called specific gravity. The specific gravity of water is defined as 1. Since specific gravity is a ratio, there is no units.

Higher the specific gravity, higher is the heating value. Its main use is in calculations involving weights and volumes. The specific gravity of various fuel oil is given in Table1.1.

Table 5.1: Specific gravity of various fuel oils

Fuel Oil	L.D.O (Light Diesel Oil)	Furnace oil	L.S.H.S (Low Sulphur Heavy Stock)
Specific Gravity	0.85-0.87	0.89-0.95	0.88-0.98

5.2.3 Viscosity

The viscosity of a fluid is a measure of its internal resistance to flow. Viscosity depends on temperature and decreases as the temperature increases. Any numerical value for viscosity has no meaning unless the temperature is also specified. Viscosity is measured in Stokes/ Centistokes. Each type of oil has its own temperature-viscosity relationship. The measurement of viscosity is made with an instrument called as viscometer.

Viscosity is the most important characteristic in the fuel oil specification. It influences the degree of pre-heat required for handling, storage and satisfactory atomization. If the oil is too viscous it may become difficult to pump, hard to light the burner and operation may become erratic. Poor atomization may result in the formation of carbon deposits on the burner tips or on the walls. Pre-heating is necessary for proper atomization.

5.2.4 Flash Point

The flash point of a fuel is the lowest temperature at which the fuel can be heated so that the vapour gives off flashes momentarily when an open flame is passed over it. Flash point for furnace oil is 660C.

5.2.5 Pour Point

The pour point of a fuel is the lowest temperature at which it will pour or flow when cooled under prescribed conditions. It is a very rough indication of the lowest temperature at which fuel oil is readily pump able

5.2.6 Specific Heat

Specific heat is the amount of heat needed to raise the temperature of 1 kg of oil by 10^0C. The unit of specific heat is kCal/kg^{0}C. It varies from 0.22 to 0.28 depending on the oil specific gravity. The specific heat determines how much steam or electrical energy it takes to heat oil to a desired temperature. Light oils have a low specific heat, whereas heavier oils have a higher specific heat.

5.2.7 Calorific Value

The calorific value is the measurement of heat or energy produced, and is measured either as gross calorific value or net calorific value. The difference being the latent heat of condensation of the water vapour produced during the combustion process. Gross calorific value assumes all vapour produced during the combustion process is fully condensed. Net calorific value assumes the water leaves with the combustion products without fully being condensed. Fuels should be compared based on the net calorific value.

5.2.8 Sulphur

The amount of sulphur in the fuel oil depends mainly on the source of the crude oil and to a lesser extent on the refining process. The normal sulphur content for the residual fuel oil (heavy fuel oil) is in the order of 2-4%.

The main disadvantage of sulphur is the risk of corrosion by sulphuric acid formed during and after combustion, and condensing in cool parts of the chimney or stack, air pre heater and economiser.

5.2.9 Ash Content

The ash value is related to the inorganic material in the fuel oil. The ash levels of distillate fuels are negligible. Residual fuels have more of the ash-forming constituents. These salts may be compounds of sodium, vanadium, calcium magnesium, silicon, iron, aluminium, nickel, etc.

Typically, the ash value is in the range 0.03-0.07%. Excessive ash in liquid fuels can cause fouling deposits in the combustion equipment. Ash has erosive effect on the burner tips, causes damage to the refractories at high temperatures and gives rise to high temperature corrosion and fouling of equipment.

5.2.10 Carbon Residue

Carbon residue indicates the tendency of oil to deposit a carbon acetous solid residue on a hot surface, such as a burner or injection nozzle, when its vaporizable constituents evaporate. Residual oil contain carbon residue ranging from 1 percent or more.

5.2.11 Water Content

Water content of furnace oil when supplied is normally very low as the product at refinery site is handled hot and maximum limit of 1% is specified in the standard.

Water may be present in free or emulsified form and can cause damage to the inside furnace surfaces during combustion especially if it contains dissolved salts. It can also cause spluttering of the flame at the burner tip, possibly extinguishing the flame and reducing the flame temperature or lengthening the flame.

Typical specification of fuel oil is summarized in the Table 5.2

Table 5.2: Typical specification of fuel

Properties	Fuel Oils		
	Furnace Oil	LS.H.S. (Low sulphur Heavy Stock)	L.D.O. (Light Diesel Oil)
Density (Approx. g/cc at 15 ^{0}C)	0.89-0.95	0.88-0.98	0.85-0.87
Flash Point (^{0}C)	66	93	66
Pour Point (^{0}C)	20	72	12 (Winter) 18 (Summer)
G.C.V. (kcal/kg)	10,500	10,600	10,700
Sediment, % Wt. Max.	0.25	0.25	0.1
Sulphur Total, % Wt. Max.	Up to 4.0	Up to 0.5	Up to 1.8
Water Content, % Vol. Max.	1.0	1.0	0.25
Ash % Wt. Max.	0.1	0.1	0.02

5.2.12 Storage of Fuel oil

It can be potentially hazardous to store furnace oil in barrels. A better practice is to store it in cylindrical tanks, either above or below the ground. Furnace oil, that is delivered, may contain dust, water and other contaminants.

The sizing of storage tank facility is very important. A recommended storage estimate is to provide for at least 10days of normal consumption. Industrial heating fuel storage tanks are generally vertical mild steel tanks mounted above ground. It is prudent for safety and environmental reasons to build bund walls around tanks to contain accidental spillages.

As a certain amount of settlement of solids and sludge will occur in tanks over time, cleaning should be carried out at regular intervals-annually for heavy fuels and every two years for light fuels. A little care should be taken when oil is decanted from the tanker to storage tank. All leaks from joints, flanges and pipelines must be attended at the earliest. Fuel oil should be free from possible contaminants such as dirt, sludge and water before it is fed to the combustion system.

Loss of Even One Drop of Oil Every Second Can Cost Over 4000 Litres A Year

5.2.13 Removal of Contaminants

Furnace oil arrives at the factory site either in tank lorries by road or by rail. Oil is then decanted into the main storage tank. To prevent contaminants such as rags, cotton waste, loose nuts or bolts or screws entering the system and damaging the pump, coarse strainer of 10 mesh size (not more than 3 holes per linear inch) is positioned on then try pipe to the storage tanks.

Progressively finer strainers should be provided at various points in the oil supply system to filter away finer contaminants such as external dust and dirt, sludge or free carbon. It is advisable to provide these filters in duplicate to enable one filter to be cleaned while oil supply is maintained through the other.

The Figure 5.1 gives an illustration of the duplex system of arrangement of strainers.

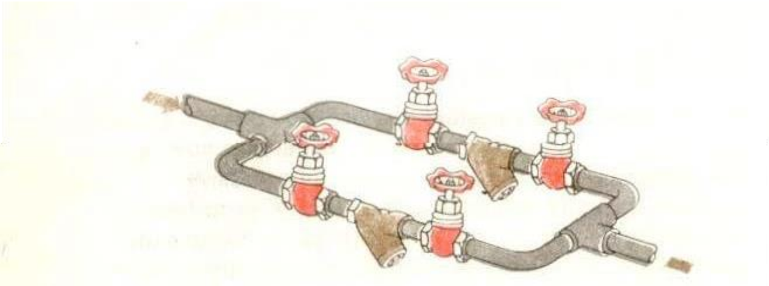


Figure 5.1: Duplex arrangement of strainers in a pipeline

5.2.14 Storage Temperature and Pumping Temperature

The viscosity of furnace oil and LSHS increases with decrease in temperature, which makes it difficult to pump the oil. At low ambient temperatures (below 25 ^{0}C), furnace oil is not easily pumpable. To circumvent this, preheating of oil is accomplished in two ways: a) the entire tank may be preheated. In this form of bulk heating, steam coils are placed at the bottom of the tank, which is fully insulated; b) the oil can be heated as it flows out with an outflow heater. To reduce steam requirements, it is advisable to insulate tanks where bulk heating is used.

Bulk heating may be necessary if flow rates are high enough to make outflow heaters of adequate capacity impractical, or when a fuel such as Low Sulphur Heavy Stock (LSHS) is used. In the case of out flow heating, only the oil, which leaves the tank, is heated to the pumping temperature. The out flow heater is essentially a heat exchanger with steam or electricity as the heating medium.

5.2.15 Temperature Control

Thermostatic temperature control of the oil is necessary to prevent overheating, especially when oil flow is reduced or stopped. This is particularly important for electric heaters, since oil may get carbonized when there is no flow and the heater is on. Thermostats should be provided at a region where the oil flows freely into the suction pipe. The temperature at which oil can readily be pumped depends on the grade of oil being handled. Oil should never be stored at a temperature above that necessary for pumping as this leads to higher energy consumption.

5.3 Properties of Solid fuel: Coal

5.3.1 Coal Classification

In general, there are three main types of coal: anthracite, bituminous, and lignite, but no clear-cut line exists between them and coal is further classed as semi anthracite, semi bituminous, and sub bituminous. Anthracite is the oldest form of coal, geologically speaking. It is a hard coal composed mainly of carbon with little volatile content and practically no moisture. Lignite is the youngest form of coal, composed mainly of volatile matter and moisture content with low fixed carbon content. Fixed carbon refers to carbon in its free state, not combined with other elements. Volatile matter refers to those combustible constituents of coal that vaporize when coal is heated.

The chemical composition of coal has a strong influence on its combustibility. The properties of coal are broadly classified as

- Physical properties
- Chemical properties

5.3.2 Physical Properties

Heating Value

The heating value of coal varies from country to country and even from mine to mine within the same country. The typical GCVs for various coals are given in the Table 5.3.

Table 1.4: Typical GCV for various coals

Parameter	Lignite	Indian Coal	Indonesian Coal	South Africal Coal	High Quality (Bituminus Coal of Barapukuria) Bangladeshi Coal
GCV (kcal/kg)	4500*	4000	5500	6000	6072

* Dry Basis

Analysis of Coal

There are two methods: the ultimate analysis splits up the fuel in to all its component elements, solid or gaseous; and the proximate analysis determines only the fixed carbon, volatile matter, moisture and ash percentages. The ultimate analysis must be carried out in a properly equipped laboratory by a skilled chemist, but proximate analysis can be made with fairly simple apparatus.

Proximate analysis indicates the percentage by weight of the Fixed Carbon, Volatiles, Ash, and Moisture Content in coal. The amounts of fixed carbon and volatile combustible matter directly contribute to the heating value of coal. Fixed carbon acts as a main heat generator during burning. High volatile matter content indicates easy ignition of fuel. The ash content is important in the design of the furnace grate, combustion volume, pollution control equipment and ash handling systems of a furnace. A typical proximate analysis of various coal is given in the Table 5.4.

Table 5.4: Typical proximate analysis of various coal (% Weight)

Parameter	Indian Coal	Indonesian Coal	South African Coal	Bangladeshi Coal
Moisture	5.98	9.43	8.5	10.00
Ash	38.56	13.99	18	12.40
Volatile matter	20.70	29.79	23.28	29.20
Fixed Carbon	34.69	46.79	51.22	48.40

5.3.3 Chemical Properties

Ultimate Analysis:

The ultimate analysis indicates the various elemental chemical constituents such as Carbon, Hydrogen, Oxygen, Sulphur, etc. It is useful in determining the quantity of air required for combustion and the volume and composition of the combustion gases. This information is required for the calculation of flame temperature and the flue duct design etc. Typical ultimate analyses of various coals are given in the Table 5.5.

Table 5.5: Ultimate analyses of various coals

Parameter	Lignite, %	Indian Coal, %	Indonesian Coal, %	Bangladeshi Coal, %
Moisture (Dry)	62.01	5.98	9.43	10
Mineral Matter	10.41	38.63	13.99	20.49
Carbon	50	41.11	58.96	61.52
Hydrogen	6.66	2.76	4.16	3.87
Nitrogen	0.60	1.22	1.02	1.52
Sulphur	0.59	0.41	0.56	0.53
Oxygen	19.73	9.89	11.88	12.07

5.3.4 Storage, Handling and Preparation of Coal

Uncertainty in the availability and transportation of fuel necessitates storage and subsequent handling. But, Stocking of coal has its own disadvantages like build-up of inventory, space constraints, deterioration in quality and potential fire hazards. Other minor losses associated with the storage of coal include oxidation, wind and carpet loss.

The main goal of good coal storage is to minimize carpet loss and the loss due to spontaneous combustion. Formation of a soft carpet, comprising of coal dust and soil causes carpet loss. On the other hand, gradual temperature builds up in a coal heap, on account oxidation may lead to spontaneous combustion of coal in storage.

The measures that would help in reducing the carpet loses are as follows:

1. Preparing a hard ground for coal to be stacked upon.

2. Preparing standard storage bays out of concrete and brick

Preparation of Coal

Preparation of coal prior to feeding in to the boiler is an important step for achieving good combustion. Large and irregular lumps of coal may cause the following problems:

1. Poor combustion conditions and inadequate furnace temperature.
2. Higher excess air resulting in higher stack loss.
3. Increase of unburnt in the ash.
4. Low thermal efficiency.

Sizing of Coal

Proper coal sizing is one of the key measures to ensure efficient combustion. Proper coal sizing, with specific relevance to the type of firing system, helps towards even burning, reduced ash losses and better combustion efficiency.

It is necessary to screen the coal before crushing, so that only oversized coal is fed to the crusher. This helps to reduce power consumption in the crusher. Recommended practices in coal crushing are:

1. Incorporation of a screen to separate fines and small particles to avoid extra fine generation in crushing.
2. Incorporation of a magnetic separator to separate iron pieces in coal, which may damage the crusher.

The Table 5.6 gives the proper size of coal for various types of firing systems

Table 5.6: Proper size of coal for various types of firing systems

S. No.	Types of Firing System	Size (in mm)
1	Hand Firing (a) Natural draft (b) Forced draft	 25-75 25-40
2	Stoker Firing (a) Chain grate i) Natural draft ii) Forced draft (b) Spreader Stoker	 25-40 15-25 15-25
3	Pulverized Fuel Fired	75% below 75 microns*
4	Fluidized bed boiler	< 10 mm

*Micron = 1/1000mm

Conditioning of Coal

The fines present in coal create problems in combustion due to segregation effects. Segregation of fines from larger coal pieces can be reduced to a great extent by conditioning coal with water. Water helps fine particles to stick to the bigger lumps due to surface tension of the moisture, thus stopping fines from falling through grate bars or being carried away by the furnace draft. While tempering the coal, care should be taken to ensure that moisture addition is uniform and preferably done in a moving or falling stream of coal.

If the percentage of fines in the coal is very high, wetting of coal can decrease the percentage of unburnt carbon and the excess air level required to be supplied for combustion. Table 5.7 shows the extent of wetting, depending on the percentage of fines in coal.

Table 5.7: Extent of wetting, depending on the percentage of fines in coal

Fines (%)	Surface Moisture (%)
10 - 15	4 - 5
15 - 20	5 - 6
20 - 25	6 - 7
25 - 30	7 - 8

Blending of Coal

In case of coal lots having excessive fines, it is advisable to blend the predominantly lumped coal with lots containing excessive fines. Coal blending may thus help to limit the extent of fines in coal being fired to not more than 25%. Blending of different qualities of coal may also help to supply uniform coal feed to the boiler.

5.4 Properties of Gaseous Fuels

Gaseous fuels in common use are liquefied petroleum gases (LPG), Natural gas, producer gas, blast furnace gas, coke oven gas etc. The calorific value of gaseous fuel is expressed in Kilocalories per cubic meter (kcal/Nm^3) i.e. at normal temperature and pressure.

Typical physical and chemical properties of various gaseous fuels are given in Table 5.8 .

Table 5.8: Typical physical and chemical properties of various gaseous fuels

Fuel Gas	Relative Density	Higher Heating Value, kCal/Nm^3	Air/Fuel ratio, m^3 of air to m^3 of Fuel	Flame Temp., ^{o}C	Flame Speed, m/s
Natural Gas	0.6	9350	10	1954	0.290
Propane	1.52	22200	25	1967	0.460
Butane	1.96	28500	32	1973	0.870

5.4.1 LPG

LPG is a predominant mixture of propane and Butane with a small percentage of unsaturated (Propylene and Butylene) and some lighter C_2 as well as heavier C_5 fractions. Included in the LPG range are propane (C_3H_8), Propylene (C_3H_6), normal and iso-butane (C_4H_{10}) and Butylene (C_4H_8). LPG vapour is denser than air. For this very reason, LPG cylinders should not be stored in cellars or basements, which have no ventilation at ground level.

5.4.2 Natural Gas

Methane is the main constituent of Natural gas and accounting for about 97% of the total volume. Other components are: Ethane, Propane, Butane, Pentane, Nitrogen, Carbon Dioxide, and traces of other gases. Very small amounts of sulphur compounds are also present. Since methane is the largest component of natural gas, generally properties of methane are used when comparing the properties of natural gas to other fuels.

Natural gas is a high calorific value fuel requiring no storage facilities. It mixes with air readily and does not produce smoke or soot. It has no sulphur content. It is lighter than air and disperses into air easily in case of leak.

A typical comparison of carbon contents in oil, coal and gas is given in the table 5.9.

Table 5.9: Comparison of carbon contents in oil, coal and gas

	Fuel Oil	Coal	Natural Gas
Carbon	84	41.11	74
Hydrogen	12	2.76	25
Sulphur	3	0.41	-
Oxygen	1	9.89	Trace
Nitrogen	Trace	1.22	0.75
Ash	Trace	38.63	-
Water	Trace	5.98	-

5.5 Properties of Agro Residues

The use of locally available agro residues is on the rise. This includes rice husk, coconut shells, groundnut shells, Coffee husk, Wheat stalk etc. The properties of a few of them are given in the table 5.10.

Table 5.10: Properties of Agro Residues

	De oiled Bran	Paddy Husk	Saw Dust	Coconut Shell
Moisture	7.11	10.79	37.98	13.95
Ash	18.46	16.73	1.63	3.52
Volatile Matter	59.81	56.46	81.22	61.91
Fixed Carbon	14.62	16.02	17.15	20.62
Mineral Matter	19.77	16.73	1.63	3.52
Carbon	36.59	33.95	48.55	44.95
Hydrogen	4.15	5.01	6.99	4.99
Nitrogen	0.82	0.91	0.80	0.56
Sulphur	0.54	0.09	0.10	0.08
Oxygen	31.02	32.52	41.93	31.94
GCV(kCal/kg)	3151	3568	4801	4565

Table 5.11: Proximate Analysis of Typical Agro Resudies

	Deoiled Bran	**Paddy Husk**	**Saw Dust**	**Coconut Shell**
Moisture	7.11	10.79	37.98	13.95
Ash	18.46	16.73	1.63	3.52
Volatile Matter	59.81	56.46	81.22	61.91
Fixed Carbon	14.62	16.02	17.15	20.62

5.6 Combustion

5.6.1 Principle of Combustion

Combustion refers to the rapid oxidation of fuel accompanied by the production of heat, or heat and light. Complete combustion of a fuel is possible only in the presence of an adequate supply of oxygen.

Oxygen (O_2) is one of the most common elements on earth making up 20.9% (by volume) of our air. Rapid fuel oxidation results in large amounts of heat. Solid or liquid fuels must be changed to a gas before they will burn. Usually, heat is required to change liquids or solids into gases. Fuel gases will burn in their normal state if enough air is present.

Most of the 79% of air (that is not oxygen) is nitrogen, with traces of other elements. Nitrogen is considered to be a temperature reducing dilutant that must be present to obtain the oxygen required for combustion.

Nitrogen reduces combustion efficiency by absorbing heat from the combustion of fuels and diluting the flue gases. This reduces the heat available for transfer through the heat exchange surfaces. It also increases the volume of combustion by-products, which then have to travel through the heat exchanger and up the stack faster to allow the introduction of additional fuel air mixture.

Carbon, hydrogen and sulphur in the fuel combine with oxygen in the air to form carbon di oxide, water vapour , sulphur dioxide and in some cases carbon mono oxide releasing heats.

$C + O_2 \rightarrow CO_2$ + 8084 kcal/kg of Carbon
$2C + O_2 \rightarrow 2\,CO$ + 2430 kcal/kg of Carbon
$2H_2 + O_2 \rightarrow 2H_2O$ + 28,922 kcal/kg of Hydrogen
$S + O_2 \rightarrow SO_2$ + 2,224 kcal/kg of Sulphur

5.6.2 3(three) T's of Combustion

The objective of good combustion is to release all of the heat in the fuel. This is accomplished by controlling the "three T's" of combustion which are-

(1) Temperature high enough to ignite and maintain ignition of the fuel,
(2) Turbulence or intimate mixing of the fuel and oxygen, and
(3) Time sufficient for complete combustion.

Complete combustion: The complete oxidation of the fuel, regardless of whether it is accomplished with an excess amount of oxygen or air, or just the theoretical amount required for perfect combustion.

Perfect combustion: The complete oxidation of the fuel, with the exact theoretical (stoichiometric) amount of oxygen (air) required.

Incomplete combustion:

exhaust gas contains- carbon mono oxide, smoke, carbon di oxide, nitrogen, water and heat

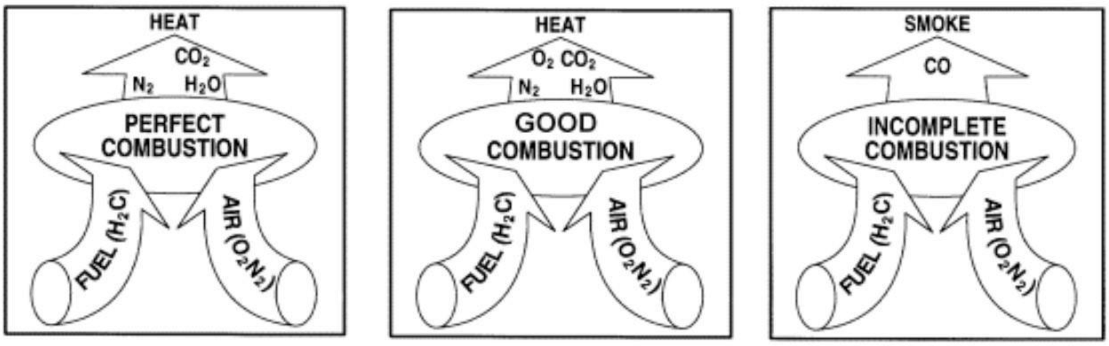


Figure 5.2: Degree of combustion

5.7 Combustion of Oil

5.7.1 Heating Oil to Correct Viscosity

When atomizing oil, it is necessary to heat it enough to get the desired viscosity. This temperature varies slightly for each grade of oil. The lighter oils do not usually require pre-heating. Typical viscosity at the burner tip (for LAP, MAP & HAP burners) for furnace oil should be 100 Redwood seconds^{-1} which would require heating the oil to about 105^0C.

5.7.2 Stoichiometric Combustion

The efficiency of a boiler or furnace depends on efficiency of the combustion system. The amount of air required for complete combustion of the fuel depends on the elemental constituents of the fuel that is Carbon, Hydrogen, and Sulphur etc. This amount of air is called stochiometric air. For ideal combustion process for burning one kg of a typical fuel oil containing 86% Carbon, 12% Hydrogen, 2% Sulphur, theoretically required quantity of air is 14.1kg. This is the minimum air that would be required if mixing of fuel and air by the burner and combustion is perfect. The combustion products are primarily Carbon Dioxide (CO_2), water vapour (H_2O) and Sulphur Dioxide (SO_2), which pass through the chimney along with the Nitrogen (N_2) in the air.

5.7.3 Rules for combustion of oil

- Atomise the oil completely to produce a fine spray
- Mix the air and fuel thoroughly
- Introduce enough air for combustion, but limit the excess air to a maximum of 15%
- Keep the burners in good condition

After surrendering useful heat in the heat absorption area of a furnace or boiler, the combustion products or fuel gases leave the system through the chimney, carrying a way a significant quantity of heat with them.

5.7.4 Calculation of Stoichiometric Air

To find out the theoretical air requirement of stoichiometric air for any oil or gaseous fuel it is essential to know the constituents of fuel and the percentage of constituents. In below table 5.12.

Table 5.12: Air Fuel ratio or Stoichiometric air requirement of some fuel

Fuel	**Chemical formula**	**AFR**
Methanol	CH_3OH	6.47:1
Ethanol	C_2H_5OH	9:1
Butanol	C_4H_9OH	11.2:1
Diesel	$C_{12}H_{23}$	14.5:1
Gasoline	C_8H_{18}	14.7:1
Propane	C_3H_8	15.67:1
Methane	CH_4	17.19:1
Hydrogen	H_2	34.3:1

5.7.5 Optimizing Excess Air and Combustion

For complete combustion of every one kg of fuel oil 14.1 kg of air is needed. In practice, mixing is never perfect, a certain amount of excess air is needed to complete combustion and ensure that release of the entire heat contained in fuel oil. If too much air than what is required for completing combustion were allowed to enter, additional heat would be lost in heating the surplus air to the chimney temperature. This would result in increased stack losses. Less air would lead to the incomplete combustion and smoke. Hence, there is an optimum excess air level for each type of fuel.

5.7.6 Control of Air and Analysis of Flue Gas

Thus, in actual practice, the amount of combustion air required will be much higher than optimally needed. Therefore, some of the air gets heated in the furnace boiler and leaves through the stack without participating in the combustion.

Chemical analysis of the gases is an objective method that helps in achieving finer air control. By measuring carbon dioxide (CO_2) or oxygen (O_2) in flue gases by continuous recording instruments or Orsat apparatus or some cheaper portable instruments, the excess air level as well as stack losses can be estimated with the graph as shown in Figure 5.3 and Figure 5.4. The excess air to be supplied depends on the type of fuel and the firing system.

For optimum combustion of fuel oil, the CO_2 should be maintained at 14-15% and O_2 should be maintained at 2-3%.

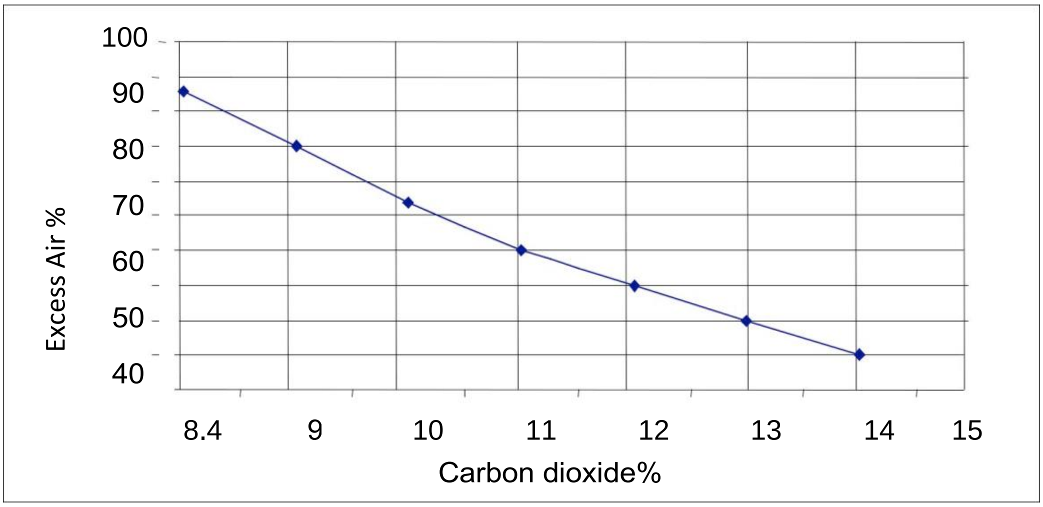


Figure 5.3: Relation between CO_2 and excess air for fuel oil

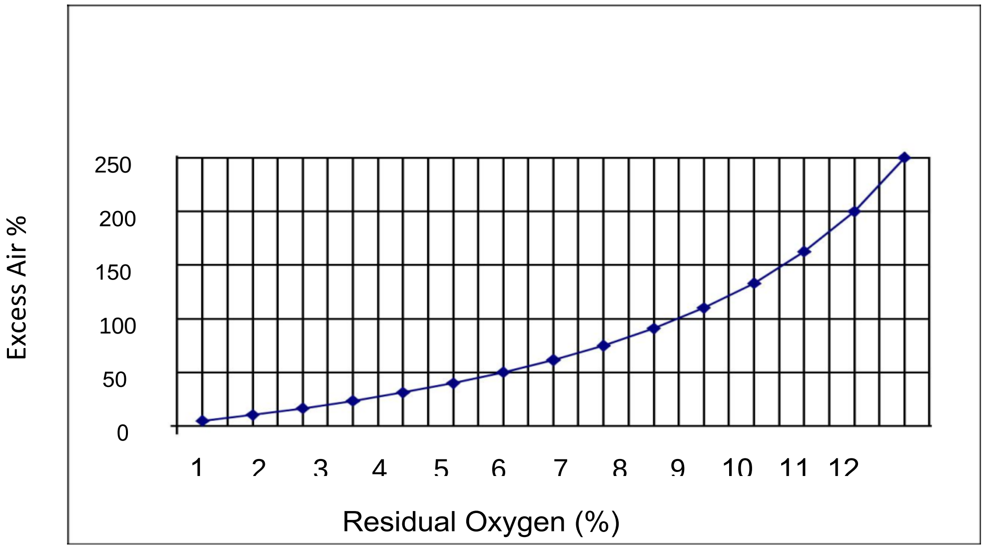


Figure 5.4: Relation between residual oxygen and excess air Oil Firing Burners

The burner is the principal device for the firing of the fuel. The primary function of burner is to atomise fuel to millions of small droplets so that the surface area of the fuel is increased enabling intimate contact with oxygen in air. The finer the fuel droplets are atomised, more readily will the particles come in contact with the oxygen in the air and burn.

Normally, atomization is carried out by primary air and completion of combustion is ensured by secondary air. Burners for fuel oil can be classified on a basis of the technique to prepare the fuel for burning i.e. atomization.

Figure 5.5 shows a simplified burner head. The air is brought in to the head by means of a forced draft blower or fan. The gas is metered into the head through a series of valves. In order to get proper combustion, the air molecules must be thoroughly mixed with the gas molecules before they actually burn.
The mixing is achieved by burner parts designed to create high turbulence. If insufficient turbulence is

produced by the burner, the combustion will be incomplete and samples taken at the stack will reveal carbon monoxide as evidence.

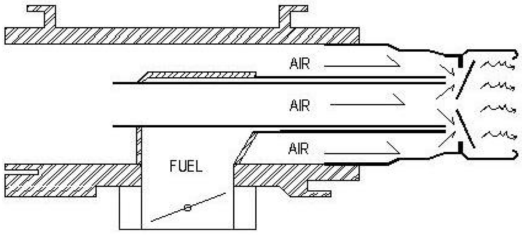


Figure 5.5: Burner head

An important aspect to be considered in selection of burner is **turn down ratio**. Turn down ratio is the relationship between the maximum and minimum fuel input without affecting the excess air level. For example, a burner whose maximum input is 250,000 kcal and minimum rate is 50,000 kcal, has a 'Turn-Down Ratio' of 5 to1.

Since the velocity of air affects the turbulence, it becomes harder and harder to get good fuel and air mixing at higher turn down ratios since the air amount is reduced. Towards the highest turndown ratios of any burner, it becomes necessary to increase the excess air amounts to obtain enough turbulence to get proper mixing. The better burner design will be one that is able to properly mix the air and fuel at the lowest possible air flow or excess air.

5.8 Combustion of Coal

5.8.1 Features of coal combustion

1kg of coal will typically require 7-8 kg of air depending upon the carbon, hydrogen, nitrogen, oxygen and sulphur content for complete combustion. This air is also known as theoretical or stoichiometric air.

If for any reason the air supplied is inadequate, the combustion will be incomplete. The result is poor generation of heat with some portions of carbon remaining unburnt (black smoke) and forming carbon monoxide instead of carbon dioxides.

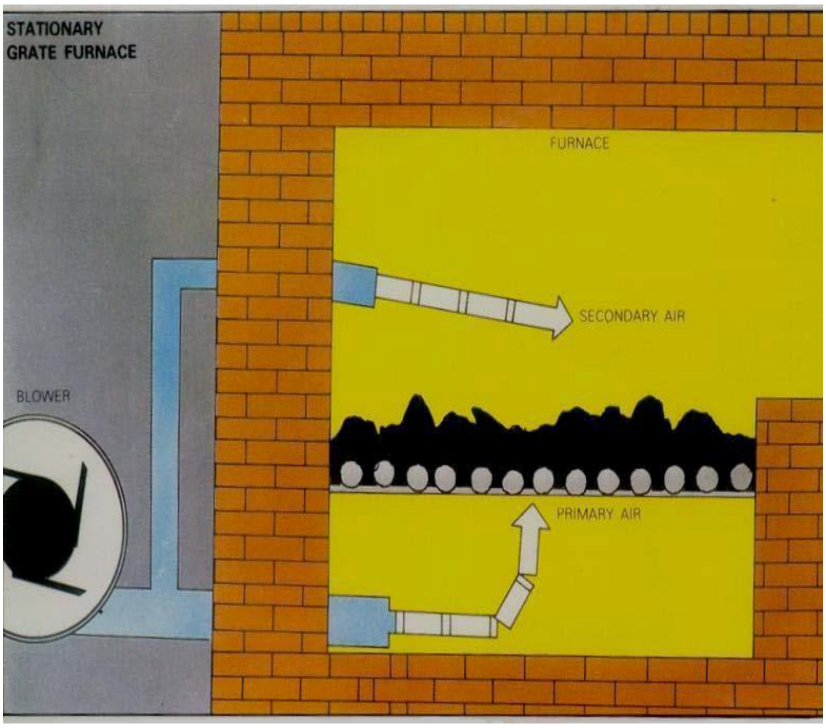


Figure 5.6: Stoker fired boilers

In actual case No fuel can be completely burnt with stoichiometric quantity of air. Complete combustion is not achieved unless an excess of air is supplied.
The excess air required for coal combustion depends on the type of coal firing equipment. Hand fired boilers use large lumps of coal and hence need very high excess air. Stoker fired boilers as shown in the figure 5.6 use sized coal and hence requires less excess air. Also in these systems primary air is supplied below the grate and secondary air is supplied over the grate to ensure complete combustion.

Fluidized bed combustion in which turbulence is created leads to intimate mixing of air and fuel resulting in further reduction of excess air. The pulverized fuel firing in which powdered coal is fired has the minimum excess air due to high surface area of coal ensuring complete combustion.

5.9 Combustion of Gas

5.9.1 Combustion Characteristics of Natural Gas

The stoichiometric ratio for natural gas (and most gaseous fuels) is normally indicated by volume. The air to natural gas (stoichiometric) ratio by volume for complete combustion vary between 9.5:1 to10:1

Natural gas is essentially pure methane, CH_4. Its combustion can be represented as follows:

$CH_4 + 2O_2 = CO_2 + 2H_2O$

Natural gas is primarily composed of methane, CH4. When mixed with the proper amount of air and heated to the combustion temperature, it burns.

5.10 Draft

The function of draft is to exhaust the products of combustion into the atmosphere. The draft can be created by natural or artificial means.

5.10.1 Natural Draft

It is the draft produced by a chimney alone. It is caused by the difference in weight between the column of hot gas inside the chimney and column of outside air of the same height and cross section. Being much lighter than outside air, chimney flue gas tends to rise, and the heavier outside airflows in through the ash pit to take its place. It is usually controlled by hand-operated dampers in the chimney and breeching connecting the boiler to the chimney. Here no fans or blowers are used. The products of combustion are discharged at such a height that it will not be a nuisance to the surrounding community.

5.10.2 Mechanical Draft

It is the draft artificially produced by fans. Three basic types of drafts that are applied are:

Balanced Draft: Forced-draft (F-D) fan (blower) pushes air into the furnace and an induced-draft (I-D) fan draws gases into the chimney there by providing draft to remove the gases from the boiler. Here the furnace is maintained at from 0.05 to 0.10 in. of water gauge below atmospheric pressure.

Induced Draft: An induced-draft fan provides enough draft for flow in to the furnace, causing the products of combustion to discharge to atmosphere. Here the furnace is kept at as light negative pressure below the atmospheric pressure so that combustion air flows through the system.

Forced Draft: The Forced draft system uses a fan to deliver the air to the furnace, forcing combustion products to flow through the unit and up the stack.

5.11 Combustion Controls

Combustion controls assist the burner in regulation of fuel supply, air supply, (fuel to air ratio), and removal of gases of combustion to achieve optimum boiler efficiency. The amount of fuel supplied to the burner must be in proportion to the steam pressure and the quantity of steam required. The combustion controls are also necessary as safety device to ensure that the boiler operates safely.

Various types of combustion controls in use are:

On/Off Control:

The simplest control, ON/OFF control means that either the burner is firing at full rate or it is OFF. This type of control is limited to small boilers.

High/Low/Off Control

Slightly more complex is HIGH / LOW / OFF system where the burner has two firing rates. The burner operates at slower firing rate and then switches to full firing as needed. Burner can also revert to low firing position at reduced load. This control is fitted to medium sized boilers.

Modulating Control

The modulating control operates on the principle of matching the steam pressure demand by altering the firing rate over the entire operating range of the boiler. Modulating motors use conventional mechanical linkage or electric valves to regulate the primary air, secondary air, and fuel supplied to the burner. Full modulation means that boiler keeps firing, and fuel and air are carefully matched over the whole firing range to maximize thermal efficiency.

CHAPTER 06: BASICS OF HEAT EXCHANGERS AND ASSESMENT SYSTEM

6.1 Introduction

Heat exchangers are used to transfer heat from one medium to another. These media may be a gas, liquid, or a combination of both. The media may be separated by a solid wall to prevent mixing or may be in direct contact.

Heat exchangers can improve a system's energy efficiency by transferring heat from systems where it is not needed to other systems where it can be usefully used.

The fluids within heat exchangers typically flow rapidly, to facilitate the transfer of heat through forced convection. This rapid flow results in pressure losses in the fluids. The efficiency of heat exchangers refers to how well they transfer heat relative to the pressure loss they incur. Modern heat exchanger technology minimizes pressure losses while maximizing heat transfer and meeting other design goals like withstanding high fluid pressures, resisting fouling and corrosion, and allowing cleaning and repairs.

6.2 Heat exchanger configurations

The two most commonly used heat exchanger flow configurations are *counter flow* and *parallel flow.* These flow patterns are represented in Figures 6.1 and 6.2 respectively, along with their characteristic temperature profiles.

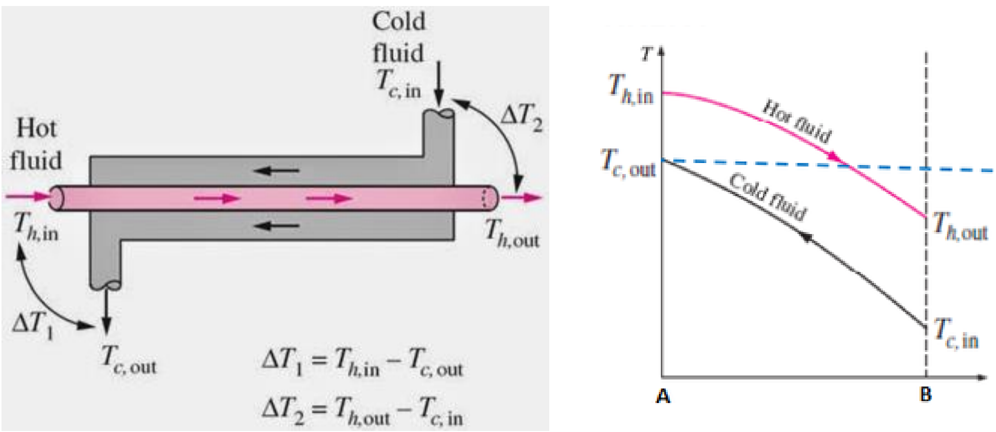


Figure 6.1: Counter Flow Heat Exchanger

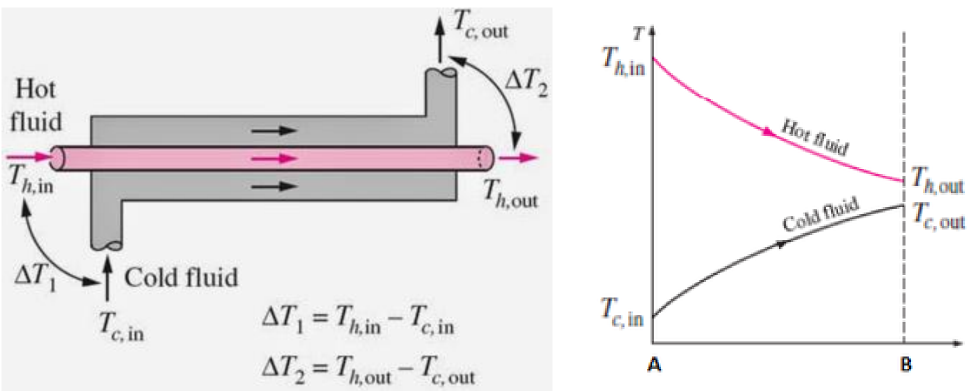


Figure 6.2: Parallel Flow Heat Exchanger

It should be noted that with the parallel flow configuration the 'hot' stream is always warmer than the 'cold' stream. With the counter flow configuration it is possible for the outlet temperature of the cold fluid to be higher than the outlet temperature of the hot fluid.
The general equations which govern the heat transfer in recuperative heat exchangers are as follows:
Total Heat Transfer/heat duty,

$$\boldsymbol{Q} = \boldsymbol{m_h C_{ph}}(\boldsymbol{t_{h.in}} - \boldsymbol{t_{h.out}}) = \boldsymbol{m_c C_{pc}}(\boldsymbol{t_{c.in}} - \boldsymbol{t_{c.out}}) \cdots\cdots\cdots (6.1)$$

$$\Rightarrow \boldsymbol{Q} = \mathrm{C_h}(\boldsymbol{t_{h.in}} - \boldsymbol{t_{h.out}}) = \mathrm{C_c}(\boldsymbol{t_{c.in}} - \boldsymbol{t_{c.out}}) \cdots\cdots\cdots (6.1.a)$$

And
Relationship with heat transfer, overall heat transfer coefficient and logarithmic mean temperature difference.

$$\mathrm{Q} = \mathrm{U}\,\mathrm{A_o}(\mathrm{LMTD})\mathrm{K} \cdots\cdots\cdots\cdots (6.2)$$

Where,

Q = rate of heat transfer (W),
m_h = mass flow rate of hot fluid (kg/s),
m_c= mass flow rate of cold fluid (kg/s),
$C_{ph} =$ specific heat of hot fluid (J/kgK),
$C_h = m_h C_{ph} =$ heat capacity of hot fluid (W/k)
$C_{pc} =$ specific heat of cold fluid (J/kgK), =
$C_c = m_c C_{pc} =$ heat capacity of cold fluid (W/k)
$t_{h,in}$ and $t_{h,out}$ are the inlet and outlet temperatures of hot fluid
$t_{c,in}$ and $t_{c,out}$ are the inlet and outlet temperatures of cold fluid
U = overall heat transfer coefficient (i.e. U value) (W/m2K),
A_o = outside surface area of heat exchanger (m2),
LMTD = logarithmic mean temperature difference
K = constant which is dependent on the type of flow through the heat exchanger
(K = 1 for counter-flow and parallel flow, and is therefore often ignored).

The logarithmic mean temperature difference (LMTD) can be determined by:

$$\mathrm{LMTD} = \frac{\Delta \mathrm{T_1} - \Delta \mathrm{T_2}}{\ln(\Delta \mathrm{T_1}/\Delta \mathrm{T_2})} \cdots\cdots\cdots\cdots\cdots\cdots (6.3)$$

where,
$\boldsymbol{\Delta T_1} = \boldsymbol{t_{h.in}} - \boldsymbol{t_{c.out}}$ and $\boldsymbol{\Delta T_2} = \boldsymbol{t_{h.out}} - \boldsymbol{t_{c.in}}$ for Counter Flow Heat Exchanger
$\boldsymbol{\Delta T_1} = \boldsymbol{t_{h.in}} - \boldsymbol{t_{c.in}}$ and $\boldsymbol{\Delta T_2} = \boldsymbol{t_{h.out}} - \boldsymbol{t_{c.out}}$ for Parallel Flow Heat Exchanger

6.3 Terminology used in Heat Exchangers

Table 6.1 : Terminology used in Heat Exchangers

Terminology	Definition	Unit
Capacity ratio	Ratio of the products of mass flow rates and specific heat capacities of the cold fluid to that of the hot fluid. It can also be determined as the ratio of temperature range of the hot fluid to that of the cold fluid. Higher the ratio higher the size of the heat exchanger	
Parallel flow	The fluid flows of cold and hot fluids are in same direction. Also	

exchanger	called as co current flow.	
Counter flow exchanger	The fluid flows of cold and hot fluids are in opposite direction.	
Cross flow	The fluid flow direction of the cold and hot fluids are in cross direction	
Density	Mass per unit volume of a material	kg/m^3
Effectiveness	Ratio of the cold fluid temperature range to that of the inlet temperature difference of the hot and cold fluid. Higher the ratio lesser will be requirement of heat transfer surface	
Fouling	The formation and development of scales and deposits over the heat transfer surface diminishing the heat flux. The fouling is indicated by the increase in pressure drop.	
Heat Duty	It is the magnitude of energy or heat transferred per unit time. The capacity of the heat exchanger equipment expressed in terms of heat transfer rate.	W
Heat Flux	The rate of heat transfer per unit surface of a heat exchanger	W/ m^2
Heat transfer surface or heat Transfer area	The surface area of the heat exchanger that provides the indirect contact between the hot and cold fluid in effecting the heat transfer. The heat transfer area is defined as the surface having both sides wetted on one side by the hot fluid and the other side by the cold fluid providing indirect contact for heat transfer	m^2
Individual Heat transfer Coefficient	The heat flux per unit temperature difference across boundary layer of the hot / cold fluid film formed at the heat transfer surface. The value of heat transfer coefficient indicates the ability of heat conductivity of the given fluid. It increases with increase intensity, velocity, specific heat, geometry of the film forming surface.	$W/(m^2.K)$
LMTD Correction factor	Calculated considering the capacity and effectiveness of a heat exchanging process. When multiplied with LMTD gives the corrected LMTD thus accounting for the temperature driving force for the cross flow pattern as applicable inside the exchanger	
Logarithmic Mean Temperature difference, LMTD	The logarithmic average of the terminal temperature approaches across a heat exchanger	°C
Overall Heat transfer Coefficient	The ratio of heat flux per unit difference in approach across a heat exchange equipment considering the individual coefficient and heat exchanger metal surface conductivity. The magnitude indicates the ability of heat transfer for a given surface. Higher the coefficient lesser will be the heat transfer surface requirement	$W/(m^2.K)$
Pressure drop	The difference in pressure between the inlet and outlet of a heat exchanger	bar
Specific heat	The heat content per unit weight of any material per degree raise/fall in temperature	J/(kg.K)
Heat Capacity	The heat content of any material per degree raise/fall in temperature It is found by multiplying mass and specific heat of a material	W/k
Temperature Approach	The difference in the temperature between the hot and cold fluids at the inlet / outlet of the heat exchanger. The greater the difference greater will be heat transfer flux	°C
Temperature Range	The difference in the temperature between the inlet and outlet of a hot/cold fluid in a heat exchanger	°C

Thermal Conductivity	The rate of heat transfer by conduction though any substance across a distance per unit temperature difference	$W/(m^2.K)$
Terminal temperature	The temperatures at the inlet / outlet of the hot / cold fluid steams across a heat exchanger	°C
Viscosity	The force on unit volume of any material that will cause per velocity	Pa

6.4 Heat Exchanger effectiveness:

The heat recovery capability of a heat exchanger is characterized by the term named "Heat Exchanger Effectiveness". Calculating the heat exchanger effectiveness helps engineers:

- To predict how a given heat exchanger will perform a new job.
- To predict the stream outlet temperatures without a trial-and-error solution.

The heat exchanger effectiveness is defined as the ratio of actual heat transfer to the maximum possible heat transfer.

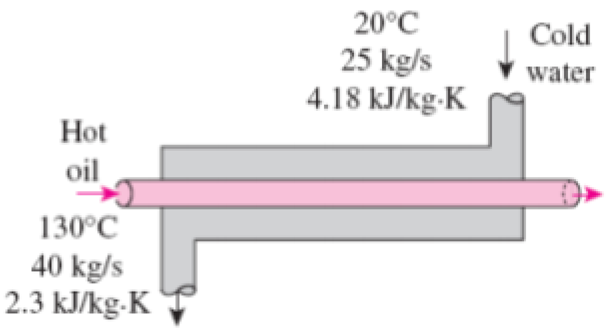
$$Effectiveness, \in = \frac{Actual\ heat\ transfer\ rate}{Maximum\ possible\ heat\ transfer\ rate}$$

$$Effectiveness, \in = \frac{Q}{Q_{\max}} \cdots\cdots\cdots (6.4)$$

Where,

$Q =$ Actual heat transfer rate
$Q_{max} =$ Maximum possible heat transfer rate $= C_{\min} \times \Delta T_{\max} \cdots\cdots (6.5)$
$C =$ Heat Capacity $=$ Mass flow rate $\times$ Specific heat capacity of the fluid
$C_{\min} =$ Lowest heat capacity between two fluid
$\Delta T_{\max} =$ Maximum temperature difference of fluids

Example 6.1 Determination of maximum rate of heat transfer in a heat exchanger



$C_c = m_c C_{pc} = 25 \times 4.18 = 104.5$ kW/K
$C_h = m_h C_{ph} = 40 \times 2.3 = 92$ kW/K

Hence, lowest heat capacity is,
$C_{min} = 92$ kW/K

$\Delta T_{max} = T_{hot\ in} - T_{cold\ in} = 130 - 20 = 110$°C

$Q_{max} = C_{\min} \times \Delta T_{\max} = 92 \times 110$
$=10{,}120$ kW

6.5 Heat Exchanger Performance Assessment

Monitoring the heat exchanger performance is done by calculating the overall heat transfer coefficient periodically. Technical records are to be maintained for all the exchangers, so that problems associated with reduced efficiency and heat transfer can be identified easily. The record comprises historical heat transfer coefficient data along with date/time of observation. A plot of heat transfer coefficient versus date/time permits rational scheduling of a heat exchanger cleaning program.

The step-by-step procedure for determination of overall heat transfer coefficient is described as follows:

Step A
Monitoring and reading of steady state parameters of the heat exchanger under evaluation are tabulated as follows:

Table 6.2: Heat Exchanger monitoring parameters

Parameters	Units	Inlet	Outlet
Hot fluid flow, m_h	Kg/h		
Cold fluid flow, m_c	Kg/h		
Hot fluid temperature, T	^{0}C		
Cold fluid temperature,	^{0}C		
Hot fluid pressure, P	bar (g)		
Cold fluid pressure, p	bar (g)		

Step B
With monitored test data, the physical properties of the stream can be tabulated for evaluation of thermal data.

Table 6.3

Parameters	Units	Inlet	Outlet
Hot fluid density, ρ_h	Kg/m^3		
Cold fluid density, ρ_c	Kg/m^3		
Hot fluid viscosity, μ_h	MpaS		
Cold fluid viscosity, μ_c	MpaS		
Hot fluid thermal conductivity, k_h	kW/(m. K)		
Cold fluid thermal conductivity, k_c	kW/(m. K)		
Hot fluid specific heat, C_{ph}	kJ/(kg. K)		
Cold fluid specific heat, C_{pc}	kJ/(kg. K)		

Density and viscosity can be determined by analysis of the samples taken from the flow stream at the recorded temperature in the plant laboratory. Thermal conductivity and specific heat capacity can be referred from hand books.

Step C

Calculate the thermal parameters of heat exchanger and compare with the design data.

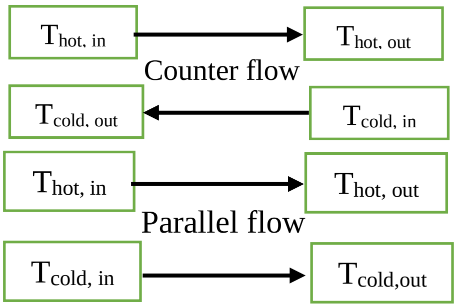
Table 6.4

Parameters	Units	Test data	Design data
Heat duty, Q	kW		
Hot fluid side pressure drop, ΔP_h	bar		
Cold fluid side pressure drop, ΔP_c	bar		
Temperature range hot fluid, ΔT	^{0}C		
Temperature range cold fluid, Δt	^{0}C		
Capacity Ratio, R	-		

Effectiveness, S	-		
Corrected LMTD	^{0}C		
Heat Transfer Coefficient, U	kW/(m^2.K)		

Step D

The following formulae are used for calculating the thermal parameters:

Sl	To find	Nomenclature and related equation
01	Heat Duty, $Q = q_S + q_L$ For sensible heat, $q_S = \frac{m_h \times C_{ph} \times (T_{hot,in} - T_{hot,out})}{3600} \quad (kW)$ or $q_S = \frac{m_c \times C_{ch} \times (T_{cold,in} - T_{cold,out})}{3600} \quad (kW)$ For latent heat, $q_L = m_h \times l_{vh}$ or $q_L = m_c \times l_{vc}$	m_h = mass flow rate of hot fluid (kg/h), m_c= mass flow rate of cold fluid (kg/h), $C_{ph} =$ specific heat of hot fluid (J/kgK), $C_{pc} =$ specific heat of cold fluid (J/kgK), $T_{hot,in} =$ inlet temp of hot fluid $T_{hot,out} =$ outlet temp. of hot fluid $T_{cold,in} =$ inlet temp. of cold fluid $T_{cold,out} =$ outlet temp. of cold fluid $l_{vh} =$ latent heat of valorization of hot fluid $l_{vc} =$ latent heat of valorization of cold fluid
02	Hot fluid side pressure drops, $\Delta P_h = P_{hot,in} - P_{hot,out}$	$P_{hot\ in}$ = inlet pressure of hot fluid $P_{hot\ out}$ = outlet pressure of hot fluid
03	Cold fluid side pressure drops, $\Delta P_c = P_{cold,in} - P_{cold,out}$	$P_{cold\ in}$ = inlet pressure of cold fluid $P_{cold\ out}$ = outlet pressure of cold fluid
04	Temperature range hot fluid, $\Delta T_{hot} = T_{hot,in} - T_{hot,out}$	$T_{hot,in} =$ inlet temp of hot fluid $T_{hot,out} =$ outlet temp. of hot fluid
05	Temperature range cold fluid, $\Delta T_{cold} = T_{cold,in} - T_{cold,out}$	$T_{cold,in} =$ inlet temp. of cold fluid $T_{cold,out} =$ outlet temp. of cold fluid
06	Capacity ratio, $R = \frac{hot\ fluid\ heat\ capcity}{Cold\ fluid\ heat\ capcity} = \frac{m_h C_{ph}}{m_c C_{pc}}$ (or) $R = \frac{hot\ fluid\ temp\ range}{Cold\ fluid\ temp\ range} = \frac{\Delta T_{hot}}{\Delta T_{cold}}$	m_h = mass flow rate of hot fluid (kg/h), m_c= mass flow rate of cold fluid (kg/h), $C_{ph} =$ specific heat of hot fluid (J/kgK), $C_{pc} =$ specific heat of cold fluid (J/kgK),
07	Effectiveness, $S = \frac{(T_{cold,out} - T_{cold,in})}{(T_{hot,in} - T_{cold,in})}$ (or) $S = \frac{Heat\ Duty,\ Q}{Q_{max}} = \frac{Q}{C_{min} \times \Delta T_{max}}$	$Q = q_S + q_L$ $\Delta T_{max} = T_{hot,in} - T_{cold,in}$ $C_{min} = Lowest\ of\ m_h\ C_{ph}\ or\ m_c\ C_{pc}$ $T_{hot,in} =$ inlet temp of hot fluid $T_{hot,out} =$ outlet temp. of hot fluid $T_{cold,in} =$ inlet temp. of cold fluid $T_{cold,out} =$ outlet temp. of cold fluid
08	Logarithmic Temp. Difference (LMTD) Counter Flow, $LMTD = \frac{(T_{hot,in} - T_{cold,out}) - (T_{hot,out} - T_{cold,in})}{ln\left(\frac{T_{hot,in} - T_{cold,out}}{T_{hot,out} - T_{cold,in}}\right)}$ Parallel flow,	

	$$LMTD = \frac{(T_{hot,in} - T_{cold,in}) - (T_{hot,out} - T_{cold,out})}{ln\left(\frac{T_{hot,in} - T_{cold,in}}{T_{hot,out} - T_{cold,out}}\right)}$$	
09	LMTD correction Factor F, If $\boldsymbol{R \neq 1}$, $$F = \frac{\sqrt{R^2+1}\ \ln\left(\frac{1 - S}{1 - RS}\right)}{(R - 1)\ \ln\left(\frac{2 - S\ (R+1 - \sqrt{R^2+1})}{2 - S\ (R+1 + \sqrt{R^2+1})}\right)}$$ Here, $$S = \frac{\alpha - 1}{\alpha - R}$$ If $\boldsymbol{R = 1}$, $$F = \frac{S\sqrt{2}}{(1 - S)\ \ln\left(\frac{2 - S\ (2 - \sqrt{2})}{2 - S\ (2 + \sqrt{2})}\right)}$$ Here, $$S = \frac{P}{N - (N - 1)\ P}$$ Corrected LMTD = F x $LMTD_{\text{for counter flow}}$	It is required for cross flow, 1st calculate R and P, $$R = \frac{T_a - T_b}{t_b - t_a}$$ $$P = \frac{t_b - t_a}{T_a - t_a}$$ Where, T_a = inlet temperature of shell-side fluid T_b = outlet temperature of shell-side fluid t_a = inlet temperature of tube-side fluid t_b = outlet temperature of tube-side fluid R, P- Dimensional parameter $$\alpha = \left[\frac{1 - RP}{1 - P}\right]^{1/N}$$ N = Number of shell-side passes
10	Overall Heat Transfer Coefficient $$U = \frac{Q}{(A \times Corrected\ LMTD)}$$	Q= Heat Duty A= Area of heat transfer Corrected LMTD = F x $LMTD_{\text{for counter flow}}$

Case Study 6.1- Liquid –Liquid Heat Exchanger

A shell and tube exchanger of following configuration is considered being used for oil cooler with oil at the shell side and cooling water at the tube side.

Tube Side	Shell Side
460 Nos x 25.4mmOD x 2.11mm thick x 7211mm long Pitch – 31.75mm 30^{o} triangular 2 Pass	787 mm ID Baffle space – 787 mm 1 Pass

The monitored parameters are as below:

Parameters	Units	Inlet	Outlet
Hot fluid flow, W	kg/h	719800	719800
Cold fluid flow, w	kg/h	881150	881150
Hot fluid Temp, $T_{hot,\ in}$	^{O}C	145	102
Cold fluid Temp, $T_{cold,\ in}$	^{O}C	25.5	49
Hot fluid Pressure, P	bar g	4.1	2.8
Cold fluid Pressure, p	bar g	6.2	5.1
Hot fluid specific heat Capacity, C_{ph}	kJ/(kg ^{O}C)	2.847	

Cold fluid specific heat Capacity, C_{pc}	kJ/(kg ^{O}C)	4.187
Heat Transfer Area	m^2	264.55

After Calculation of the Parameter an Energy Auditor calculated as below,

Parameters	Units	Calculated Data	Design Data
Heat Duty, Q	kW	24477.4	25623
Hot fluid side pressure drop, ΔP_h	Bar	1.3	1.34
Cold fluid side pressure drop, ΔP_c	Bar	1.1	0.95
Temperature Range hot fluid, ΔT_h	^{O}C	43	45
Temperature Range cold fluid, ΔT_c	^{O}C	23.5	25
Corrected LMTD, MTD	^{O}C	83.8	82.2
Heat Transfer Coefficient, U	kW/(m^2. K)	1.104	1.178

What are the observations on this Heat Exchanger can be made as an Energy Manager?

Solution:

Heat Duty: Actual duty differences will be practically negligible as these duty differences could be because of the specific heat capacity deviation with the temperature. Also, there could be some heat loss due to radiation from the hot shell side.

Pressure drop: Also, the pressure drop in the shell side of the hot fluid is reported normal (only slightly less than the design figure). This is attributed with the increased average bulk temperature of the hot side due to decreased performance of the exchanger.

Temperature range: As seen from the data the deviation in the temperature ranges could be due to the increased fouling in the tubes (cold stream), since a higher-pressure drop is noticed.

Heat Transfer coefficient: The estimated value has decreased due to increased fouling that has resulted in minimized active area of heat transfer.

Physical properties: If available from the data or Lab analysis can be used for verification with the design data sheet as a cross check towards design considerations.

Case Study 6.2- Air Heater

A finned tube exchanger of following configuration is considered being used for heating air with steam in the tube side. The monitored parameters with design values are as follows:

Parameters	Units	Test Data	Design Data
Duty, Q	kW	1748	1800
Hot fluid side pressure drop,ΔP_h	bar	Negligible	Negligible
Cold fluid side pressure drop, Δp_c	Bar	20	15
Temperature range hot fluid, ΔT	°C		
Temperature range cold fluid, Δt	°C	65	65
Capacity ratio, R	-----		
Effectiveness, S	-----		

Corrected LMTD, MTD	°C	79	79
Heat Transfer Coefficient, U	kW/(m^2. K)	0.026	0.03

What are the observations on this Heat Exchanger can be made as an Energy Manager?

Solution:

Heat duty: The heat exchanger is under performing.
Pressure drop: The air side pressure drop has increased even with condensation at the steam side indicating choking and blockage (dirt) on the airside.
Temperature range: No deviations.
Heat Transfer coefficient: Heat transfer coefficient decreased because of reduced fin efficiency due to choking on the air side.
Recommendation: Trouble shooting is recommended. Pulsejet cleaning with steam / blow air on the air side is recommended and performance can be verified after cleaning. Mechanical cleaning has to be planned during down time.

6.6 Instruments for monitoring performance

The test and evaluation of the performance of the heat exchanger equipment is carried out by measurement operating parameter sup stream and downstream of the exchanger. The instruments used for measurements require calibration before measurement.

Table 6.5: Instrumentation for measurement of parameters

Parameters	Units	Instruments used
Fluid flow	kg/h	Orifice flow meter, Vortex flow meter, Venturi meters, Coriollis flow meters, Magnetic flow meter
Temperature	°C	Thermo gauge for low ranges, RTD (Resistance Temperature Detector)
Pressure	bar (g)	Liquid manometers, Draft gauge, Pressure gauges Bourdon and diaphragm type, Absolute pressure transmitters.
Density	kg/m^3	Hydrometer Laboratory measurements as per ASTM standards.
Viscosity	MpaS	Viscometer Laboratory Measurements as per ASTM standards.
Specific heat capacity	J/(kg.K)	Laboratory Measurements as per ASTM standards.
Thermal conductivity	W/(m.K)	Laboratory Measurements as per ASTM standards.
Composition	%weight (or) % Volume	Laboratory Measurements as per ASTM standards using Chemical analysis, HPLC, GC, Spectrophotometer, etc.

CHAPTER 07: BOILER & STEAM SYSTEM

7.1 Introduction

A boiler is an enclosed vessel that provides a means of same anchor combustion heat to be transferred into water until it becomes heated water or a steam. The steam or hot water under pressure is then usable for transfer ring the heat to a process. Water is a useful and cheap medium for transferring heat to a process. When water is boiled in to steam its volume increases about 1,600 times, producing a force that is almost as explosive as gun powder. This causes the boiler to be extremely dangerous equipment that must be treated with utmost respect.

7.2 Typical Boiler Specification

Boiler make and year	XYZ & 2003
MCR rating	6 TPH (F & A 100 ^{0}C)
Type of boiler	3 Pass Fire tube Package Boiler
Design steam pressure	10.5 kg/cm2 (150 PSIG) Package Boiler
Operating pressure	110-130PSIG
Fuel used	Furnace oil

7.3 Bangladeshi Boiler Regulation

The Boilers Act was enacted in 1923 in the undivided India to consolidate and amend the law relating to steam boilers. Bangladesh Boiler Regulation (BBR) was created in 1951 in exercise of the powers conferred by section 28 of the Boilers Act, 1923 and further amended in 2007.

As per 'The Boilers Act, 1923' Boiler is defined as, 'A pressure vessel in which steam is generated for use external to itself by application of heat which is wholly or partly under pressure when steam is shut off but does not include a pressure vessel with capacity less than 22.76 litres (such capacity being measured from the feed check valve to the main steam stop valve).

The following points are important regarding the definition of boiler as per the Boilers Act, 1923.

i. It must be a 'Closed vessel'
ii. It must generate steam for 'external use'
iii. Volume of vessel must be over '22.76 Litres'
iv. Working pressure more than 1.0 kg/cm^2

'Boiler component' means steam piping, feed piping, economizer, super heater, any mountings or other fitting and any other external or internal part of a boiler which is subjected to a pressure more than 1.0 kg/cm^2.

'Economiser' means any part of feed-pipe that is wholly or partially exposed to the action of flue gases for the purpose of recovery of waste heat.
'Steam-pipe" means any main pipe exceeding 7.62 cm in internal diameter through which steam passes directly from a boiler to a prime-mover or other first user, and includes any connected fitting of a steam-pipe.

The boiler system comprises of feed water system, steam system and fuel system. The feed water system provides water to the boiler and regulates it automatically to meet the steam demand. A typical boiler room schematic is shown in Figure 7 .1.

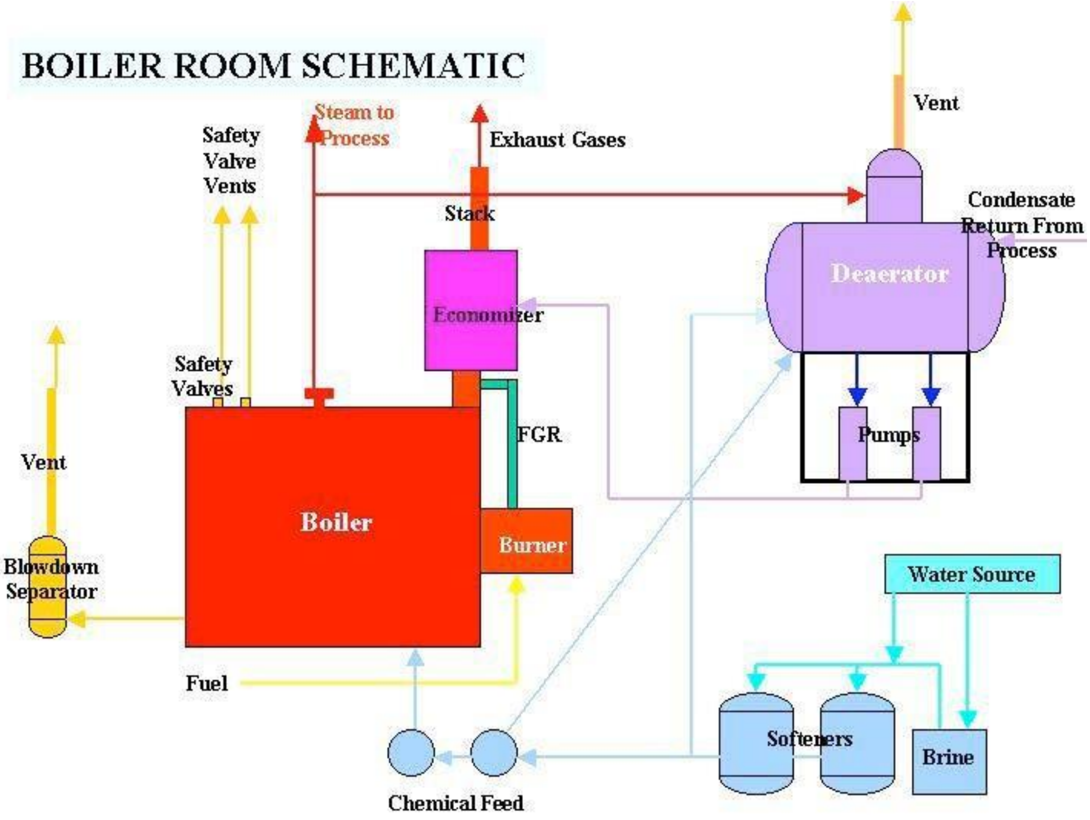


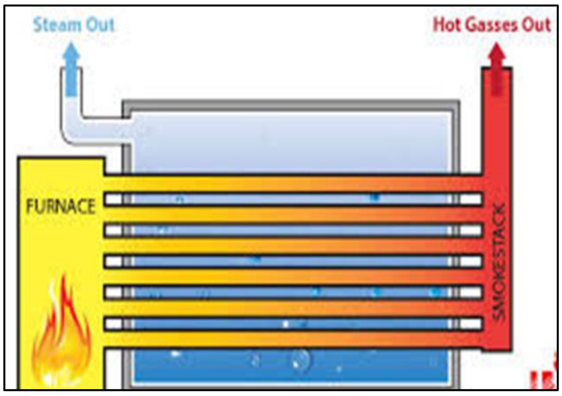
Figure 7 .1: Boiler room

7.4 Boiler Types and Classifications

There are virtually infinite numbers of boiler designs but generally they fit into one of the two categories:

7.4.1 Fire tube boiler

In a fire tube steam boiler, hot gases of combustion pass through the tube surrounded by water (Refer Figure 7.2). Fire tube boilers, typically have a lower initial cost, are more fuel efficient and easier to operate but they are limited generally to capacities of 25 tons/hr and pressures of 17.5 kg/cm^2. All fire tube boilers have the same basic operating principles. However, fire tube boilers have different designs like 2 passes, 3 pass, and 4 pass based on application and installation considerations.



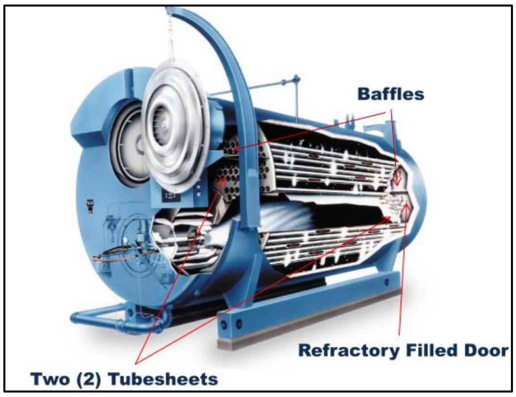
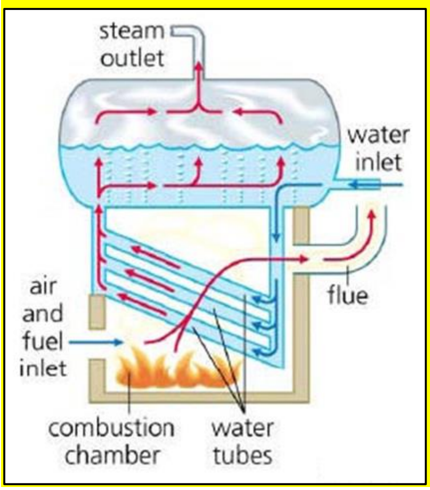


Figure 7.2: Fire tube boiler

7.4.2 Water tube boiler

In a water tube boiler water is inside the tubes and combustion gases pass around the outside of the tubes (Refer figure 7.3). Water-tube boilers are available in sizes far greater than a fire-tube design, up to several million pounds-per-hour of steam and able to handle higher pressures up to 5,000 psig. Disadvantages of water-tube boilers include:

High initial capital cost, cleaning is more difficult due to the design. These boilers can be single or multiple drum type design.



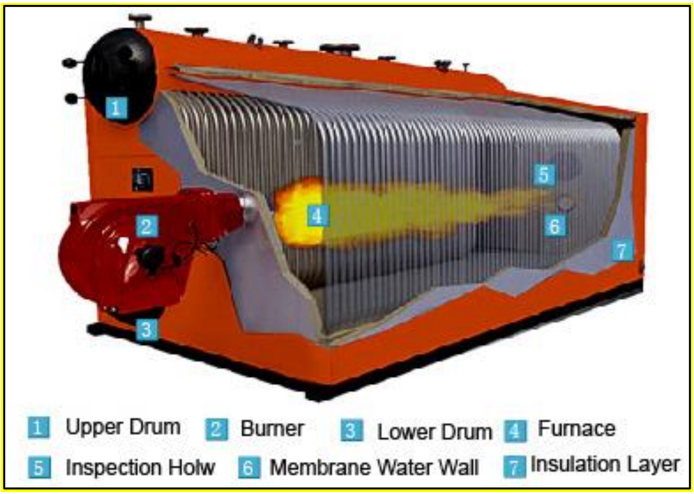


Figure 7.3: Water tube boiler

7.4.3 Once Through Boiler

Feed water from the bottom header, evaporating it in water tubes, and taking out steams from the top header. In this type of boiler the water flow is only one way.

Traditionally boilers circulate water within them and only a portion gets turned into steam on any one pass. Circulation ratios (the amount of water recirculated versus the amount taken out as steam) can vary from 3 to 20.

A once through boiler passes the water through the tubes only once and there is no circulation ratio. Small once-through boilers will have a mixture of steam and water coming out boiler which is separated and the water is returned to the front of the boiler. Large scale power plant type once through boilers will have 100% conversion to steam before it comes out of the boiler.

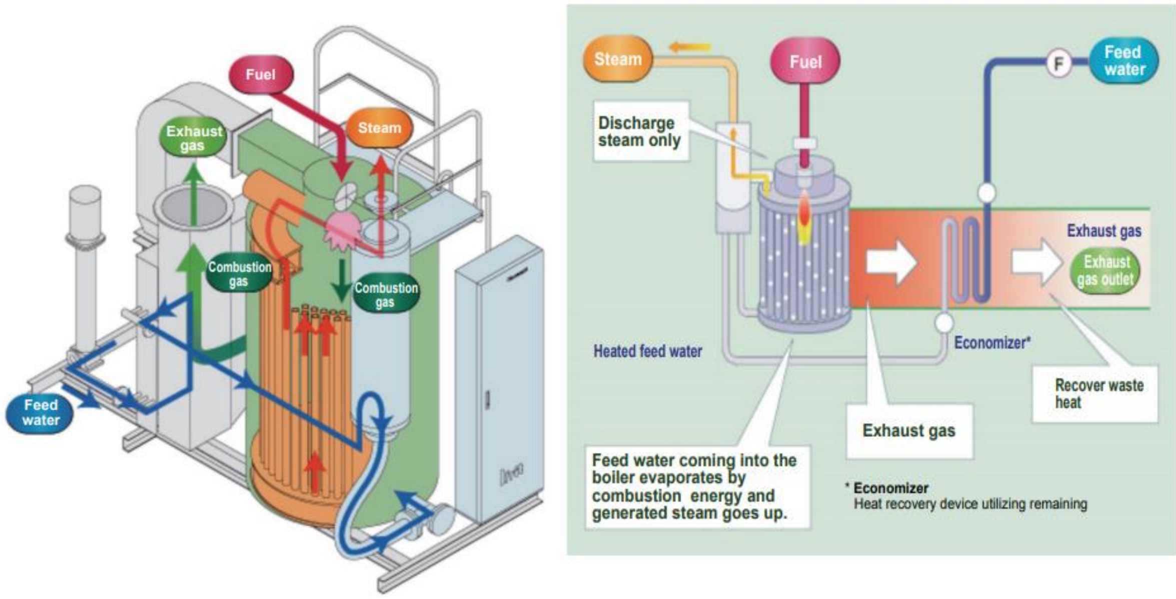


Figure 7.4: Basics of once through boiler

Effects of using once through boiler are;

1. High efficiency: Boiler efficiency of 98%
2. Stable steam pressure: ±0.01MPa with static load
3. Long life: Designed to last for 15 years

7.4.4 Pulverized Fuel Boiler

Pulverized coal firing system is most efficient and modern technology. This is mostly applied in power plants boiler.

In this system coal is made as powder. The coal is ground (pulverized) to a fine powder, so that less than 2% is + 300 micro meter (μm) and 70-75% is below 75 microns, for a bituminous coal. The pulverized coal is blown with part of the combustion air into the boiler plant through a series of burner nozzles. Secondary and tertiary air may also be added. Combustion takes place at temperatures from 1300-1700°C, depending largely on coal rank. Particle residence time in the boiler is typically 2-5 seconds, and the particles must be small enough for complete burn out to have taken place during this time.
This technology is well developed, and there are thousands of units around the world, accounting for well over 90% of coal-fired capacity. Pulverized coal fired boiler can be used to fire a wide variety of coals.

One of the most popular systems for firing pulverized coal is the tangential firing, using four burners corner to corner to create a fire ball at the center of the furnace. See Figure 7.5 below.

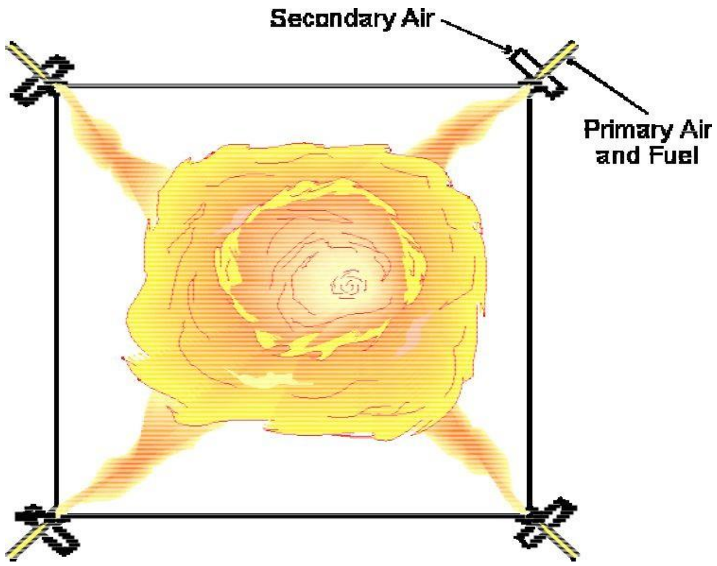


Figure 7.5: Tangential Firing

7.4.5 Fluidized Bed Combustion (FBC) Boiler

Fluid is edged combustion has significant advantages over conventional firing systems and offers multiple benefits namely fuel flexibility, reduced mission of noxious pollutants such as SO_x and NO_x, compact boiler design and higher combustion efficiency.

When an evenly distributed air or gas is passed upward through a finely divided bed of solid particles such as sand supported on a fine mesh, the particles are undisturbed at low velocity. As air velocity is gradually increased, a stage is reached when the individual particles are suspended in the air stream. Further, increase in velocity gives rise to bubble formation, vigorous turbulence and rapid mixing and the bed is said to be fluidized.

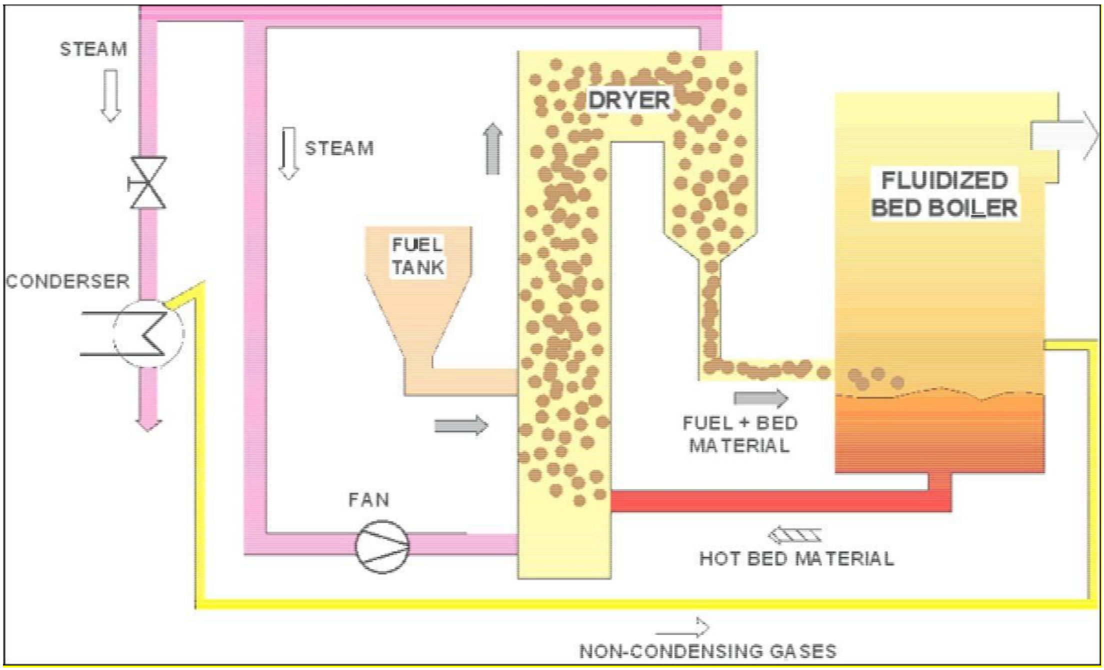


Figure 7.6: Schematic of fluidized bed boiler

Advantages of Fluidized Bed Combustion Boilers:

1. High Efficiency

FBC boilers can burn fuel with a combustion efficiency of over 95% irrespective of ash content. FBC boilers can operate with overall efficiency of 84% (plus or minus 2%).

2. Reduction in Boiler Size

High heat transfer rate over a small heat transfer area immersed in the bed result in overall size reduction of the boiler.

3. Fuel Flexibility

FBC boilers can be operated efficiently with a variety of fuels. Even fuels like flotation slimes, washer rejects, agro waste can be burnt efficiently. These can be fed either independently or in combination with coal into the same furnace.

4. Ability to Burn Low Grade Fuel

FBC boilers would give the rated output even with inferior quality fuel. The boilers can fire coals with ash content as high as 62% and having calorific value as low as 2,500 kcal/kg. Even carbon content of only 1% by weight can sustain the fluidized bed combustion.

5. Ability to Burn Fines

Coal containing fines below 6 mm can be burnt efficiently in FBC boiler, which is very difficult to achieve in conventional firing system.

6. Pollution Control

SO2 formation can be greatly minimized by addition of limestone or dolomite for high sulphur coals. 3% limestone is required for every 1% sulphur in the coal feed. Low combustion temperature eliminates NO_x formation.

7. Low Corrosion and Erosion

The corrosion and erosion effects are less due to lower combustion temperature, softness of ash and low particle velocity (of the order of 1 m/sec).

8. Easier Ash Removal — No Clinker Formation

Since the temperature of the furnace is in the range of 750 — 900 °C in FBC boilers, even coal of low ash fusion temperature can be burnt without clinker formation. Ash removal is easier as the ash flows like liquid from the combustion chamber. Hence less manpower is required for ash handling.

9. Less Excess Air — Higher CO2 in Flue Gas

The CO2 in the flue gases will be of the order of 14 — 15% at full load. Hence, the FBC boiler can operate at low excess air - only 20 — 25%.

10. Simple Operation, Quick Start-Up

High turbulence of the bed facilitates quick start up and shut down. Full automation of start-up and operation using reliable equipment is possible.

11. Fast Response to Load Fluctuations

Inherent high thermal storage characteristics can easily absorb fluctuation in fuel feed rates. Response to changing load is comparable to that of oil fired boilers.

12. No Slagging in the Furnace-No Soot Blowing

In FBC boilers, volatilization of alkali components in ash does not take place and the ash is non-sticky. This means that there is no slagging or soot blowing.

13. Provisions of Automatic Coal and Ash Handling System

Automatic systems for coal and ash handling can be incorporated, making the plant easy to operate comparable to oil or gas fired installation.

14. Provision of Automatic Ignition System

Control systems using micro-processors and automatic ignition equipment give excellent control with minimum manual supervision.

15. High Reliability

The absence of moving parts in the combustion zone results in a high degree of reliability and low maintenance costs.

16. Reduced Maintenance

Routine overhauls are infrequent and high efficiency is maintained for long periods.

17. Quick Responses to Changing Demand

A fluidized bed combustor can respond to changing heat demands more easily than stoker fired systems. This makes it very suitable for applications such as thermal fluid heaters, which require rapid responses.

18. High Efficiency of Power Generation

By operating the fluidized bed at elevated pressure, it can be used to generate hot pressurized gases to power a gas turbine. This can be combined with a conventional steam turbine to improve the efficiency of electricity generation and give a potential fuel savings of at least 4%.

7.4.6 Super Critical Boiler

In the temperature entropy diagram of steam, a point is reached where the boiling water and dry saturated steam lines converge and at that point, the latent heat is zero. The critical point corresponds to a pressure of 221.2 bar absolute and a temperature of 374.18 °C.

If water is heated beyond the above condition, steam parameters are referred to as super critical. A boiler producing steam above the critical pressure is called the supercritical boiler. While sub-critical boiler has three distinct sections - economiser, evaporator and super heater the supercritical boiler has only an economiser and super heater. The advantages of super critical boilers are

- Higher heat transfer rate
- More flexible in accepting load variation
- Greater ease of operation
- High thermal efficiency (40-42% of power generating stations)
- The absence of two-phase mixer minimise the problems of erosion and corrosion
- Steadier pressure level

The super critical boilers call for special materials to be used for constituent heat transfer surfaces like drum, water walls, economizer and re-heaters, in order to withstand the elevated pressure & temperature conditions.

7.5 Performance Evaluation of Boilers

The performance of boiler, like efficiency and evaporation ratio reduces with time due to poor combustion, heat transfer surface fouling and poor operation and maintenance. Deteriorating fuel quality, water quality etc. also leads to poor boiler performance. Efficiency tests help us to find out the deviation of boiler efficiency from the best efficiency and target problems for corrective action.

7.5.1 Boiler Efficiency Calculation

Thermal efficiency of boiler is defined as the percentage of heat input that is effectively utilized to generate steam. There are two methods of assessing boiler efficiency.

- **a)** The Direct Method: Where the energy gain of the working fluid (water and steam) is compared with the energy content of the boiler fuel.
- **b)** The Indirect Method: Where the efficiency is the difference between the losses and the energy input.

a. Direct Method

This is also known as 'input-output method' due to the fact that it needs only the useful output (steam) and the heat input (i.e. fuel) for evaluating the efficiency. This efficiency can be evaluated using the formula.

$$Boiler\ Efficiency = \frac{HeatOutput}{HeatInput} x100$$

Parameters to be monitored for the calculation of boiler efficiency by direct method are:

- Quantity of steam generated per hour (Q) in kg/hr.
- Quantity of fuel used per hour (q) in kg/hr.
- The working pressure (in kg/cm^2(g)) and superheat temperature (ºC), if any
- The temperature of feed water (ºC)
- Type of fuel and Gross Calorific Value (GCV) of the fuel in kJ/kg of fuel

$$BoilerEfficiency(\eta) = \frac{Qx(h_g - h_f)}{qxGCV} \times 100 \cdots\cdots\cdots (7.1)$$

Where, h_g - Enthalpy of saturated steam in kJ/kg of steam
h_f - Enthalpy of feed water in kJ/kg of water

The fuel calorific value may be gross or net and accordingly, the efficiency reported is referred to as efficiency on GCV or NCV basis.

Example 7.1
Find out the efficiency of the boiler by direct method with the data given below:

Type of boiler	: Coal fired
Quantity of steam (dry) generated	: 8 TPH
Steam pressure / temp	: 10 kg/cm^2(g)/ 180 ^{0}C
Quantity of coal consumed	: 1.8 TPH
Feed water temperature	: 85 ^{0}C
GCV of coal	: 13440 kJ/kg
Enthalpy of saturated steam at 10 kg/cm^2 pressure	: 2793 kJ/kg(saturated)
Enthalpy of feed water	: 357 kJ/kg

Solution:

Boiler Efficiency (η) $= \frac{8\times(2793-357)}{1.8\times 13440} \times 100$

= 80% (on GCV basis)

It should be noted that boiler may not generate 100% saturated dry steam and there may be some amount of wetness in the steam. Since it is practically difficult to measure the dryness fraction, it is assumed the boiler generates 100% saturated steam for calculation purposes. The resulting errors are likely to be in significant.

Advantages:
- Plant people can evaluate quickly the efficiency of boilers
- Requires few parameters for computation
- Needs few instruments for monitoring

Disadvantages:
- Does not give clues to the operator as to why efficiency of system is lower
- Does not calculate various losses accountable for various efficiency levels

b. Indirect Method

Indirect method also called as heat loss method. The efficiency can be arrived at, by subtracting the heat loss fractions from 100. All standard does not include blow down loss in the efficiency determination process.
However, the efficiency calculations are meant for practicing energy managers, simpler calculation procedure is being adopted in industries.

There are reference standards for Boiler Testing at Site using indirect method namely British Standard, BS845:1987 and USA Standard is 'ASME PTC-4.1 Power Test Code Steam Generating Units'**.**

The principal losses that occur in a boiler are:

- Loss of heat due to dry flue gas
- Loss of heat due to combustion of hydrogen
- Loss of heat due to moisture in fuel
- Loss of heat due to moisture in combustion air
- Loss of heat due to partial combustion of fuel
- Loss of heat due to radiation

- Loss of heat due to fly and bottom ash content in fuel (for solid fuels only)

Loss due to moisture in fuel and the loss due to combustion of hydrogen cannot be controlled by design and is dependent on the fuel and these two losses are practically zero while computing the efficiency on the basis of **net calorific value**

The data required for calculation of boiler efficiency using indirect method are:

1. Ultimate analysis of fuel (H_2, O_2, S, C, moisture content, ash content)
2. Percentage of Oxygen or CO_2 in the flue gas
3. Flue gas temperature in ^0C (T_f)
4. Ambient temperature in ^0C (T_a)
5. Humidity of air in kg/kg of dry air
6. GCV of fuel kJ/kg
7. Percentage combustible in ash (in case of solid fuels)
8. GCV of ash in kJ/kg (in case of solid fuels)
9. Heat Transfer area for radiation and convection losses

In order to calculate the boiler efficiency by indirect method, all the losses that occur in the boiler must be established. These losses are conveniently related to the amount of fuel burnt.

Process of Calculation of Boiler Efficiency by Indirect Method:

Step 1: Theoretical Air requirement, Excess Air (EA) supplied and Actual air supplied(AAS)

Table 7.1: Equation for Air Requirement for Boiler

Theoretical air required for combustion	=	$\frac{11.6 \times C + 34.8 \times \left(H_2 - \frac{O_2}{8}\right) + 4.35 \times S}{100}$ kg/kg of fuel (from fuel analysis) Where C, H_2, O_2 and S are the percentage of carbon, hydrogen, oxygen and sulphur present in the fuel
Actual O_2% in Flue Gas		O_2% measured from flue gas [measured]
Excess air supplied (EA) kg	=	$\frac{O_2\,\%}{21 - O_2\%}\ X\ 100$
Actual Air Supplied (AAS) kg	=	$\left\{1 + \frac{EA}{100}\right\} \times \ Theoretical\ air\ required$
Total Mass of Flue gas	=	Actual Air Supplied (AAS)+1 kg of fuel

Box 7.1 (Optional)

If O_2 measurement cannot be found we can use CO_2 percentage in flue gas by below formula

Actual CO_2 percentage	=	$(CO_2\%)_a$ measured from flue gas
Theoretical CO_2 Percentage		$(CO_2\%)_t = \frac{\text{Moles of C}}{\text{Moles of N}_2 + \text{Moles of C}}$ $Moles\ of\ N_2 = \frac{\text{Weight of N}_2\text{ in theoretical air}}{\text{Molecular weight of N}_2} + \frac{\text{Weight of N}_2\text{ in fuel}}{\text{Molecular weight of N}_2}$ $Moles\ of\ C = \frac{Weight\ of\ C\ in\ Fuel}{\text{Molecular weight of C}}$
Excess air	=	$7900 \times\ [(CO_2\%)_t - [(CO_2\%)_a]$

Step 2: Finding Loss

Table 7.2: Loss Equations of Boiler

1. Dry flue gas loss (%)	$L1 = \frac{\text{m X C}_P\text{ X (T}_f - \text{T}_a\text{)}}{\text{GCV of fuel (kJ/Kg)}}\text{ X 100}$ m = Mass of dry flue gas in per kg of fuel $or, m = m_{CO_2} + m_{SO_2} + m_{N_2\ in\ fuel} + m_{N_2\ in\ supplied\ air} + m_{O_2\ in\ flue\ gas}$ C_p = Specific heat of flue gas kJ/kg°C T_f = Flue gas temperature in °C T_a = Ambient temperature in °C
2. Loss due to hydrogen in fuel	$L2 = 9\text{ x H}_2\text{ x }\frac{\{l_v + C_p(T_f - T_a)\}}{\text{GCV of fuel(kJ/Kg)}}\text{ x 100}$ Where, H_2 = mass (kg) of hydrogen present in 1 kg of fuel C_p = Specific heat of superheated steam in kJ/kg °C T_f = Flue gas temperature in °C T_a = Ambient temperature in °C l_v = Latent heat of Vaporization of water at 25°C = 2441 kJ/kg or 584
3. Loss due to moisture in fuel	$L3 = \text{M x }\frac{\{l_v + C_p(T_f - T_a)\}}{\text{GCV of fuel (kJ/Kg)}}\text{ x 100}$ Where, M= mass (kg) moisture present in 1 kg of fuel C_p= Specific heat of superheated steam in kJ/kg °C T_f = Flue gas temperature in °C T_a = Ambient temperature in °C l_v = Latent heat of Vaporization of water at 25°C = 2441 kJ/kg or 584
4. Loss due to moisture in air	$L4 = \frac{\text{AAS x Humidity factor x C}_p\text{ x (T}_f - \text{T}_a\text{) x 100}}{\text{GCV of fuel(kJ/Kg)}}$ Where, AAS = Actual mass of air supplied for per kg of fuel

	Humidity factor = kg of water per kg of dry air Cp = Specific heat of superheated steam in kJ/kg °C T_f = Flue gas temperature in °C T_a = Ambient temperature in °C
5. Partial combustion of fuel (CO formation)	$L5 = \frac{\%CO \text{ x } C}{\% CO + \%CO_2} \text{ x } \frac{23{,}747}{\text{GCV of fuel(kJ/Kg)}} \text{ x } 100$ Where, L5 = % heat loss due to partial conversion of C to CO (1% = 10000 PPM) CO = Volume of CO in flue gas leaving economizer (%) CO_2= Actual volume of CO_2 in flue gas (%) C = Carbon content kg/kg of fuel *23,747 kJ/kg - Heat loss due to partial combustion of carbon
6. Surface heat losses (Radiation + Convection)	L6 $= \frac{0.548 \text{ x } [\left(\frac{T_s}{55.55}\right)^4 - \left(\frac{T_a}{55.55}\right)^4] + 1.957 \text{ x } (T_s - T_a)^{1.25} \text{ x } \sqrt{\frac{(196.85 V_m + 68}{68.9}}}{GCV\ of\ fuel(\text{kJ/Kg})}$ $\times 3.6 \times A$ L6 = Radiation loss in kJ/hr V_m = Wind velocity in m/s T_s = Surface temperature (K) T_a = Ambient temperature (K) A = Heat transfer Area for convection and radiation
7. Loss due to Unburnt in fly ash (for solid fuels only)	$L7 = \frac{Ash\ collected\ /kg\ of\ fuel\ burnt \times GCV\ of\ fly\ ash \times 100}{GCV\ of\ fuel(\text{kJ/Kg})}$
8. Loss due to Unburnt in bottom ash (for solid fuels only)	$L8 = \frac{Ash\ collected\ /kg\ of\ fuel\ burnt \times GCV\ of\ bottom\ ash \times 100}{GCV\ of\ fuel(\text{kJ/Kg})}$

Step 3:
Heat Balance:
Having established the magnitude of all the losses mentioned above, a simple heat balance would give the efficiency of the boiler. The efficiency is the difference between the energy input to the boiler and the heat losses calculated.

Boiler Heat Balance:

Input/output parameter		kJ / kg of Fuel oil	%
Heat Input in fuel	=	GCV of fuel	100
Various Heat losses in boiler			
1. Dry flue gas loss	=		
2. Loss due to hydrogen in fuel	=		
3. Loss due to moisture in fuel	=		
4. Loss due to moisture in air	=		
5. Partial combustion of fuel	=		
6. Surface heat losses	=		

7. Loss due to Unburnt in fly ash (for solid fuels only)	=		
8. Loss due to Unburnt in bottom ash (for solid fuels only)	=		
Total Losses	=		
Boiler efficiency = 100 - (1+2+3+4+5+6+7+8) =			

7.5.2 Boiler Evaporation Ratio

Evaporation ratio means kilogram of steam generated per kilogram of fuel consumed. An Energy Manager can monitor Evaporation ratio for any boiler when its own performance is compared on day-to-day basis as a performance indicator; given that enthalpy gain in steam and fuel calorific value remain constant.

A drop in evaporation ratio indicates a drop in Boiler efficiency.

Typical values of Evaporation ratio for different type of fuels are as follows:

Biomass fired boilers : 2.0 to 3.0
Coal fired boilers : 4.0 to 5.5
Oil fired boilers : 13.5 to 14.5
Gas fired boilers : 11.0 to 13.0
However, the above ratio will depend upon the type of boiler and associated efficiencies.

7.6 Boiler Blow down

The impurities found in boiler water depend on the untreated feed water quality, the treatment process used and the boiler operating procedures. As a general rule, the higher is the boiler operating pressure, the greater will be the sensitivity to impurities. As the feed water materials evaporate in to steam, dissolved solids concentrate in the boiler either in a dissolved or suspended state. Above a certain level of concentration, these solids encourage foaming and cause carryover of water in to the steam. This leads to scale formation inside the boiler, resulting in localized overheating and ending finally in tube failure.

It is therefore necessary to control the level of concentration of the solids and this is achieved by the process of' blowing down', where a certain volume of water is blown off and maintaining the optimum level of total dissolved solids (TDS) in the water. Blow down is necessary to protect the surfaces of the heat exchanger in the boiler. However, blow down can be a significant source of heat loss, if improperly carried out. The maximum amount of total dissolved solids (TDS) concentration permissible in various types of boilers is given in Table 7.3.

Table 7.3: Recommended TDS levels for various boilers

SN	Boiler Type	Maximum TDS (ppm)
1	Smoke and water tube boilers (12 kg/cm2)	5,000 ppm
2	Low pressure Water tube boiler	2000-3000
3	High Pressure Water tube boiler with super heater etc.	3,000 - 3,500 ppm
4.	Package and economic boilers	3,000 ppm
5.	Coil boilers and steam generators	2000 (in the feed water)

Conductivity as Indicator of Boiler Water Quality

Conductivity is a standard measurement for monitoring the overall total dissolved solids present in the boiler. Arise in conductivity indicates arise in the" contamination" of the boiler water.

7.6.1 Intermittent vs. Continuous Blow down

Conventional methods for blowing down the boiler depend on two kinds of blow down –intermittent and continuous.

Intermittent Blow down

The parameters that are most often monitored to ensure the quality of steam are TDS or conductivity, pH, Silica and Phosphates concentration. The boiler is blown down by manually operating a valve fitted to discharge pipe at the lowest point of boiler shell to reduce these levels and keeping them controlled to a point where the steam quality is not likely to be affected. A substantial amount of heat energy is lost in this process. In intermittent blow down, a large diameter line is opened for a short period of time, the time being based on a thumb rule such as “once a shift for 2 minutes”.

Continuous Blow down

There is a steady and constant dispatch of small stream of concentrated boiler water. In a continuous blow down, large quantities of heat are wasted though it is inevitable especially in large high-pressure boilers. However, opportunity exists for recovering this heat by blowing in to a flash tank and generating flash steam. This flash steam can be used for pre-heating boiler feed water or for any other purpose.

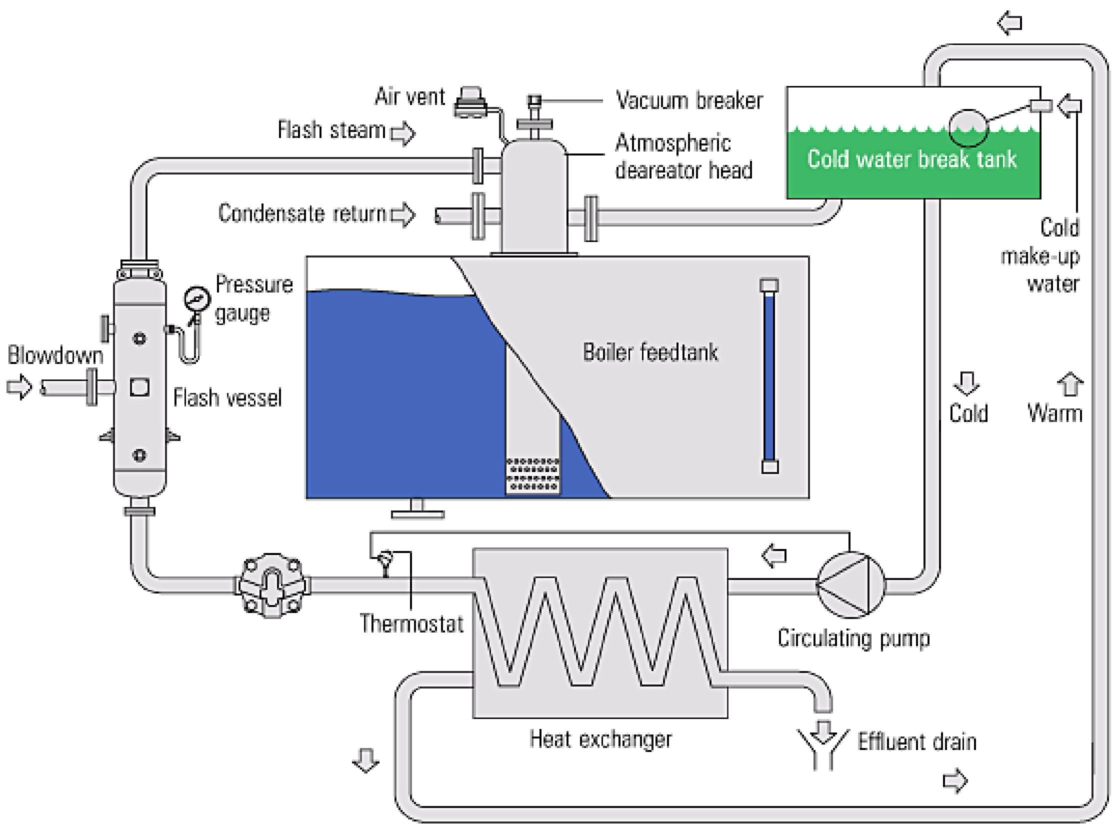


Figure 7.7: Blow down heat recovery system

7.6.2 Benefits of Blow down

Good boiler blow down control can significantly reduce treatment and operation al costs that include:

- Lower pre-treatment costs
- Less make-up water consumption
- Reduced maintenance own time
- Increased boiler life
- Lower consumption of treatment chemicals

The following formula gives the quantity of blow down required:

$$\text{Blow down (\%)} = \frac{\text{[Feed water TDS x \% Make up water]}}{\text{(Maximum Permissible TDS in Boiler water -Feed water TDS)}} \cdots (7.2)$$

Example 7.2: Blow Down Percentage

If maximum permissible limit of TDS as in a package boiler is 3000ppm, percentage make up water is 10% and TDS in feed water is 300ppm, then the percentage blow down is given as:

$$\text{Blow down (\%)} = \frac{300 \times 10}{3000 - 300}$$

= 1.11%

If boiler evaporation rate is 3000 kg/hr, then required blow down rate is:

$$Blow\ Down\ Rate = Evaporation\ Rate \times \frac{Blow\ Down\ (\%)}{100} \cdots (7.2.\text{a})$$
$$= 3000 \times 0.0111$$
$$= 33.3\text{kg/hr}$$

7.7 Boiler Water Treatment

Producing quality steam on demand depends on properly managed water treatment to control steam purity, deposits and corrosion. Boiler performance, efficiency, and service life are direct products of selecting and controlling feed water used in the boiler.

The boiler water must be sufficiently free of deposit forming solids to allow rapid and efficient heat transfer and it must not be corrosive to the boiler metal.

7.7.1 Deposit Control

Deposits in boilers may result from hardness contamination of feed water and corrosion products from the condensate and feed water system. Hardness contamination of the feed water may arise due to deficient softener system. Deposits and corrosion result in efficiency losses and may result in boiler tube failures and inability to produce steam. Deposits act as insulators and slow heat transfer. Large amounts of deposits throughout the boiler could reduce the heat transfer enough to reduce the boiler efficiency significantly.

Different type of deposits affects the boiler efficiency differently. Thus, it may be useful to analyse the deposits for its characteristics. The insulating effect of deposits causes the boiler metal temperature to rise and may lead to tube-failure by overheating.

Impurities causing deposits

The most important chemicals contained in water that influences the formation of deposits in the boilers are the salts of calcium and magnesium, which are known as hardness salts. Calcium and magnesium **bicarbonate** dissolve in water to form an alkaline solution and these salts are known as alkaline hardness. They decompose upon heating, releasing carbon dioxide and forming a soft sludge, which settles out. These are called **temporary hardness**, hardness that can be removed by boiling.

Calcium and magnesium sulphates, chlorides and nitrates, etc. when dissolved in water are chemically neutral and are known as non-alkaline hardness. These are called **permanent hardness** and form hard scales on boiler surfaces, which are difficult to remove. Non-alkalinity hardness chemicals fall out the solution due to reduction in solubility as the temperature rises, by concentration due to evaporation which takes place within the boiler, or by chemical change to a less soluble compound.

Silica

The presence of silica in boiler water can rise to formation of hard silicate scales. It can also associate with calcium and magnesium salts, forming calcium and magnesium silicates of very low thermal conductivity. Silica can give rise to deposits on steam turbine blades, after been carried over either in droplets of water in steam, or in volatile form in steam at higher pressures.

7.7.2 Boiler Water Treatment

Two major types of boiler water treatment are: Internal water treatment and External water treatment,

Internal Water Treatment

Internal treatment is carried out by adding chemicals to boiler to prevent the formation of scale by converting the scale-forming compounds to free-flowing sludge's, which can be removed by blow down.

This method is limited to boilers, where feed water is low in hardness salts, operating pressure is low also when only small quantity of water is required to be treated. If these conditions are not applied, then high rates of blow down are required to dispose the sludge. They become uneconomical from heat and water loss consideration.

Different waters require different chemicals. Sodium carbonate, sodium aluminate, sodium phosphate, sodium sulphite and compounds of vegetable or inorganic origin are all used for this purpose. Proprietary chemicals are available to suit various water conditions. The specialist must be consulted to determine the most suitable chemicals to use in each case.

Internal treatment alone is not a recommended Solution.

External Water Treatment

External treatment is used to remove suspended solids, dissolved solids (particularly the calcium and magnesium ions which are major causes of scale formation) and dissolved gases (oxygen and carbon

dioxide).
The external treatment processes available are:

(1) ion exchange;
(2) demineralization;
(3) reverse osmosis and
(4) de-aeration.

Before any of these are used, it is necessary to remove suspended solids and colour from the raw water, because these may foul the resins used in the subsequent treatment sections.

Methods of pre-treatment include simple sedimentation in settling tanks or settling in clarifiers with aid of coagulants and flocculants. Pressure sand filters, with spray aeration to remove carbon dioxide and iron, may be used to remove metal salts from bore well water.

The first stage of treatment is to remove hardness salt and possibly non-hardness salts. Removal of only hardness salts is called softening, while total removal of salts from solution is called demineralization.

(1) Ion-exchange process (Softener Plant)

In ion-exchange process, the hardness is removed by exchanging calcium and magnesium ions with sodium ions.

The sodium salts are soluble in water, do not form scales in boilers. But it does not reduce the TDS content, and blow down quantity. It also does not reduce the alkalinity. So, blow down is required.

(2) Demineralization

Demineralization is the complete removal of all salts. This is achieved by using a hydrogen ion which exchanges with metal ions producing hydrochloric, sulphuric and carbonic acid. Carbonic acid is removed in degassing tower in which air is blown through the acid water. Other acids are removed by using mineral acid and caustic soda respectively. The complete removal of silica can be achieved by correct choice of anion.

Ion exchange processes can be used for almost total demineralization if required, as is the case in large electric power plant boilers

(3) De-aeration

In de-aeration (Figure 7.8), dissolved gases, such as oxygen and carbon dioxide, are expelled by preheating the feed water before it enters the boiler.

All natural waters contain dissolved gases in solution. Certain gases, such as carbon dioxide and oxygen, greatly increase corrosion. When heated in boiler systems, carbon dioxide (CO_2) and oxygen (O_2) are released as gases and combine with water (H_2O) to form carbonic acid, (H_2CO_3).

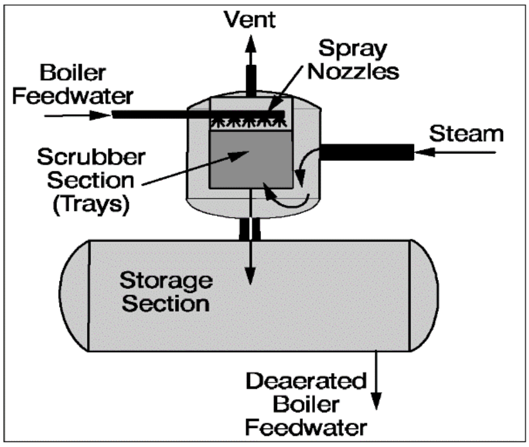


Figure 7.8: Deaerator

Removal of oxygen, carbon dioxide and other non-condensable gases from boiler feed water is vital to boiler equipment longevity as well as safety of operation. Carbonic acid corrodes metal reducing the life of equipment and piping. It also dissolves iron (Fe) which when returned to the boiler precipitates and causes scaling on the boiler and tubes. This scale not only contributes to reducing the life of the equipment but also increases the amount of energy needed to achieve heat transfer.

De-aeration can be done by mechanical de-aeration, by chemical de-aeration or by both together.

Mechanical de-aeration

Mechanical de-aeration for the removal of these dissolved gases is typically utilized prior to the addition of chemical oxygen scavengers. Mechanical de-aeration is based on Charles' and Henry's laws of physics. Simplified, these laws state that removal of oxygen and carbon dioxide can be accomplished by heating the boiler feed water, which reduces the concentration of oxygen and carbon dioxide in the atmosphere surrounding the feed water. Mechanical de-aeration can be the most economical.

Where excess low-pressure steam is available, the operating pressure of de-aerator can be selected to make use of this steam and hence improve fuel economy. In boiler systems, steam is preferred for de-aeration because:

- Steam is essentially free from O_2 and CO_2
- Steam is readily available
- Steam adds the heat required to complete the reaction.

Chemical de-aeration

While the most efficient mechanical deaerators reduce oxygen to very low levels (0.005 mg/litre), even trace amounts of oxygen may cause corrosion damage to a system. Consequently, good operating practice requires removal of that trace oxygen with a chemical oxygen scavenger such as sodium sulphite or hydrazine. Sodium sulphite reacts with oxygen to form sodium sulphate, which increases the TDS in the boiler water and hence increases the blow down requirements and make-up water quality. Hydrazine reacts with oxygen to form nitrogen and water. It is invariably used in high pressures boilers when low boiler water solids are necessary, as it does not increase the TDS of the boiler water.

(4) Reverse Osmosis

When solutions of differing concentrations are separated by a semi-permeable membrane, water from less concentrated solution passes through the membrane to dilute the liquid of high concentration, which is called osmosis. If the solution of high concentration is pressurized, the process is reversed and the water from the solution of high concentration flows to the weaker solution. This is known as reverse osmosis.

Reverse Osmosis is suitable for waters with very high TDS, such as sea water.

7.7.3 Recommended boiler and feed water quality

The impurities found in boiler water depend on the untreated feed water quality, the treatment process used and the boiler operating procedures. As a general rule, the higher the boiler operating pressure, the greater will be the sensitivity to impurities. Recommended feed water and boiler water limits are shown in Table 7.4 and Table 7.5.

Table 7.4: Recommended feed water limits

Factor	Up to $20 Kg/cm^2$	21 - $40 Kg/cm^2$	41 - $60 Kg/cm^2$
Total iron (max)ppm	0.05	0.02	0.01
Total copper (max)ppm	0.01	0.01	0.01
Total silica (max)ppm	1.0	0.3	0.1
Oxygen (max)ppm	0.02	0.02	0.01
Hydrazine residual ppm	-	-	-0.02-0.04
pH at 25^oC	8.8-9.2	8.8-9.2	8.2-9.2
Hardness	1.0	0.5	-

Table 7.5: Recommended boiler water limits (IS 10392, Year 1982)

Factor	Up to $20 Kg/cm^2$	21 - $40 Kg/cm^2$	41 - $60 Kg/cm^2$
TDS	3000-3500	1500-2000	500-750
Total iron dissolved solids ppm	500	200	150
Specific electrical conductivity at 25 ^0C (mho)	1000	400	300
Phosphate residual ppm	20-40	20-40	15-25
pH at 25 ^0C	10-10.5	10-10.5	9.8-10.2
Silica (max) ppm	25	15	10

7.8 Energy Conservation Opportunities

The various energy efficiency opportunities in boiler system can be related to combustion, heat transfer, avoid able losses, high auxiliary power consumption, and water quality and blow down.

Examining the following factors can indicate if a boiler is being run to maximize its efficiency:

1. Stack Temperature

The stack temperature should be low as possible. However, it should not be so low that water vapor in the exhaust condenses on the stack walls. This is important in fuels containing significant sulphur as low temperature can lead to sulphur dew point corrosion. Stack temperatures greater than 200°C indicates potential for recovery of waste heat.

Stack temperatures greater than 200°C indicates scale formation on heat transfer equipment. Urgent need action for water and flue side cleaning

2. Feed Water Preheating using Economizer

Typically, the flue gases leaving a modern 3-pass shell boiler are at temperatures of 200 to 300^{0}C. Thus, there is a potential to recover heat from these gases. The flue gas exit temperature from a boiler is usually maintained at a minimum of 200^{0}C, so that the sulphur oxides in the flue gas do not condense and cause corrosion in heat transfer surfaces. When a clean fuel such as natural gas, LPG or gas oil is used, the economy of heat recovery must be worked out, as the flue gas temperature may be well below 200 ^{0}C.

The potential for energy saving depends on the type of boiler installed and the fuel used. For a typically older model shell boiler, with a flue gas exit temperature of 260 ^{0}C, an economizer could be used to reduce it to 200 ^{0}C, increasing the feed water temperature by 15 ^{0}C. Increase in overall thermal efficiency would be in the order of 3%. For a modern 3-pass shell boiler firing natural gas with a flue gas exit temperature of 140 ^{0}C a condensing economizer would reduce the exit temperature to 65 ^{0}C increasing thermal efficiency by 5%.

3. Combustion Air Pre heat

Combustion air preheating is an alternative to feed water heating. In order to improve thermal efficiency by 1%, the combustion air temperature must be raised by 20^{0}C. Most gas and oil burners used in a boiler plant are not designed for high air preheat temperatures.

Modern burners can withstand much higher combustion air preheat, so it is possible to consider such units as heat exchangers in the exit flue as an alternative to an economizer, when either space or a high feed water return temperature make it viable.

4. Incomplete Combustion

Incomplete combustion can arise from a shortage of air or surplus of fuel or poor distribution of fuel. It is usually obvious from the colour or smoke, and must be corrected immediately.

In the case of oil and gas fired systems, CO or smoke (for oil fired systems only) with normal or high excess air indicates burner system problems. A more frequent cause of incomplete combustion is the poor mixing of fuel and air at the burner. Poor oil fires can result from improper viscosity, worn tips, carbonization on tips and deterioration of diffusers or spinner plates.

With coal firing, unburned carbon can comprise a big loss. It occurs as grit carry-over or carbon-in-as hand may amount to more than 2% of the heat supplied to the boiler. Non uniform fuel size could be one of the reasons for incomplete combustion. In chain grate stokers, large lumps will not burnout completely, while small pieces and fines may block the air passage, thus causing poor air distribution.

In sprinkler stokers, stoker grate condition, fuel distributors, wind box air regulation and over-fire systems can affect carbon loss. Increase in the fines in pulverized coal also increases carbon loss.

5. Excess Air Control

Excess air is required in all practical cases to ensure complete combustion, to allow for the normal variations in combustion and to ensure satisfactory stack conditions for some fuels. The optimum excess air level for maximum boiler efficiency occurs when the sum of the losses due to incomplete combustion and loss due to heat in flue gases is minimum. This level varies with furnace design, type of burner, fuel and process variables. It can be determined by conducting tests with different air fuel ratios. Typical values of excess air supplied for various fuels are given in Table 7.6

Table 7.6: Excess air supplied for various fuels

Fuel	Type of Furnace or Burners	Excess Air (% by wt.)
Pulverised coal	Completely water-cooled furnace for slag-tap or dry-ash removal	15-20
	Partially water-cooled furnace for dry-ash removal	15-40
Coal	Spreader stoker	30-60
	Water-cooler vibrating-grate stokers	30-60
	Chain-grate and traveling-grate stokers	15-50
	Underfeed stoker	20-50
Fuel oil	Oil burners, register type	15-20
	Multi-fuel burners and flat-flame	20-30
Natural gas	High pressure burner	5-7
Wood	Dutch over (10-23% through grates) and Hoff t type	20-25
Bagasse	All furnaces	25-35
Black liquor	Recovery furnaces for draft and soda-pulping processes	30-40

Controlling excess air to an optimum level always results in reduction in flue gas losses; for every 1% reduction in excess air there is approximately 0.6% rise inefficiency.

Various methods are available to control the excess air:

- Portable oxygen analysers and draft gauges can be used to make periodic readings to guide the operator to manually adjust the flow of air for optimum operation. Excess air reduction up to 20% is feasible.
- The most common method is the continuous oxygen analyzer with a local read out mounted draft gauge, by which the operator can adjust air flow. A further reduction of 10-15% can be achieved over the previous system.
- The same continuous oxygen analyser can have a remote controlled pneumatic damper positioned, by which the readouts are available in a control room. This enables an operator to remotely control a number of firing systems simultaneously.
- The most sophisticated system is the automatic stack damper control, whose cost is really justified only for large systems.

6. Radiation and Convection Heat Loss

The external surfaces of a shell boiler are hotter than the surroundings. The surfaces thus lose heat to the surroundings depending on the surface area and the difference in temperature between the surface and the surroundings.

The heat loss from the boiler shell is normally a fixed energy loss, irrespective of the boiler output. With modern boiler designs, this may represent only 1.5% on the gross calorific value at full rating, but will increase to around 6%, if the boiler operates at only 25 percent output.

Repairing or augmenting insulation can reduce heat loss through boiler walls and piping.

7. Automatic Blow down control

Uncontrolled continuous blow down is very wasteful. Automatic blow down controls can be installed that sense and respond to boiler water conductivity and pH. A 10% blow down in a 15 kg/cm^2 boiler results in 3% efficiency loss.

The following formula gives the quantity of blow down required:

$$Blowdown\ Rate\ (kg/h) = \frac{F \times S}{B - F} \cdots\cdots\cdots\cdots \ (7.3)$$

Where,
F= Feed Water TDS in parts per million
B= Required boiler water TDS in parts per million
S= Steam generation rate in kg/h

Example 7.3

A 10000 kg/h boiler operated at 10 bar g and has a maximum allowable boiler TDS of 2500ppm and boiler feedwater TDS 250ppm. Find rate of Energy Blown down. Saturated steam enthalpy from steam table is 782 kJ/kg at 10 bar g pressure.

Solution:

From Equation 7.3,

$$Blowdown\ Rate\ (kg/h) = \frac{F \times S}{B - F}$$
$$= \frac{250 \times 10000}{2500 - 250}$$
$$= 1111\ kg/h.$$
$$= \frac{1111}{3600} kg/s = 0.31 kg/s$$

The amount of energy in each kg of steam blown down at 10bar g, h_f = 782 kJ/kg

Rate of Energy Blown down (kW) = $0.31 kg/s\ \times 782 kJ/kg = 241\ kW\ (ans)$

Further work: if blow down flash vessel is installed energy and flash steam can be recovered

8. Reduction of Scaling and Soot losses

In oil and coal-fired boilers, soot build upon tubes acts as an insulator against heat transfer. Any such deposits should be removed on a regular basis. **Elevated stack temperatures may indicate excessive soot build-up**. Also, same result will occur due to scaling on the waterside.

High exit gas temperatures at normal excess air indicate poor heat transfer performance. This condition can result from a gradual build-up of gas-side or waterside deposits. Water side deposits require are view of water treatment procedures and tube cleaning to remove deposits. An estimated 1% efficiency loss occurs with every 4.4 ^{0}C increase ion stack temperature.

Stack temperature should be checked and recorded regularly as an indicator of soot deposits. When the flue gas temperature raises about 20^{0}C above the temperature for a newly cleaned boiler, it is time to remove the soot deposits. It is, therefore, recommended to install a dial type thermometer at the base of the stack to monitor the exhaust flue gas temperature.

Every millimetre thickness of soot coating increases the stack temperature by about 55^{0}C. It is also estimated that 3mm of soot can cause an increase in fuel consumption by 2.5%. Periodic off-line cleaning of radiant furnace surfaces, boiler tube banks, economizers and air heaters may be necessary to remove stubborn deposits.

9. Reduction of Boiler Steam Pressure

This is an effective means of reducing fuel consumption, if permissible, by as much as 1 to 2%. Lower steam pressure gives a lowers saturated steam temperature and without stack heat recovery, a similar reduction in the temperature of the flue gas temperature results.

Steam is generated at pressures normally dictated by the highest pressure /temperature requirements for a particular process. In some cases, the process does not operate all the time, and there are periods when the boiler pressure could be reduced. The energy manager should consider pressure reduction carefully, before recommending it. Adverse effects, such as an increase in water carry over from the boiler owing to pressure reduction, may negate any potential saving. Pressure should be reduced in stages, and no more than a 20 percent reduction should be considered.

10. Variable Speed Control for Fans, Blowers and Pumps

Variable speed control is an important means of achieving energy savings. Generally, combustion air control is effected by throttling dampers fitted at forced and induced draft fans. Though dampers are simple means of control, they lack accuracy, giving poor control characteristics at the top and bottom of the operating range. In general, if the load characteristic of the boiler is variable, the possibility of replacing the dampers by a VSD should be evaluated.

11. Effect of Boiler Loading on Efficiency

The maximum efficiency of the boiler does not occur at full load, but at about two-thirds of the full load. If the load on the boiler decreases further, efficiency also tends to decrease. At zero output, the efficiency of the boiler is zero, and any fuel fired is used only to supply the losses. The factors affecting boiler efficiency are:

- As the load falls, so does the value of the mass flow rate of the flue gases through the tubes. This reduction in flow rate for the same heat transfer area reduced the exit flue gas temperatures by a small extent, reducing the sensible heat loss.
- Below half load, most combustion appliances need more excess air to burn the fuel completely. This increases the sensible heat loss.

The net effect of these factors is to produce a load / efficiency curve. It has been generally noticed that the fall in efficiency begins to become serious below about a quarter load, and as far as possible, operation of boilers below this level should be avoided.

12. **Proper Boiler Scheduling**

Since the optimum efficiency of boilers occurs at 65-85% of full load, it is usually more efficient, on the whole, to operate a fewer number of boilers at higher loads, than to operate a large number at low loads.

13. **Boiler Replacement**

The potential savings from replacing a boiler depend on the anticipated change in overall efficiency. A change in a boiler can be financially attractive if the existing boiler is:

- old and inefficient
- not capable of firing cheaper substitution fuel
- over or under-sized for present requirements not
- designed for ideal loading conditions

The feasibility study should examine all implications of long-term fuel availability and company growth plans. All financial and engineering factors should be considered. Since boiler plants traditionally have a useful life of well over 25 years, replacement must be carefully studied.

Case Study: Installing Boiler Economiser

A paper mill retrofitted an economizer to existing boiler. The general specification of the boiler is given below:

Boiler capacity (T/h)	Feed water Temp. (^{0}C)	Steam pressure (bar)	Fuel oil
8	110	18	No.6

The thermal efficiency of the boiler was measured and calculated by the indirect method using flue gas analyzer and data logger. The result is summarized below:

Thermal efficiency : 80.99%

Flue gas temperature : 315^{0}C
CO_2 % : 13
CO (PPM) : 167

The temperature in the flue gas is in the range of 315 to 320^{0}C. The waste heat in the flue gas is recovered by installing an economizer, which transfers waste heat from the flue gases to the boiler feed water. This resulted in a rise in feed water temperature by about 26^0C.

Basic Data

Average quantity of steam generated	: 5.04 T/h
Average flue gas temperature	: 315^0C
Average steam generation / kg of fuel oil	: 16.05 kg
Feed water in let temperature	: 110^0C
Fuel oil supply rate	: 314 kg/h
Flue gas quantity	: 17.4 kg/kg of fuel

Cost Economics

Quantity of flue gases (m) : 5463.6 kg/h

Quantity of heat available : $5463.6 \times 0.25 \times (315 - 200)$

[from equation 2.24, $Q = m\, C_p\, \Delta T$, flue gas $C_{p,\ \text{flue gas}}$ = 0.25 kCal/kg°C, (letting min. temp. 200°C)]

=157078 kCal/h

Rise in the feed water temperature : 26^0C

Heat required for pre-heating the feed water : $5040 \times 1.065 \times 26$

[from equation 2.24, $Q = m\, C_p\, \Delta T$, $C_{p,\ \text{water}}$ = 1.065 kCal/kg°C]

=139557 kCal/h

Saving in terms of HSD fuel : 139557 kCal/h /10000 kCal/kg

= 14kg/h

Annual operating hours : 8600

Annual savings of fuel oil : 120400kg

Conclusion

Through recovery of waste heat by installation of an economizer, the paper mill was able to save14kg/hr of HSD fuel, which amounts to about 1, 20,400 kg of fuel oil per annum.

Example 7.4

Oil fired Boiler is generating 100 TPH of steam at 85% efficiency, operating 330 days in a year. Management has installed a water treatment plant at Bangladeshi Taka (BDT) 1.16 Crore investment for reducing the TDS in boiler feed from 450 ppm to 150 ppm. The maximum permissible limit of TDS in the boiler is 3000 ppm and make up water is 10%. Temperature of blow down water is 175°C and boiler feed water temperature is 45°C. Calorific value of Fuel oil is 1200 kCal/kg.

Calculate the payback period if the cost of fuel is 23150 BDT / Ton.

Solution:

Here, Feed water TDS = 450ppm
Maximum Permissible TDS in Boiler water = 3000ppm
% Make up water= 10%
Evaporation Rate = 100 TPH = 100* 1000 kg/h

From equation 7.2,

$$\text{Blow down (\%)} = \frac{\text{[Feed water TDS x \% Make up water]}}{\text{(Maximum Permissible TDS in Boiler water -Feed water TDS)}}$$

Initial blow down (%) $= \frac{450 \times 10}{3000 - 450}$

= 1.76 %

Improved blow down (%) $= \frac{150 \times 10}{3000 - 150}$

= 0.53 %

Reduction in blow down (%) = 1.76 – 0.53
= 1.24 %

From equation 7.2.a,

Reduction in blow down rate $= Evaporation\ Rate \times Blow\ Down\ (\%)$
= 100 * 1000 * (1.24 /100)
= 1238 kg/hr

We know, Specific heat of water is 1 kCal/kg°C

Heat savings = m * Cp * ($T_1 - T_2$) = 1238 * 1 * (175 – 45)
= 160991 kcal/hr

Fuel oil saving $= \frac{Heat\ Savings}{Calorific\ Value\ of\ fuel \times efficiency\ of\ boiler} = \frac{160991}{1200 * 0.85}$ = 157.83 kg/hr

Annual fuel oil savings = 157.83 * 24 * 330 / 1000
= 1250 MT / annum

Fuel oil cost savings per annum = 1250 * 23150 = BDT 289.4 Lakh

Investment on water treatment plant = BDT 1.16 Crore
From equation 2.43

$$\text{Simple Pay Back Period (SPP)} = \frac{\text{Capital cost of the project (in BDT)}}{\text{Net Annual Savings (in BDT)}}$$

$$\Longrightarrow SPP = \frac{1.16}{2.894} = 0.4\ Years\ or\ 5\ Months\ \ (answer)$$

7.9 Factors Affecting Boiler Performance

The various factors affecting the boiler performance are as follows:

- Periodical cleaning of boilers
- Periodical soot blowing
- Proper water treatment programme and blow down control
- Draft control
- Excess air control
- Percentage loading of boiler
- Steam generation pressure and temperature

- Boiler insulation
- Quality of fuel

All these factors individually/combined, contribute to the performance of the boiler and reflected either in boiler efficiency or evaporation ratio. Based on the results obtained from the testing, further improvements have to be carried out for maximizing the performance. The test can be repeated after modification or rectification of the problems and compared with standard norms. Energy auditor should carry out this test periodically once in six months and report to the management for necessary action.

7.9.1 Data Collection Format for Boiler Performance Assessment

Sheet 1: Technical specification of boiler
Boiler ID code and Make Year of Make Boiler capacity rating Type of Boiler Type of fuel used Maximum fuel flow rate Efficiency by GCV Steam generation pressure & super heat temperature Heat transfer area in m^2 Is there any waste heat recovery device installed? Type of draft Chimney height in metre
Sheet 2: Fuel analysis details
Fuel fired GCV of fuel Specific gravity of fuel (Liquid) Bulk density of fuel (Solid)

Proximate analysis	Date of test	%
Fixed carbon Volatile matter Ash Moisture		
Ultimate analysis	Date of test	%
Carbon Hydrogen Sulphur Nitrogen Ash Moisture Oxygen		
Water analysis	Date of test	%
1 Feed water TDS 2 Blow down TDS 3 PH of feed water 4 PH of blow down		
Flue gas Analysis	Date of test	%
CO_2 O_2 CO Flue gas temperature		°C

Sheet 3: Format sheet for boiler efficiency testing															
S. No.	Time	Ambient air		Fuel		Feed water		Steam			Flue gas analysis				Surface temperature of boiler, °C
		Dry bulb Temp. °C	Wet Bulb Temp, °C	Flow rate kg/hr	Temp, °C	Flow rate m^3/hr	Temp. °C	Flow rate m^3/hr	Temp. °C	Pressure kg/cm^2	O_2	CO_2	CO	Temp. °C	
1.															
2.															
3.															

7.10 Boiler Terminology

MCR: Steam boilers rated output is usually defined as MCR (Maximum Continuous Rating). This is the maximum evaporation rate that can be sustained for 24 hours and may be less than a shorter duration maximum rating.

a. Boiler Rating

Conventionally, boilers are specified by their capacity to hold water and the steam generation rate. Often, the capacity to generate steam is specified in terms of equivalent evaporation (kg of steam / hour at 100 ^{0}C). Equivalent evaporation- "from and at" 100 ^{0}C. The equivalent of the evaporation of 1 kg of water at 100 ^{0}C to steam at 100 ^{0}C.

Efficiency: In the boiler industry there are four common definitions of efficiency:

b. Combustion efficiency

Combustion efficiency is the effectiveness of the burner only and relates to its ability to completely burn the fuel. The boiler has little bearing on combustion efficiency. A well- designed burner will operate with as little as 15 to 20% excess air, while converting all combustibles in the fuel to useful energy.

c. Thermal efficiency

Thermal efficiency is the effectiveness of the heat transfer in a boiler. It does not take into account boiler radiation and convection losses - for example from the boiler shell water column piping etc.

d. Boiler efficiency

The term boiler efficiency is often substituted for combustion or thermal efficiency. True boiler efficiency is the measure of fuel to steam efficiency.

e. Fuel to steam efficiency

Fuel to steam efficiency is calculated using either of the two methods as prescribed by the ASME (American Society for Mechanical Engineers) power test code, PTC 4.1. The first method is input output method. The second method is heat loss method.

f. Boiler turndown

Boiler turndown is the ratio between full boiler output and the boiler output when operating at low fire. Typical boiler turndown is 4:1. The ability of the boiler to turndown reduces frequent on and off cycling. Fully modulating burners are typically designed to operate down to 25% of rated capacity. At a 20% of the load capacity, the boiler will turn off and cycle frequently.

A boiler operating at low load conditions can cycle as frequently as12 times per hour or 288 times per day. With each cycle, pre and post purge air flow removes heat from the boiler and sends it out the stack. Keeping the boiler on at low firing rates can eliminate the energy loss. Every time the boiler cycles off, it must go through a specific start-up sequence for safety assurance. It requires about a minute or two to place the boiler back on line. And if there is a sudden load demand, the start-up sequence cannot be accelerated. Keeping the boiler on line assures the quickest response to load changes. Frequent cycling also accelerates wear of boiler components. Maintenance increases and more importantly, the chance of component failure increases.

Boiler(s) capacity requirement is determined by much different type of load variations in the system. Boiler over sizing occurs when future expansion and safety factors are added to assure that the boiler is large enough for the application. If the boiler is oversized the ability of the boiler to handle minimum loads without cycling is reduced. Therefore capacity and turndown should be considered together for proper boiler selection to meet overall system load requirements.

Primary air: That part of the air supply to a combustion system which the fuel first encounters.

Secondary air: The second stage of admission of air to a combustion system, generally to complete combustion initiated by the primary air. It can be injected into the furnace of a boiler under relatively high pressure when firing solid fuels in order to create turbulence above the burning fuel to ensure good mixing with the gases produced in the combustion process and thereby complete combustion

Tertiary air: A third stage of admission of air to a combustion system, the reactions of which have largely been completed by secondary air. Tertiary air is rarely needed.

Stoichiometric: In combustion technology, stoichiometric air is that quantity of air, and no more, which is theoretically needed to burn completely a unit quantity of fuel. 'Sub-stoichiometric' refers to the partial combustion of fuel in a deficiency of air

Balanced draught: The condition achieved when the pressure of the gas in a furnace is the same as or slightly below that of the atmosphere in the enclosure or building housing it.

Carbon monoxide (CO): Produced from any source that burns fuel with incomplete combustion, causes chest pain in heart patients, headaches and reduced mental alertness.

Saturated steam: It is the steam, whose temperature is equal to the boiling point corresponding to that pressure.

Wet Steam: Saturated steam which contains moisture

Dry Steam: Either saturated or superheated steam containing no moisture.

Super-heated Steam: Steam heated to a temperature above the boiling point or saturation temperature corresponding to its pressure.

7.11 Properties of Steam

7.11.1 Liquid Enthalpy

Liquid enthalpy is the "Enthalpy"(heat energy) in the water when it has been raised to its boiling point to produce steam, and is measured in kJ/kg or kCal/kg, its symbol is **h_f**. (also known as "Sensible Heat"). If temperature is increased/decreased when adding/removing heat, this heat is called sensible heat.

7.11.2 Enthalpy of Evaporation (Heat Content of Steam)

The Enthalpy of evaporation is the heat energy to be added to the water (when it has been raised to its boiling point) in order to change it into steam. There is no change in temperature, the steam produced is at the same temperature as the water from which it is produced, but the heat energy added to the water changes its state from water into steam at the same temperature.

When the steam condenses back in to water, it gives up its enthalpy of evaporation, which it had acquired on changing from water to steam. The enthalpy of evaporation is measured in kJ/kg or kCal/kg. Its symbol is **h_{fg}**. Enthalpy of evaporation is also known as latent heat.

To change the water to steam an additional 540kcal/ 2257kJ would be required. This quantity of heat required to change a chemical from the liquid to the gaseous state is called latent heat.

For a boiler is operating at a pressure of 8kg/cm^2, steam saturation temperature is170^{0}C,and steam enthalpy or total heat of dry saturated steam is given by:

$h_f + h_{fg}$= 171.35 +489.46 = 660.81 kCal/kg.

If the same steam contains 4% moisture, the total heat of steam is given by:

$$h_g = h_f + X\, h_{fg} \cdots (7.4)$$

$$\Rightarrow 641.23\, kCal/kg = 171.35\, kCal/kg + 0.96 \times 489.46\, kCal/kg$$

Here, X= dryness factor

In this example, dryness= (1-0.04)= 0.96

Table 7.7: Extract from the Steam Tables

Pressure (kg/cm^2)	Temperature ^{o}C	Enthalpy in kcal/kg			Specific volume (m^3/kg)
		Water (h_f)	Evaporation (h_{fg})	Steam (h_g)	
1	100	100.09	539.06	639.15	1.673
2	120	119.92	526.26	646.18	0.901
3	133	133.42	517.15	650.57	0.616
4	143	143.70	509.96	653.66	0.470
5	151	152.13	503.90	656.03	0.381
6	158	159.33	498.59	657.92	0.321

7	164	165.67	493.82	659.49	0.277
8	170	171.35	489.46	660.81	0.244

7.12 Steam Distribution System

The steam distribution system is the essential link between the steam generator and the steam user. Whatever the source, an efficient steam distribution system is essential if steam of the right quality and pressure is to be supplied, in the right quantity, to the steam using equipment. Installation and maintenance of the steam system are important issues, and must be considered at the design stage.

As steam condenses in a process, flow is induced in the supply pipe. Condensate has a very small volume compared to the steam, and this causes a pressure drop, which causes the steam to flow through the pipes. The steam generated in the boiler must be conveyed through pipe work to the point where its heat energy is required. Initially there will be one or more main pipes, or 'steam mains', which carry steam from the boiler in the general direction of the steam using plant. Smaller branch pipes can then carry the steam to the individual pieces of equipment. A typical steam distribution system is shown in Figure 3.2.

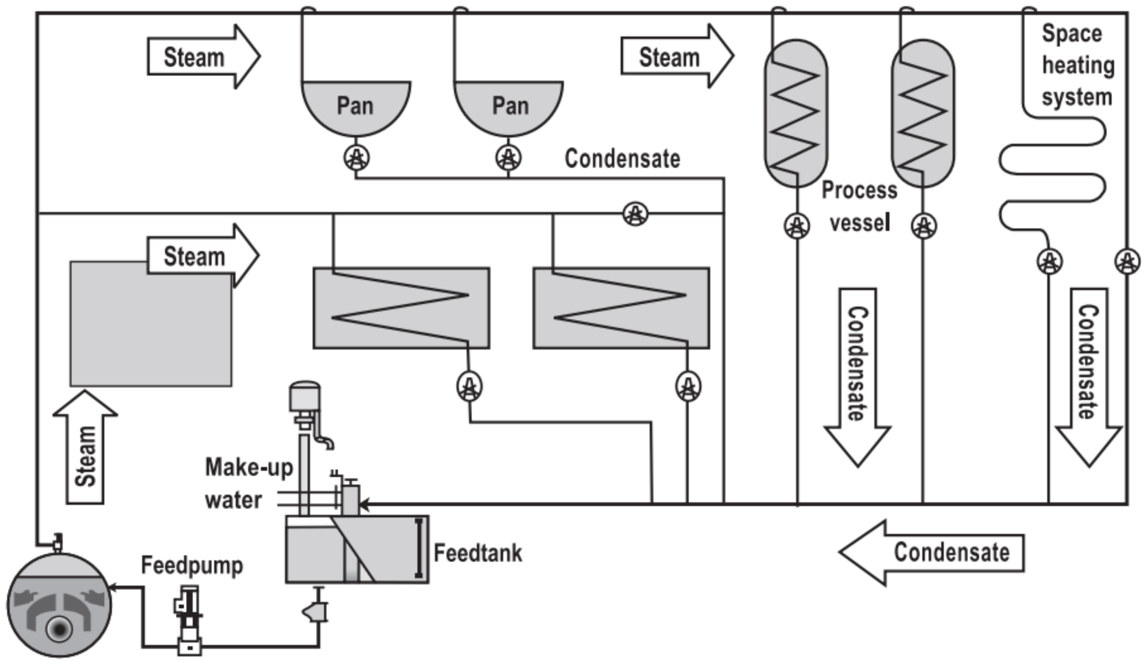


Figure 7.9 : Steam distribution System

7.12.1 Steam Pipe Sizing and Design

Any modification and alteration in the existing steam piping, for supplying higher quality steam at right pressure and quantity must consider the following points:

Pipe Sizing

The objective of the steam distribution system is to supply steam at the correct pressure to the point of use. It follows therefore, that pressure drop through the distribution system is an important feature.
Proper sizing of steam pipelines help in minimizing pressure drop. The velocities for various types of steam are:

Superheated :50-70 m/sec
Saturated :30-40 m/sec

Wet or Exhaust :20-30 m/sec

For fluid flow to occur, there must be more energy at Point 1 than Point 2 (Figure 7.10). The difference in energy is used to overcome frictional resistance between the pipe and the flowing fluid.

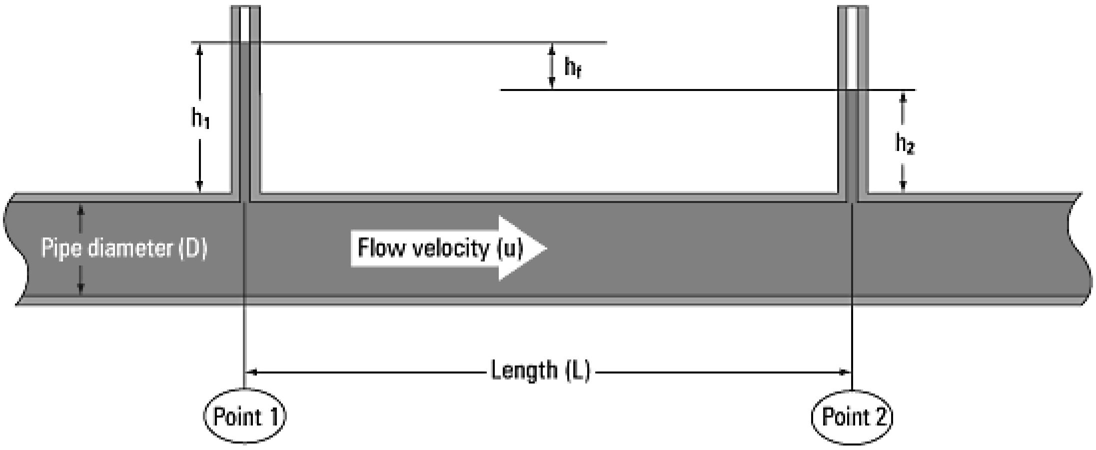


Figure 7.10: Pressure drop in steam pipes

This is illustrated by the equation,

$$Head\ Loss\ due\ to\ friction, h_f = \frac{4fLu^2}{2gD} \cdots\cdots\cdots\cdots (7.5)$$

Where,

h_f = Head loss to friction (m)
f = Friction factor (dimensionless), usually obtained from charts
L = Length (m)
u = Flow velocity (m/s)
g = Gravitational constant (9.81 m/s²)
D = Pipe diameter (m)

> In practice whether for water pipes or steam pipes, a balance is drawn between pipe size and pressure loss. The steam piping should be sized, based on permissible velocity and the available pressure drop in the line. Selecting a higher pipe size will reduce the pressure drop and thus the energy cost. However, higher pipe size will increase the initial installation cost. By use of smaller pipe size, even though the installation cost can be reduced, the energy cost will increase due to higher-pressure drop. It is to be noted that the pressure drop change will be inversely proportional to the 5th power of diameter change. Hence, care should be taken in selecting the optimum pipe size.

Guide for proper drainage and layout of steam lines:

1. The steam mains should be run with a falling slope of not less than 125 mm for every 30 meters length in the direction of the steam flow.
2. Drain points should be provided at intervals of 30-45 meters along the main.
3. Drain points should also be provided at low points in the mains and where the steam main rises. Ideal locations are the bottom of expansion joints and before reduction and stop valves.
4. Drain points in the main lines should be through an equal tee connection only.
5. It is preferable to choose open bucket or TD traps on account of their resilience.
6. The branch lines from the mains should always be connected at the top. Otherwise, the branch line itself will act as a drain for the condensate.
7. Insecure supports as well as an alteration in level can lead to formation of water pockets in steam, leading to wet steam delivery. Providing proper vertical and support hangers helps overcome such eventualities.
8. Expansion loops are required to accommodate the expansion of steam lines while starting from cold.
9. To ensure dry steam in the process equipment and in branch lines, steam separators can be installed as required.

7.12.2 Proper Air Venting

When steam is first admitted to a pipe after a period of shutdown, the pipe is full of air. Further, amounts of air and other non-condensable gases will enter with the steam, although the proportions of these gases are normally very small compared with the steam. When the steam condenses, these gases will accumulate in pipes and heat exchangers. Precautions should be taken to discharge them. The consequence of not removing air is a lengthy warming up period, reduction in plant efficiency and process performance.

Automatic air vents for steam systems (which operate on the same principle as thermostatic steam traps) should be fitted above the condensate level so that only air or steam-air mixtures can reach them. The best location for them is at the end of the steam mains.

In addition to air venting at the end of a main, air vents should also be fitted:

- In parallel with an inverted bucket trap or, in some instances, a thermodynamic trap. These traps are sometimes slow to vent air on start-up.
- In awkward steam spaces (such as at the opposite side to where steam enters a jacketed pan).
- Where there is a large steam space (such as an autoclave), and a steam/air mixture could affect the process quality.

Example 7.5 Effect of air in steam system

If 20% of air is entrained in a steam system at 5 kg/cm^2 (g) then the effect of air will be as follows

Steam quality = 80% Steam + 20% Air
Pressure =$0.80 \times 5 + 0.20 \times 5$ = 4 kg/cm^2 (g) + 1 kg/cm^2 (g) (steam) (air)

Temp. of steam at 5 kg/cm^2 (g) = 158 °C

Temp. of vapour mixture is = 152 °C (equivalent to steam at 4 kg/cm^2 (g))

So Temperature is reduced.

7.12.3 Steam Pipe Insulation

The insulation of steam conveying pipes and the steam consuming equipment is very essential to retard the flow of heat from the system to the environment. Broadly the purpose of steam pipe insulation is as follows

- Conserve energy by reducing heat loss
- Facilitate temperature control of a process
- Prevent condensation of steam
- Prevent or reduce damage to pipe from exposure to fire or corrosive atmospheres
- Control surface temperature for personal protection and comfort

The following table 7.8 indicates the effect of insulating bare pipes

Table 7.8 Effect of Insulation on Steam Pipes

Pipe Size, inch	Economic Insulation Thickness, mm	Radiation Losses* (kW/m)	
		Insulated	Uninsulated
1/2	15	125	692
2	25	243	1820
4	40	298	2942
12	50	588	7614

*** Comparison of Radiation Losses (Pipe Surface Temperature at 150 °C)**

Heat can be lost due to radiation from steam pipes. As an example while lagging steam pipes, it is common to see leaving flanges uncovered. An uncovered flange is equivalent to leaving 0.6 metre of pipe line unlagged. If a 0.15 m steam pipe diameter has 5 uncovered flanges, there would be a loss of heat equivalent to wasting 5 tons of coal or 3000 litres of oil a year. This is usually done to facilitate checking the condition of flange but at the cost of considerable heat loss. The remedy is to provide easily detachable insulation covers, which can be easily removed when necessary. The various insulating materials used are cork, Glass wool, Rock wool and Asbestos.

7.12.4 Thermo compressor

In many of the steam utilization equipment where condensate comes out at high pressure, a major portion of it flashes into low pressure steam which goes wasted. Using a thermo compressor (Figure 7.11) it becomes feasible to compress this low-pressure steam by high pressure steam and reuse it as a medium pressure steam in the process. The major energy in steam is in its latent heat value and thus thermo compressing would give a large improvement in waste heat recovery.

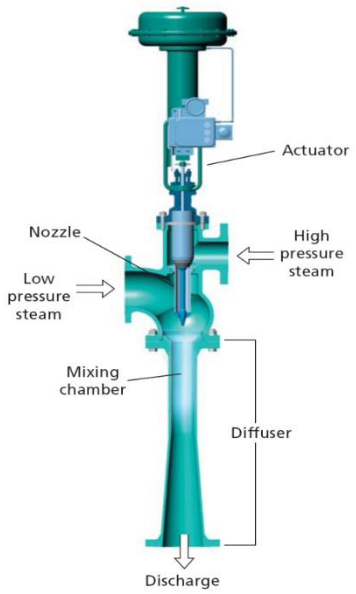


Figure 7.11: Thermo Compressor

Advantages of thermo compressors-

- No condensation losses take place
- Thermal efficiency of the system is extremely high
- Entrainment of low pressure steam results is substantial savings
- No moving parts and hence maintenance needs are minimal
- No major operational charges
- Low space requirement
- Insensitive to fouling
- High operating reliability

7.13 Dryers

Drying is a process by which a liquid (commonly water) is removed from a material. This is usually achieved by applying heat, typically steam and/or the flow of carrier gas (commonly air) through or over the surface of the material (Figure 7.12). The objective of drying is to form a product that meets a water-content specification, so the amount of water removed depends on the desired product.

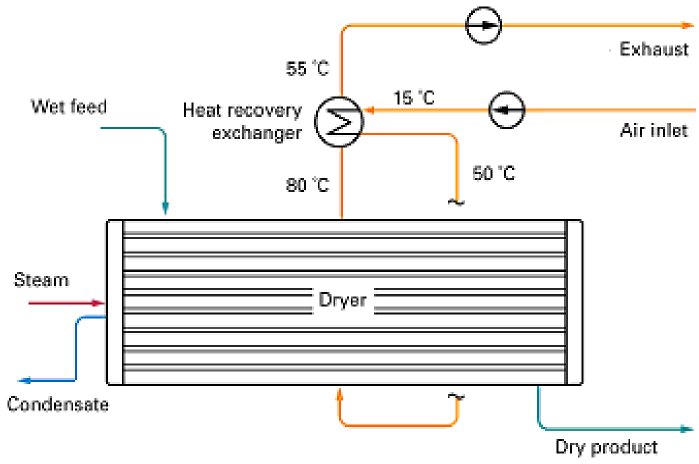


Figure 7.12: Hot Air Dryer Using Steam

The basic drying energy requirement is the latent heat needed to evaporate the water. Clearly, this depends on the amount of water being evaporated. In most cases, the product material, the carrier gas and the equipment also need to be hot. So the total energy required includes:

- Heat leaving the dryer in the exhaust flow. This includes the latent heat of the water evaporated, but the sensible heat of the hot gas can also be significant.
- Heat lost from equipment and ducting. However good the insulation, there is always some heat loss.
- Heat leaving the dryer as hot product.
- Motive power for fans and conveyors.

Common factors resulting in excessive energy use

- Excessive drying load – for example, unnecessarily wet feed material, or off-specification product that needs to be reprocessed
- Excessive airflows
- Unnecessarily hot exhaust flow
- Hot air leaks
- Poor insulation
- Excessive fan power (for example, over specified fans restricted by dampers)
- Steam system inefficiencies

Example 7.6 Heat Energy in Air Drying

A food containing 80% water is to be dried at 100 °C down to moisture content of 10%. If the initial temperature of the food is 21 °C, calculate the quantity of heat energy required per unit weight of the original material, for drying under atmospheric pressure. The latent heat of vaporization of water at 100°C and at standard atmospheric pressure is 2257 kJ/kg. The specific heat capacity of the food is 3.8 kJ/kg°C and of water is 4.186 kJ/kg °C. Find also the energy requirement/kg water removed.

Solution:

Calculating for 1 kg food

Initial moisture = 80%, that is, 800 g moisture is associated with 200 g dry matter.

Final moisture = 10 %, that is, 100 g moisture is associated with 900 g dry matter.

Now, with 10% moisture. Using One's rule,

90g dry matter found when final product weight is	- 100g
1g " " " " " " "	- 100g/90g
200g " " " " " " "	- 200*100/90 = 222.2g

Therefore (222.2-200) = 22.2 g moisture are associated with 200g dry matter.

1 kg of original matter must lose (800 – 22.2) g moisture = 777.8 g = 0.7778 kg moisture to retain 10% moisture with it.

Heat energy required for 1 kg original material [*using equation 2.24 and 2.26,* $C_{p,\,food}$*=3.8 kJ/kg*^oC]
= heat energy to raise temperature to 100°C + latent heat to remove water
$= 1 \times 3.8 \times (100 - 21) + 0.778 \times 2257$
= 300.2 + 1755.9
= 2056 kJ.

Energy/kg water removed, as 2056 kJ are required to remove 0.778 kg of water
= 2056/0.778
= 2643 kJ.

Steam is often used to supply heat to air or to surfaces used for drying. In condensing, steam gives up its latent heat of vaporization; in drying, the substance being dried must take up latent heat of vaporization to convert its liquid into vapour, so it might be reasoned that 1 kg of steam condensing will produce 1 kg of vapour, neglecting minor losses.

7.14 Proper Selection, Operation and Maintenance of Steam Traps

The purpose of installing the steam traps is to obtain fast heating of the product and equipment by keeping the steam lines and equipment free of condensate, air and non-condensable gases. A steam trap is a valve device that discharges condensate and air from the line or piece of equipment without discharging the steam.

7.14.1 Functions of Steam Traps

The three important functions of steam traps are:

- To discharge condensate as soon as it is formed
- Not to allow steam to escape.
- To be capable of discharging air and other incondensable gases.

7.14.2 Types of Steam Traps

The steam traps are classified as follows.

Table 7.9 Steam trap classification

Group	Principle	Sub-group
Mechanical trap	Difference in density between steam and condensate.	Bucket type a) Open bucket b) Inverted bucket (with lever, without lever) c) Float type d) Float with lever e) Free Float
Thermodynamic trap	Difference properties in thermodynamic between steam and condensate	a) Disc type b) Orifice type
Thermostatic trap	Difference in temperature between steam and condensate	a) Bimetallic type b) Metal expansion type.

Some of the important traps in industrial use are explained as follows:

1. Inverted Bucket

The inverted bucket trap is a mechanically actuated model that uses an upside down bucket as a float. The bucket, connected to an outlet valve through a mechanical linkage, sinks when condensate fills the steam trap, opening the outlet valve. The bucket floats when steam enters the trap, closing the valve (Figure 7.13).

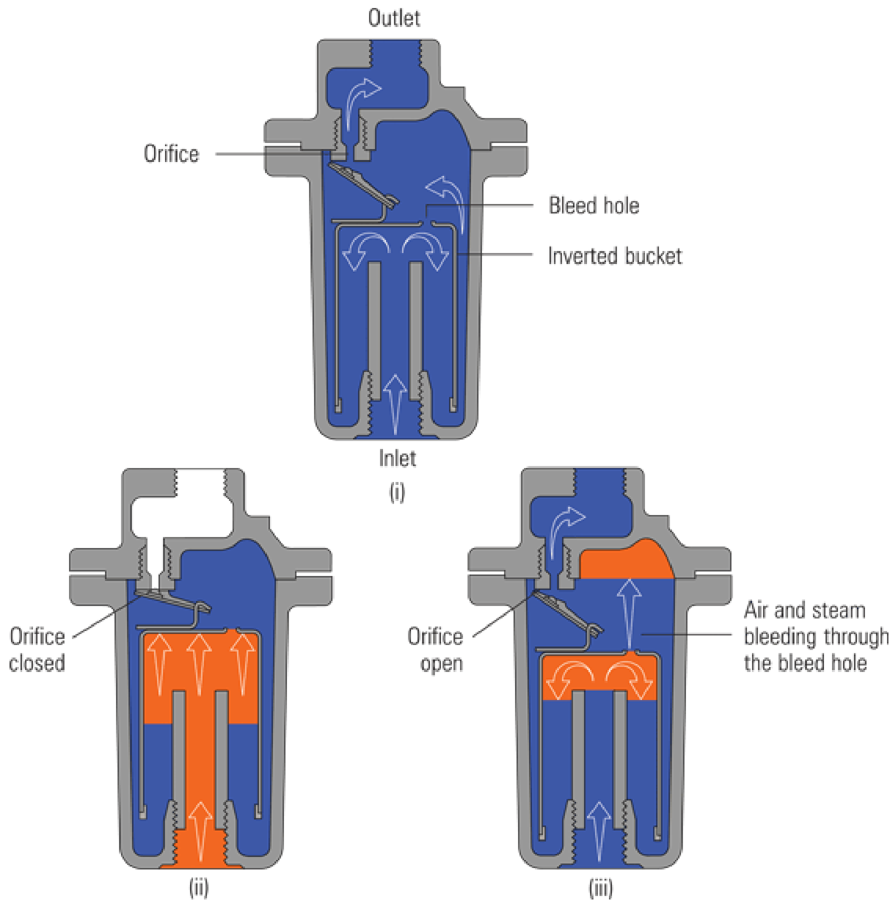


Figure 7.13: Inverted bucket trap

Advantages of the inverted bucket steam trap

- The inverted bucket steam trap can be made to withstand high pressures.
- Like a float-thermostatic steam trap, it has a good tolerance to water hammer conditions.
- Can be used on superheated steam lines with the addition of a check valve on the inlet.
- Failure mode is usually open, so it's safer on those applications that require this feature, for example turbine drains.

Disadvantages of the inverted bucket steam trap

- The small size of the hole in the top of the bucket means that this type of trap can only discharge air very slowly. The hole cannot be enlarged, as steam would pass through too quickly during normal operation.

- There should always be enough water in the trap body to act as a seal around the lip of the bucket. If the trap loses this water seal, steam can be wasted through the outlet valve. This can often happen on applications where there is a sudden drop in steam pressure, causing some of the condensate in the trap body to 'flash' into steam. The bucket loses its buoyancy and sinks, allowing live steam to pass through the trap orifice. Only if sufficient condensate reaches the trap will the water seal form again, and prevent steam wastage.

2. Float and Thermostatic

The ball float type trap operates by sensing the difference in density between steam and condensate. In the case of the trap shown in Figure 7.14A, condensate reaching the trap will cause the ball float to rise, lifting the valve off its seat and releasing condensate. As can be seen, the valve is always flooded and neither steam nor air will pass through it, so early traps of this kind were vented using a manually operated cock at the top of the body. Modern traps use a thermostatic air vent, as shown in Figure 7.14B. This allows the initial air to pass whilst the trap is also handling condensate.

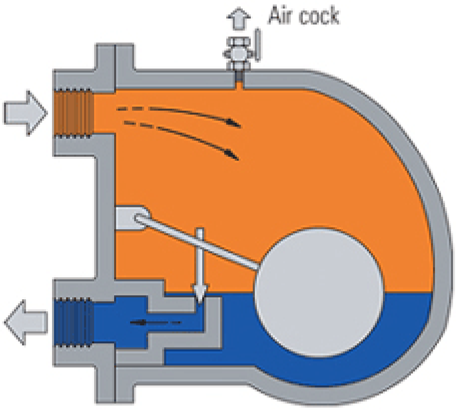


Figure 7.14A Float trap with air cock

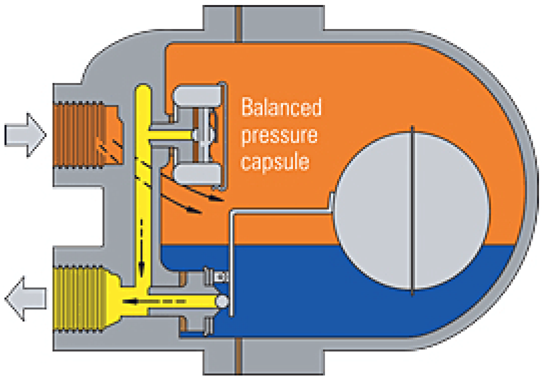


Figure 7.14B Float trap with thermostatic air vent

In many ways the float-thermostatic trap is the closest to an ideal steam trap. It will discharge condensate as soon as it is formed, regardless of changes in steam pressure. Float and Thermostatic traps are an economical solution for light-to-medium condensate loads and lower pressures

3. Thermodynamic Trap

The thermodynamic trap is an extremely robust steam trap with a simple mode of operation. The trap operates by means of the dynamic effect of flash steam as it passes through the trap, as depicted in Figure 7.15(i). The only moving part is the disc above the flat face inside the control chamber or cap.

On start-up, incoming pressure raises the disc, and cool condensate plus air is immediately discharged from the inner ring, under the disc, and out through three peripheral outlets [Figure 7.15(i)].

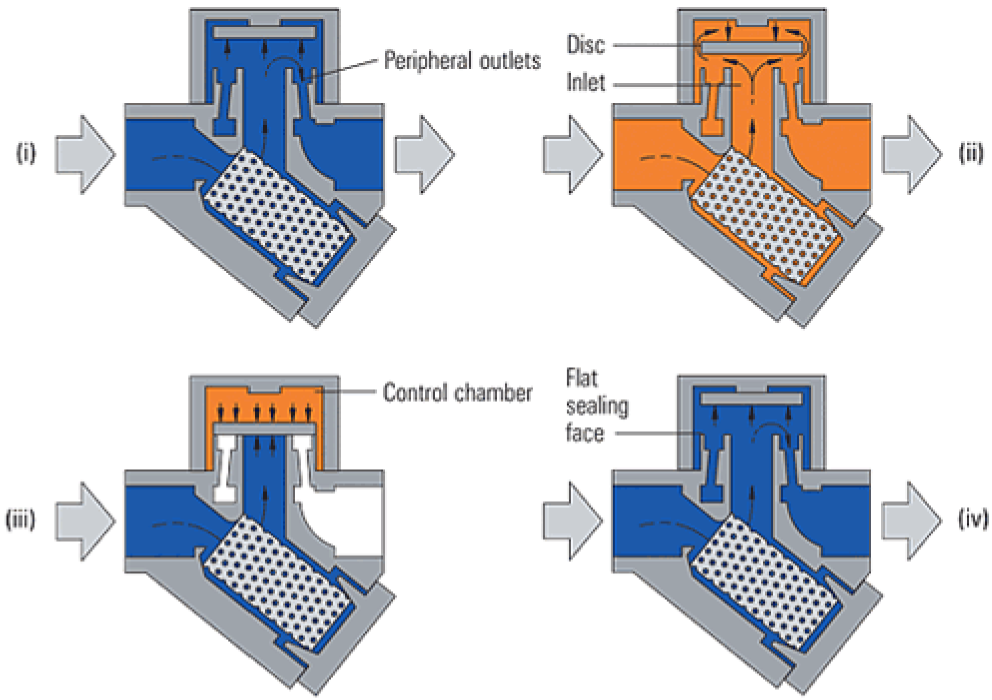


Figure 7.15: Thermodynamic Trap

Hot condensate flowing through the inlet passage into the chamber, under the disc drops in pressure and releases flash steam moving at high velocity. This high velocity creates a low pressure area under the disc, drawing it towards its seat [Figure 7.15(ii)].

At the same time, the flash steam pressure builds up inside the chamber above the disc, forcing it down against the incoming condensate until it seats on the inner and outer rings. At this point, the flash steam is trapped in the upper chamber, and the pressure above the disc equals the pressure being applied to the underside of the disc from the inner ring. However, the top of the disc is subject to a greater force than the underside, as it has a greater surface area.
Eventually the trapped pressure in the upper chamber falls as the flash steam condenses. The disc is raised by the now higher condensate pressure and the cycle repeats (Figure 3.7, iv).

4. Thermostatic Trap

Thermal-element thermostatic traps are temperature actuated. On start up the thermal element is in a contracted position with the valve wide-open, purging condensate, air, and other non-condensable gases. As the system warms up, heat generates pressure in the thermal element, causing it to expand and throttle the flow of hot condensate through the discharge valve.

When steam follows the hot condensate into the trap, the thermal element fully expands, closing the trap. If condensate enters the trap during system operation, it cools the element, contracting it off the seat, and quickly discharging condensate (Figure 7.16).

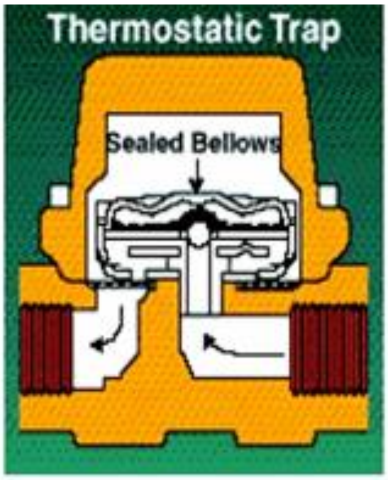


Figure 7.16: Thermostatic Trap

Thermostatic traps are small, lightweight, and compact. One trap operates over extremely broad pressure and capacity ranges. Thermal elements can be selected to operate within a range of steam temperatures. In steam tracing applications, it may be desirable to actually back up hot condensate in the lines to extract its thermal value.

5. Bimetallic Type Steam trap

Bimetallic steam traps operate on the same principle as a heating thermostat. A bimetallic strip or wafer connected to a valve bends or distorts when subjected to a change in temperature. When properly calibrated, the valve closes off against a seat when steam is present, and opens when condensate, air, and other non-condensable gases are present (Figure 7.17).

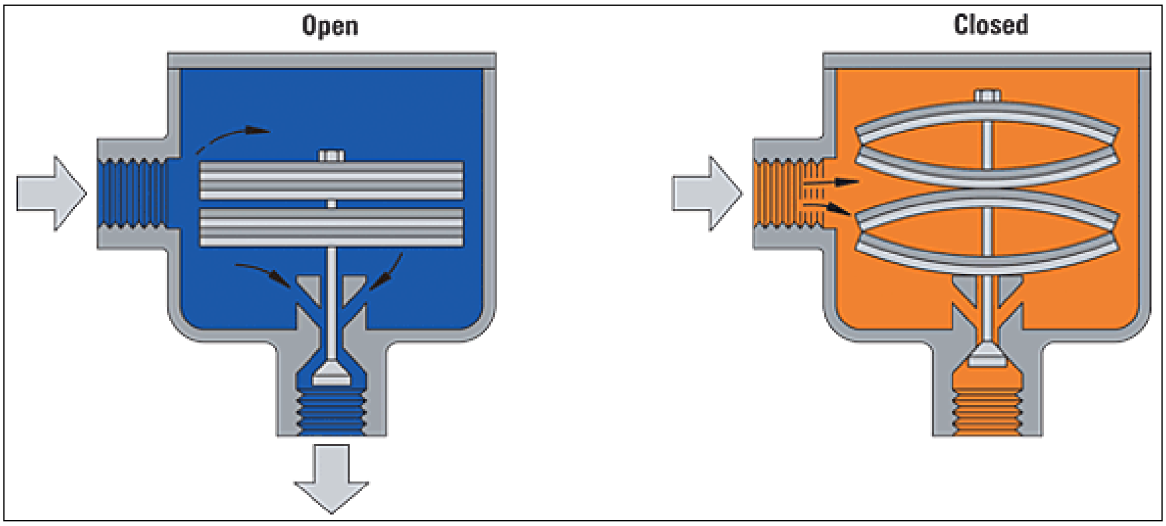


Figure 7.17: Bimetallic Trap

Advantages of the bimetallic steam trap

- Relatively small size for the condensate loads they handle
- Resistance to damage from water hammer

A disadvantage is that they must be set, generally at the plant, for a particular steam operating pressure. If the trap is used for a lower pressure, it may discharge live steam. If used at a higher steam pressure, it can back up condensate into the system.

Thermostatic traps are often considered a universal steam trap; however, they are normally not recommended for extremely high condensate requirements (over 7000 kg/hr). For light-to-moderately high condensate loads, thermostatic steam traps offer advantages in terms of initial cost, long-term energy conservation, reduced inventory, and ease in application and maintenance.

7.14.3 Installation of Steam Traps

In most cases, trapping problems are caused by bad installation rather than by the choice of the wrong type or faulty manufacture. To ensure a trouble-free installation, careful consideration should be given to the drain point, pipe sizing, air venting, steam locking, group trapping vs. individual trapping, dirt, water hammer, lifting of the condensate, etc.

1. Drain Point

The drain point should be so arranged that the condensate can easily flow into the trap. This is not always appreciated. For example, it is useless to provide a 15mm drain hole in the bottom of a 150 mm steam main, because most of the condensate will be carried away by the steam velocity. A proper pocket at the lowest part of the pipe line into which the condensate can drop of at least 100mm diameter is needed in such cases.

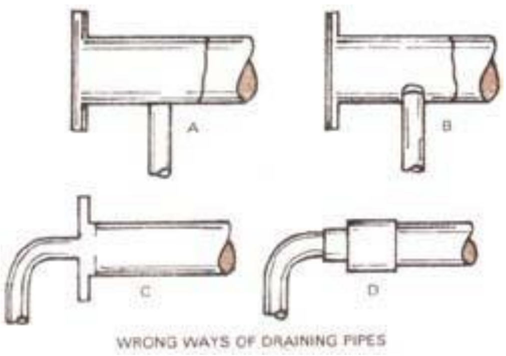


Figure 7.18 A: Wrong ways of Draining Pipes

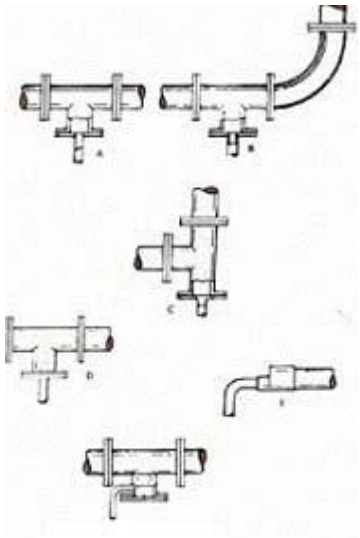


Figure 7.18 B: Right ways of Draining Pipes

Figures 7.18 A and 7.18 B show the wrong and the correct practices in providing the drain points on the steam lines.

2. Pipe Sizing

The pipes leading to and from steam traps should be of adequate size. This is particularly important in the case of thermodynamic traps, because their correct operation can be disturbed by excessive resistance to flow in the condensate pipe work. Pipe fittings such as valves, bends and tees close to the trap will also set up excessive backpressures in certain circumstances.

3. Air Binding

When air is pumped into the trap space by the steam, the trap function ceases. Unless adequate provision is made for removing air either by way of the steam trap or a separate air vent, the plant may take a long time in warming up and may never give its full output.

4. Steam Locking

This is similar to air binding except that the trap is locked shut by steam instead of air. The typical example is a drying cylinder. It is always advisable to use a float trap provided with a steam lock release arrangement.

5. Group Trapping vs. Individual Trapping

It is tempting to try and save money by connecting several units to a common steam trap as shown in Figure 7.19 A. This is known as group trapping. However, it is rarely successful, since it normally causes water-logging and loss of output.

The steam consumption of a number of units is never the same at a moment of time and therefore, the pressure in the various steam spaces will also be different. It follows that the pressure at the drain outlet of a heavily loaded unit will be less than in the case of one that is lightly or properly loaded. Now, if all these units are connected to a common steam trap, the condensate from the heavily loaded and therefore lower pressure steam space finds it difficult to reach the trap as against the higher pressure condensate produced by lightly or partly loaded unit. The only satisfactory arrangement, thus would be to drain each steam space with own trap and then connect the outlets of the various traps to the common condensate return main as shown in above Figure 7.19 B.

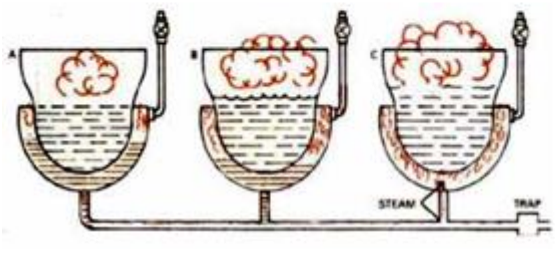


Figure 7.19 A: Group Trapping

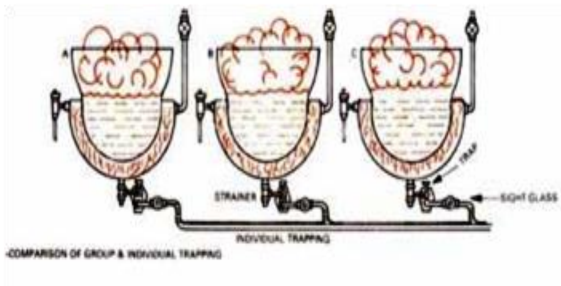


Figure 7.19 B: Individual Trapping

6. Dirt

Dirt is the common enemy of steam traps and the causes of many failures. New steam systems contain scale, castings, weld metal, piece of packing and jointing materials, etc. When the system has been in use for a while, the inside of the pipe work and fittings, which are exposed to corrosive condensate, can get rusted. Thus, rust in the form of a fine brown powder is also likely to be present. All this dirt will be carried through the system by the steam and condensate until it reaches the steam trap. Some of it may pass through the trap into the condensate system without doing any harm, but some dirt will eventually jam the trap mechanism. It is advisable to use a strainer positioned before the steam trap to prevent dirt from passing into the system.

7. Water Hammer

A water hammer in a steam system is caused by condensate collection in the plant or pipe work picked up by the fast moving steam and carried along with it. When this collection hits obstructions such as bends, valves, steam traps or some other pipe fittings, it is likely to cause severe damage to fittings and equipment and result in leaking pipe joints.

The problem of water hammer can be eliminated by positioning the pipes so that there is a continuous slope in the direction of flow. In case of steam mains, a slope of at least 1 m in every 100 meters is necessary, as also an adequate number of drain points every 30 to 50 meters.

8. Lifting the condensate

It is sometimes necessary to lift condensate from a steam trap to a higher level condensate return line (Figure 7.20). The condensate will rise up the lifting pipe work when the steam pressure upstream of the trap is higher than the pressure downstream of the trap.

The pressure downstream of the trap is generally called backpressure, and is made up of any pressure existing in the condensate line plus the static lift caused by condensate in the rising pipe work. The upstream pressure will vary between start-up conditions, when it is at its lowest and running conditions, when it is at its highest.

Backpressure is related to lift by using the following approximate conversion: 1 metre lift in pipe work = 1 m head static pressure or 0.1 bar backpressure. If a head of 5 m produces a backpressure of 0.5 bar, then this reduces the differential pressure available to push condensate through the trap; although under running conditions the reduction in trap capacity is likely to be significant only where low upstream pressures are used.

In steam mains at start-up, the steam pressure is likely to be very low, and it is common for water to back-up before the trap, which can lead to water hammer in the space being drained. To alleviate this problem at start-up, a liquid expansion trap, fitted as shown in Figure 7.20, will discharge any cold condensate formed at this time to waste.

As the steam main is warmed, the condensate temperature rises, causing the liquid expansion trap to close. At the same time, the steam pressure rises, forcing the hot condensate through the ‘working’ drain trap to the return line.

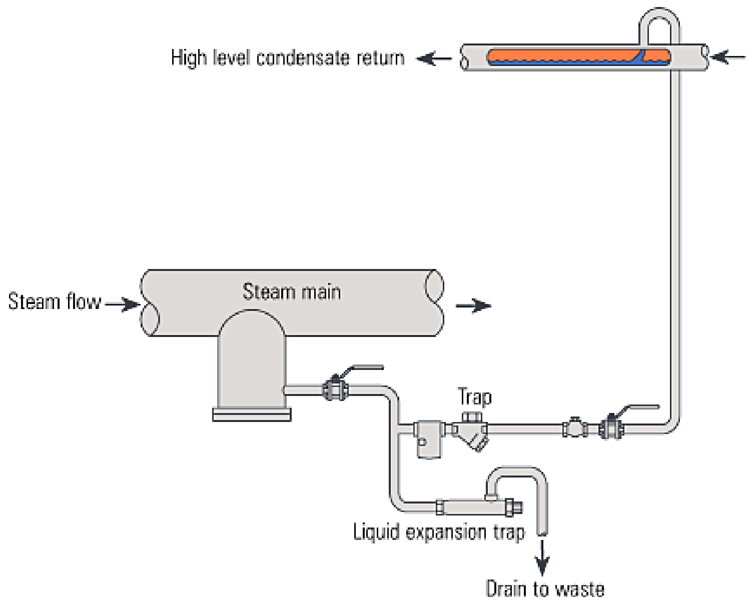


Figure 7.20: Use of a Liquid Expansion Trap

The discharge line from the trap to the overhead return line preferably discharges into the top of the main rather than simply feed to the underside, as shown in Figure 3.12. This assists operation, because although the riser is probably full of water at start-up, it sometimes contains little more than flash steam once hot condensate under pressure passes through. If the discharge line were fitted to the bottom of the return line, it would fill with condensate after each discharge and increase the tendency for water hammer and noise.

It is also recommended that a check valve be fitted after any steam trap from where condensate is lifted, preventing condensate from falling back towards the trap. The above general recommendations apply not just to traps lifting condensate from steam mains, but also to traps draining any type of process running at a constant steam pressure. Temperature controlled processes will often run with low steam pressures. Rising condensate discharge lines should be avoided at all costs, unless automatic pump-traps are used.

7.15 Guide to Steam Trap Selection

Actual energy efficiency can be achieved only when

a) Selection
b) Installation and
c) Maintenance of steam traps meet the requirements for the purpose it is installed

The following Table 7.10 gives installation of suitable traps for different process applications.

Table 7.10 Selection of Steam trap

Application	Feature	Suitable trap

Steam mains	• Open to atmosphere, small capacity • Frequent change in pressure • Low pressure - high pressure	Thermodynamic type
Equipment • Reboiler • Heater • Dryer • Heat exchanger etc.	• Large capacity • Variation in pressure and temperature is undesirable • Efficiency of the equipment is a problem	Mechanical trap, Bucket, Inverted bucket, float
• Tracer line • Instrumentation	• Reliability with no over heating	Thermodynamic & Bimetallic

7.16 Performance Assessment Methods for Steam Traps

Steam trap performance assessment is basically concerned with answering the following two questions:

- Is the trap working correctly or not?
- If not, has the trap failed in the open or closed position?

Traps that fail 'open' result in a loss of steam and its energy. Where condensate is not returned, the water is lost as well. The result is significant economic loss, directly via increased boiler plant costs, and potentially indirectly, via decreased steam heating capacity.

Traps that fail 'closed' do not result in energy or water losses, but can result in significantly reduced heating capacity and/or damage to steam heating equipment.

7.16.1 Visual Testing

Visual testing includes traps with open discharge sight glasses (Figure 7.21), sight checks, test tees and three-way test valves. In every case, the flow or variation of flow is visually observed. This method works well with traps that cycle on/off, or dribbles on light load. On high flow or process, due to the volume of water and flash steam, this method becomes less viable. If condensate can be diverted ahead of the trap or a secondary flow can be turned off, the load on the trap will drop to zero or a very minimal amount so the visual test will allow in determining the leakage.

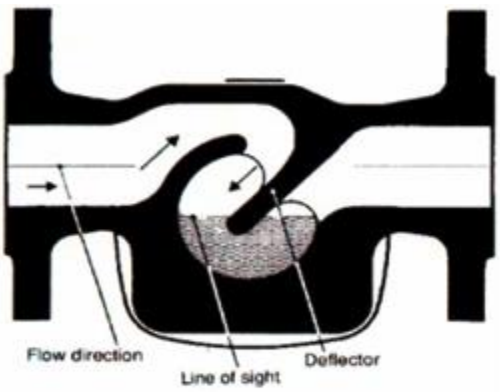


Figure 7.21: Sight Glass

7.16.2 Sound Testing

Sound testing includes ultrasonic leak detectors (Figure 7.22), mechanics stethoscopes, screwdriver or metal rod with a human ear against it. All these use the sound created by flow to determine the trap function like the visual method. This method works best with traps that cycle on/off or dribbles on light load. Traps which have modulating type discharge patterns are hard to check on high flows. (Examples are processes, heat exchangers, air handling coils, etc.). Again by diverting condensate flow ahead of the trap or shutting off a secondary flow as mentioned under visual testing, the noise level will drop to zero or a very low level if the trap is operating correctly. If the trap continues to flow heavily after diversion it would be leaking or blowing through.

Figure 7.22: Ultrasonic Testing

7.16.3 Temperature Testing

Temperature testing includes infrared guns (Figure 7.23), surface pyrometers, temperature tapes, and temperature crayons. Typically they are used to gauge the discharge temperature on the outlet side of the trap. In the case of temperature tapes or crayon, they are set for a predetermined temperature and they indicate when temperature exceeds that level. Infrared guns and surface pyrometer can detect temperatures on both sides of the trap. Both the infrared and surface pyrometers require bare pipe and a clean surface to achieve a reasonable reading. The temperature reading will typically be lower than actual internal pipe temperature due to the fact that steel does have some heat flow resistance. Scale on the inside of the pipe can also affect the heat transfer. Some of the more expensive infrared guns can compensate for wall thickness and material differences. Blocked or turned off traps can easily be detected by infrared guns and surface pyrometers, as they will show low or cold temperatures. They could also pick up traps which may be undersized or backing up large amounts of condensate by detecting low temperature readings.

Figure 7.23: Infra-Red Testing

7.17 Energy Saving Opportunities

7.17.1 Monitoring Steam Traps

For testing a steam trap, there should be an isolating valve provided in the downstream of the trap and a test valve shall be provided in the trap discharge. When the test valve is opened, the following points have to be observed:

Condensate discharge-Inverted bucket and thermodynamic disc traps should have intermittent condensate discharge. Float and thermostatic traps should have a continuous condensate discharge. Thermostatic traps can have either continuous or intermittent discharge depending upon the load. If inverted bucket traps are used for extremely small load, it will have a continuous condensate discharge.

Flash steam-This shall not be mistaken for a steam leak through the trap. The users sometimes get confused between a flash steam and leaking steam. The flash steam and the leaking steam can be approximately identified as follows:
If steam blows out continuously in a blue stream, it is a leaking steam.
If a steam floats out intermittently in a whitish cloud, it is a flash steam.

7.17.2 Continuous steam blow and no flow indicate there is a problem in the trap.

Whenever a trap fails to operate and the reasons are not readily apparent, the discharge from the trap should be observed. A step-by-step analysis has to be carried out mainly with reference to lack of discharge from the trap, steam loss, continuous flow, sluggish heating, to find out whether it is a system problem or the mechanical problem in the steam trap.

7.17.3 Avoiding Steam Leakages

Steam leakage is a visible indicator of waste and must be avoided. It has been estimated that a 3 mm diameter hole on a pipeline carrying 7kg/cm^2 steam would waste 33 Kilo Litre of fuel oil per year. Steam leaks on high-pressure mains are prohibitively costlier than on low pressure mains. Any steam leakage must be quickly attended to. In fact, the plant should consider a regular surveillance programme for identifying leaks at pipelines, valves, flanges and joints. Indeed, by plugging all leakages, one may be surprised at the extent of fuel savings, which may reach up to 5% of the steam consumption in a small or medium scale industry or even higher in installations having several process departments.

Figure 7.24: Steam Loss vs Plume Length

To avoid leaks it may be worthwhile considering replacement of the flanged joints which are rarely opened in old plants by welded joints. Figure 7.24 provides a quick estimate for steam leakage based on plume length.

7.17.4 Providing Dry Steam for Process

The best steam for industrial process heating is the dry saturated steam. Wet steam reduces total heat in the steam. Also water forms a wet film on heat transfer and overloads traps and condensate equipment. Super-heated steam is not desirable for process heating because it gives up heat at a rate slower than the condensation heat transfer of saturated steam.

It must be remembered that a boiler without a super heater cannot deliver perfectly dry saturated steam. At best, it can deliver only 95% dry steam. The dryness fraction of steam depends on various factors, such as the level of water, improper boiler water treatment etc.
As steam flows through the pipelines, it undergoes progressive condensation due to the loss of heat to the colder surroundings; the extent of the condensation depends on the effectiveness of the lagging. For example, with poor lagging, the steam can become excessively wet.

Since dry saturated steam is required for process equipment, due attention must be paid to the boiler operation and lagging of the pipelines. The steam produced in a boiler designed to generate saturated steam is inherently wet. Although the dryness fraction will vary according to the type of boiler, most shell type steam boilers will produce steam with a dryness fraction of between 95 and 98%.

Wet steam can reduce plant productivity and product quality, and can cause damage to most items of plant and equipment. The water content of the steam produced by the boiler is further increased if priming and carryover occur.

A steam separator (Figure 7.25) may be installed on the steam main as well as on the branch lines to reduce wetness in steam and improve the quality of the steam going to the units. By change of direction of steam, steam separators causes the entrained water particles to be separated out and delivered to a point where they can be drained away as condensate through a conventional steam trap.

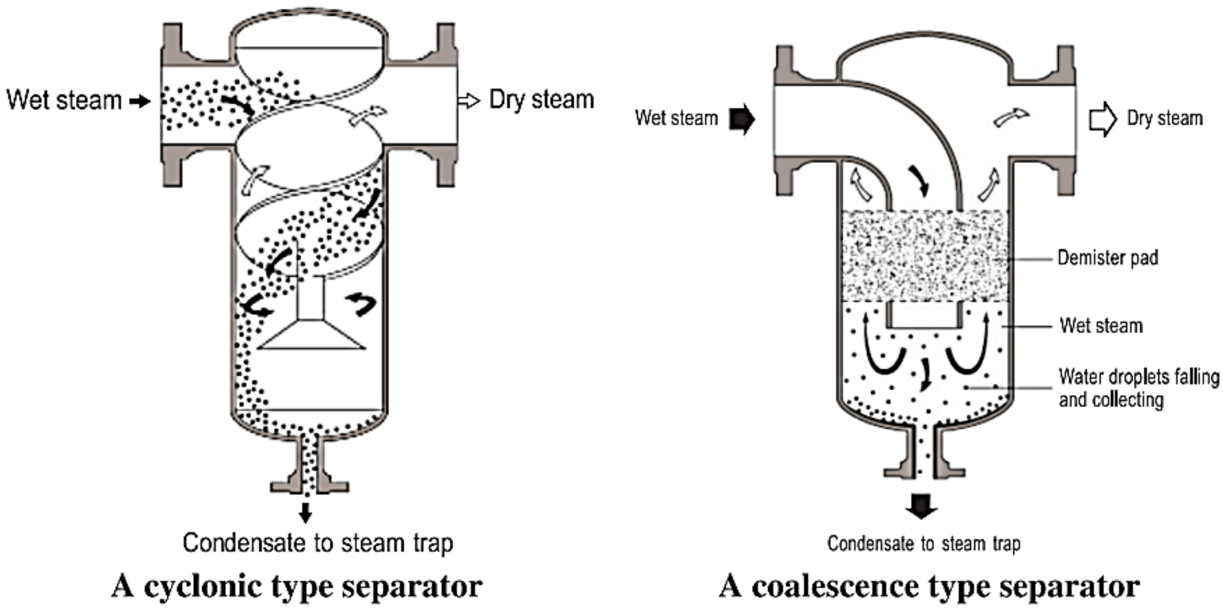


Figure 7.25: Steam Separators

7.17.5 Utilizing Steam at the Lowest Acceptable Pressure for the Process

A study of the steam tables would indicate that the latent heat in steam reduces as the steam pressure increases. It is only the latent heat of steam, which takes part in the heating process when applied to an indirect heating system. Thus, it is important that its value be kept as high as possible. This can only be achieved if we go in for lower steam pressures. As a guide, the steam should always be generated and distributed at the highest possible pressure, but utilized at a low pressure as possible since it has higher latent heat.

However, it may also be seen from the steam tables that the lower the steam pressure, the lower will be its temperature. Since temperature is the driving force for the transfer of heat at lower steam pressures, the rate of heat transfer will be slower and the processing time greater. In equipment where fixed losses are high (e.g. big drying cylinders), there may even be an increase in steam consumption at lower pressures due to increased processing time. There are however, several equipment in certain industries where one can profitably go in for lower pressures and realize economy in steam consumption without materially affecting production time.

Therefore, there is a limit to the reduction of steam pressure. Depending on the equipment design, the lowest possible steam pressure with which the equipment can work should be selected without sacrificing either on production time or on steam consumption.

7.17.6 Proper Utilization of Directly Injected Steam

The heating of a liquid by direct injection of steam is often desirable. The equipment required is relatively simple, cheap and easy to maintain. No condensate recovery system is necessary. The heating is quick, and the sensible heat of the steam is also used up along with the latent heat, making the process thermally efficient. In processes where dilution is not a problem, heating is done by blowing steam into the liquid (i.e.) direct steam injection is applied. If the dilution of the tank contents and agitation are not acceptable in the process (i.e.) direct steam agitation are not acceptable, indirect steam heating is the only answer.

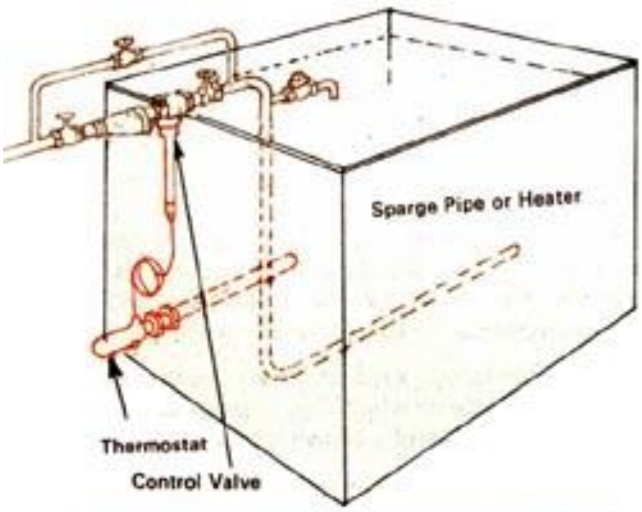


Figure 7.26: Temperature Control for Directly Injected Steam

Ideally, the injected steam should be condensed completely as the bubbles rise through the liquid. This is possible only if the inlet steam pressures are kept very low - around 0.5 kg/cm^2-and certainly not exceeding 1 kg/cm^2. If pressures are high, the velocity of the steam bubbles will also be high and they will not get sufficient time to condense before they reach the surface. Figure 3.18 shows a recommended arrangement for direct injection of steam.

A large number of small diameter holes (2 to 5mm), facing downwards, should be drilled on the separate pipe. This will help in dissipating the velocity of bubbles in the liquid. A thermostatic control of steam admitted is highly desirable.

7.17.7 Minimizing Heat Transfer Barriers

The metal wall may not be the only barrier in a heat transfer process. There is likely to be a film of air, condensate and scale on the steam side. On the product side, there may also be baked-on product or scale, and a stagnant film of product.

Agitation of the product may eliminate the effect of the stagnant film, whilst regular cleaning on the product side should reduce the scale.

Regular cleaning of the surface on the steam side may also increase the rate of heat transfer by reducing the thickness of any layer of scale; however, this may not always be possible. This layer may also be reduced by careful attention to the correct operation of the boiler, and the removal of water droplets carrying impurities from the boiler.

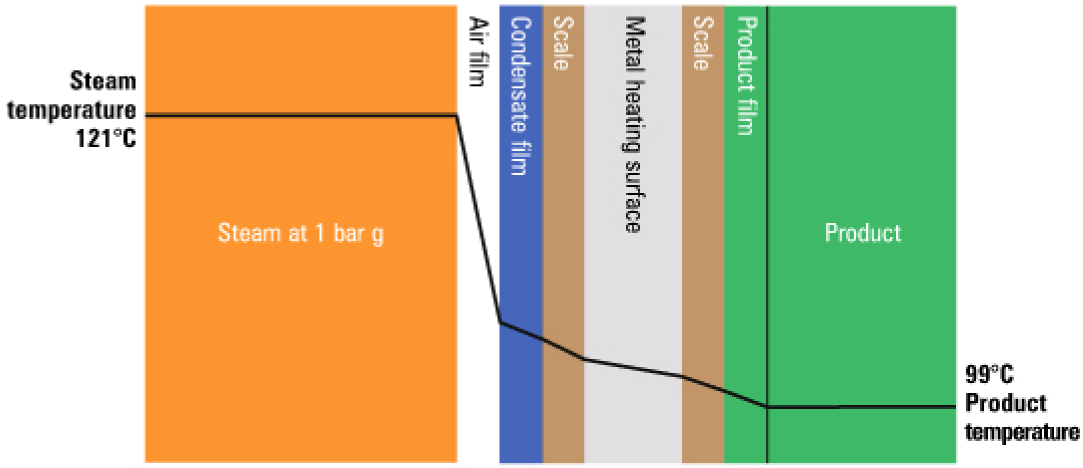


Figure 7.27: Heat Transfer Barriers

The elimination of the condensate film is not quite as simple. As the steam condenses to give up its enthalpy of evaporation, droplets of water may form on the heat transfer surface. These may merge together to form a continuous film of condensate. The condensate film may be between 100 and 150 times more resistant to heat transfer than a steel heating surface, and 500 to 600 times more resistant than copper.
As air is a good insulator, it provides even more resistance to heat transfer. Air may be between 1500 and 3000 times more resistant to heat flow than steel, and 8000 to 16000 more resistant than copper. This means that a film of air only 0.025 mm thick may resist as much heat transfer as a wall of copper 400 mm thick. These comparative relationships depend on the temperature profiles across each layer.
Figure 3.19 illustrates the effect this combination of layers has on the heat transfer process. These barriers to heat transfer not only increase the thickness of the entire conductive layer, but also greatly reduce the mean thermal conductivity of the layer.

The more resistant the layer to heat flow, the larger the temperature gradient is likely to be. This means that to achieve the same desired product temperature, the steam pressure may need to be significantly higher.

To achieve the desired product output and minimise the cost of process steam operations, a high heating performance may be maintained by reducing the thickness of the films on the condensing surface and removal of air from the supply steam.

7.17.8 Proper Air Venting

When steam is first admitted to a pipe after a period of shutdown, the pipe is full of air. Further, amounts of air and other non-condensable gases will enter with the steam, although the proportions of these gases are normally very small compared with the steam. When the steam condenses, these gases will accumulate in pipes and heat exchangers. Precautions should be taken to discharge them. The consequence of not removing air is a lengthy warming up period, reduction in plant efficiency and process performance. Air in the steam system will also affect the system temperature. Air will exert its own pressure within the system, which will add to the pressure of the steam to give a total pressure.

A layer of air only 1 mm thick can offer the same resistance to heat as a layer of water 25 µm thick, a layer of iron 2 mm thick or a layer of copper 15 mm thick. It is very important therefore to remove air from any steam system.

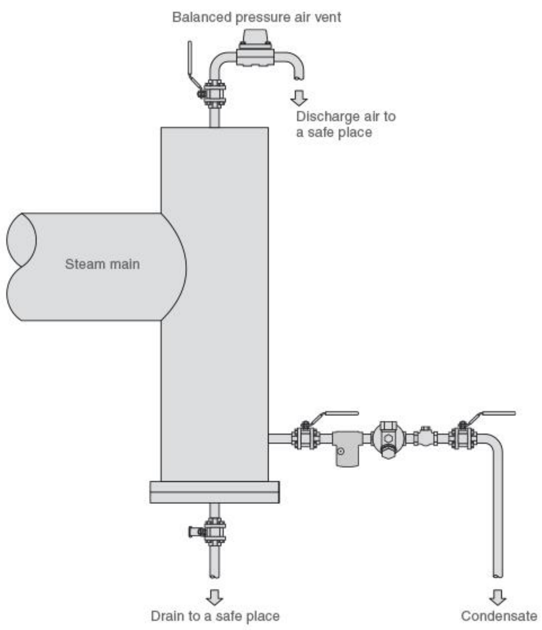


Figure 7.28: Air Vent

Automatic air vents for steam systems (which operate on the same principle as thermostatic steam traps) should be fitted above the condensate level so that only air or steam-air mixtures can reach them. The best location for them is at the end of the steam mains. In addition to air venting at the end of a main, air vents should also be fitted in parallel with an inverted bucket trap or a thermodynamic trap.

7.17.9 Condensate Recovery

The steam condenses after giving off its latent heat in the heating coil or the jacket of the process equipment. A sizable portion (about 25%) of the total heat in the steam leaves the process equipment as hot water. If this water is returned to the boiler house, it will reduce the fuel requirements of the boiler. For every 6 ^{0}C rise in the feed water temperature, there will be approximately 1% saving of fuel in the boiler. However, in most cases, the boiler water has to be chemically treated to prevent or reduce scale formation, whereas the condensate is almost entirely pure water which needs no treatment. With a good percentage of the condensate returning to the boiler house, the expenses involved for water treatment will be reduced by an appreciable amount.

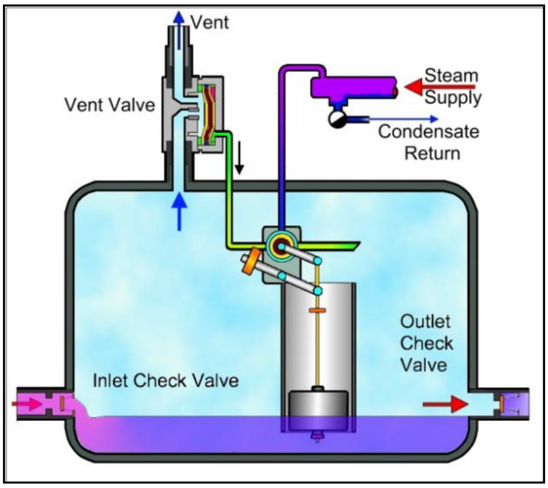


Figure 7.29: Pressure Powered Pump

Use a Steam Driven Pump: A pressure powered pump (Figure 7.29) uses steam pressure to push the condensate from the receiver back to the boiler house. In principle it consists of a receiver which receives condensate from different process/equipment. Once the condensate reaches a set level, the steam valve is opened and the steam pressure pushes the condensate to the boiler room. The operation is cyclic in nature. The advantage is pumping of condensate without losing much heat in the form of flash steam without any cavitation problems.

7.17.10 Insulation of Steam Pipelines and Hot Process Equipment

Steam lines including flanges and valves should be insulated to prevent heat loss. The recommended thickness of insulation will mainly depend on surface temperature desired after insulation. The energy and cost savings will depend on the size of the pipe (diameter and length of run), the temperature of steam and the surroundings, heat transfer co-efficient and the number of hours of operation of the plant.

The following Table 7.11 indicates the effect of insulating bare pipes

Table 7.11 Effect of Insulation on Steam Pipes

Pipe Size, inch	Economic Insulation Thickness, mm	Radiation Losses* (kW/m)	
		Insulated	Uninsulated
½	15	125	692
2	25	243	1820
4	40	298	2942
12	50	588	7614

** Comparison of Radiation Losses (Pipe Surface Temperature at 150 ^oC)*

7.17.11 Flash Steam Recovery

Flash steam is produced when condensate at a high pressure is released to a lower pressure and can be used for low pressure heating.

The higher the steam pressure and lower the flash steam pressure the greater the quantity of flash steam that can be generated. In many cases, flash steam from high pressure equipment is made use of directly on the low-pressure equipment to reduce use of steam through pressure reducing valves.

Flash steam can be used on low pressure applications like direct injection and can replace an equal quantity of live steam that would be otherwise required. The demand for flash steam should exceed its supply, so that there is no build-up of pressure in the flash vessel and the consequent loss of steam through the safety valve. Generally, the simplest method of using flash steam is to flash from a machine/equipment at a higher pressure to a machine/equipment at a lower pressure, thereby augmenting steam supply to the low pressure equipment.

In general, a flash system should run at the lowest possible pressure so that the maximum amount of flash is available and the backpressure on the high pressure systems is kept as low as possible.
Flash steam from the condensate can be separated in an equipment called the ‘flash vessel’. This is a vertical vessel as shown in the Figure 3.22. The diameter of the vessel is such that a considerable drop in velocity allows the condensate to fall to the bottom of the vessel from where it is drained out by a steam trap preferably a float trap. Flash steam itself rises to leave the vessel at the top. The height of the vessel should be sufficient enough to avoid water being carried over in the flash steam.

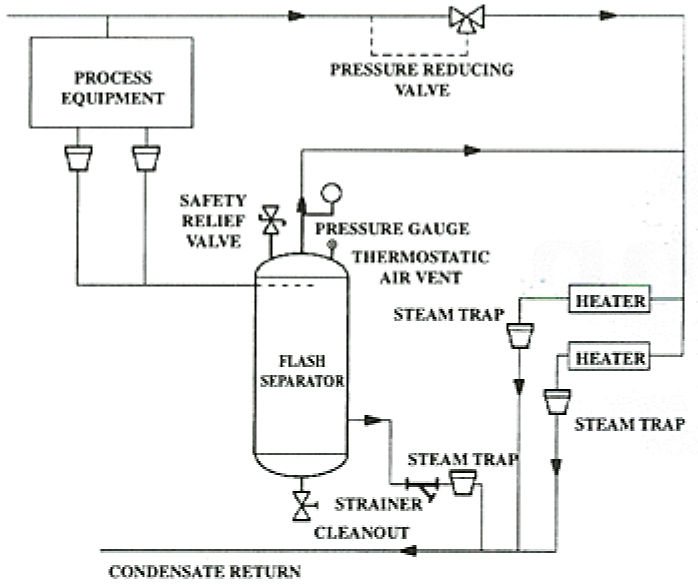


Figure 7.30: Flash Steam Recovery

The condensate from the traps (A) along with some flash steam generated passes through vessel (B). The flash steam is let out through (C) and the residual condensate from (B) goes out through the steam trap (D). The flash vessel is usually fitted with a 'pressure gauge' to know the quality of flash steam leaving the vessel. A 'safety valve' is also provided to vent out the steam in case of high pressure build up in the vessel.

7.17.12 Pipe Redundancy

All redundant (piping which are no longer needed) pipelines must be eliminated, which could be, at times, up to 10-15 % of total length. This would reduce steam distribution losses significantly. The pipe routing shall be made for transmission of steam in the shortest possible way, so as to reduce the pressure drop in the system, thus saving the energy. However, care should be taken that, the pipe routing shall be flexible enough to take thermal expansion and to keep the terminal point loads, within the allowable limit.

7.17.13 Reducing the Work to be done by Steam

The equipment should be supplied with steam as dry as possible. The plant should be made efficient. For example, if any product is to be dried such as in a laundry, a press could be used to squeeze as much water as possible before being heated up in a dryer using steam.

When the steam reaches the place where its heat is required, it must be ensured that the steam has no more work to do than is absolutely necessary. Air-heater batteries, for example, which provide hot air for drying, will use the same amount of steam whether the plant is fully or partly loaded. So, if the plant is running only at 50 per cent load, it is wasting twice as much steam (or twice as much fuel) than necessary.

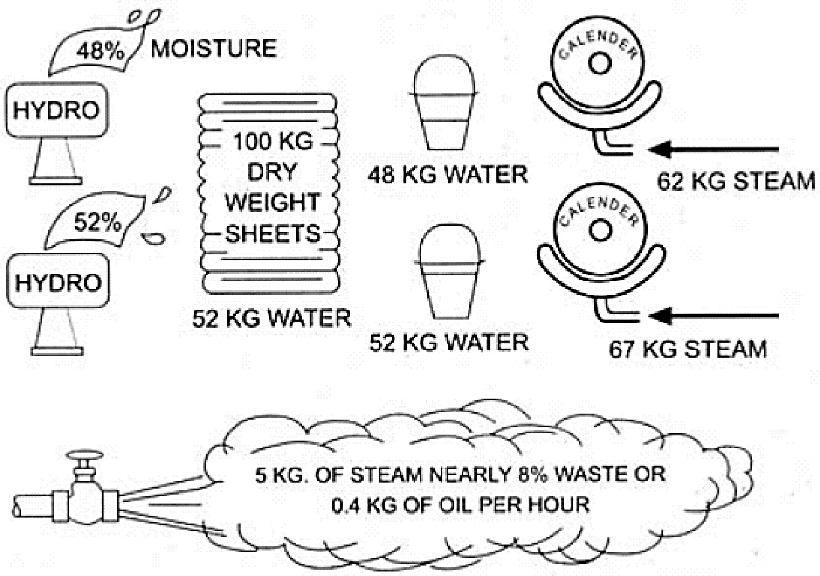


Figure 7.31 Steam Wastage Due to Insufficient Mechanical Drying

The energy saving is affected by following measures:

- Reduction in operating hours
- Reduction in steam quantity required per hour
- Use of more efficient technology
- Minimizing wastage.

Always use the most economical way to removing the bulk of water from the wet material. Steam can then be used to complete the process. For this reason, hydro-extractors, spin dryers, squeeze or calendar rolls, presses, etc. are initially used in many drying processes to remove the mass of water. The efficiency with which this operation is carried out is most important. For example, in a laundry for finishing sheets (100 kg/hr dry weight), the normal moisture content of the sheets as they leave the hydro extractor is 48% by weight.

Thus, the steam heated iron has to evaporate nearly 48 kg of water. This requires 62 kg of steam. If, due to inefficient drying in the hydro-extractor, the steam arrive at the iron with 52% moisture content i.e. 52 kg of water has to be evaporated, requiring about 67 kg of steam. So, for the same quantity of finished product, the steam consumption increases by 8 per cent. This is illustrated in Figure 7.31

CHAPTER 8: INDUSTRIAL FURNACES

A furnace is an equipment to melt metals for casting or heat materials for change of shape (rolling, forging etc.) or change of properties (heat treatment).

8.1 Types and Classification of Different Furnaces

Based on the method of generating heat, furnaces are broadly classified into two types namely combustion type (using fuels) and electric type. The combustion type furnace can be broadly classified as oil fired, coal fired or gas fired.

Based on the mode of charging of material furnaces can be classified as (i) Intermittent or Batch type furnace or Periodical furnace and (ii) Continuous furnace.

Based on mode of waste heat recovery as recuperative and regenerative furnaces.

Another type of furnace classification is made based on mode of heat transfer, mode of charging and mode of heat recovery as shown in the figure 4.1 below.

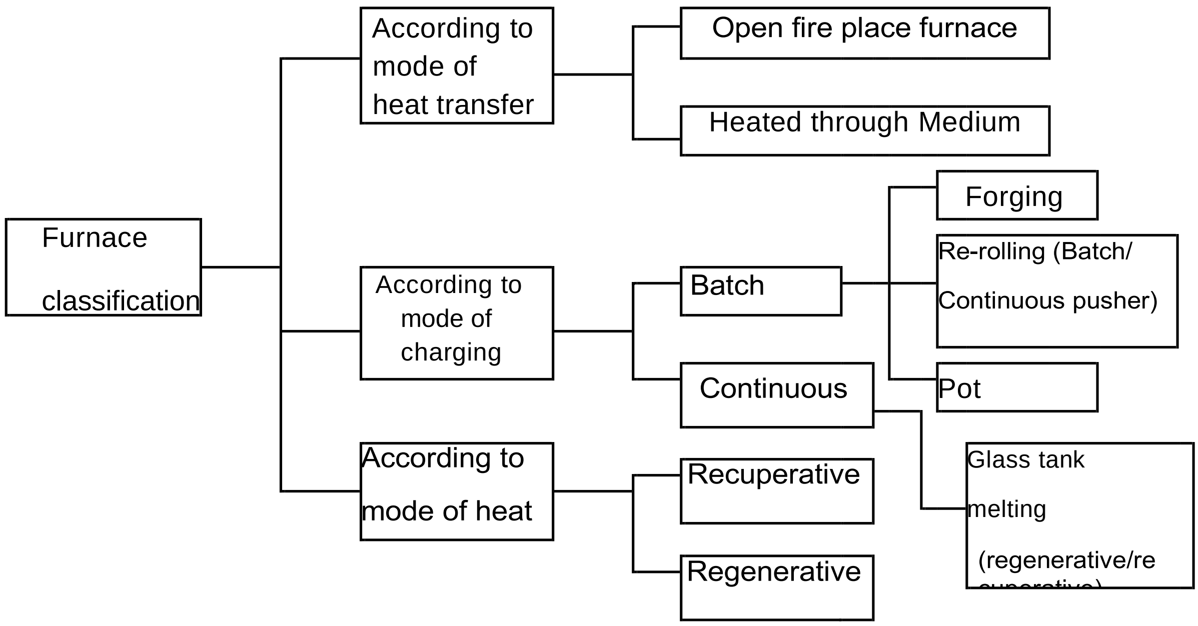


Figure 8.1: Furnace Classification

The electric furnaces can be broadly classified as resistance type for heating and induction and arc furnace for melting of metals.

8.2 Characteristics of an Efficient Furnace

Furnace should be designed so that in a given time, as much of material as possible can be heated to a uniform temperature as possible with the least possible fuel and labour. To achieve this end, the following parameters can be considered.

- Determination of the quantity of heat to be imparted to the material or charge.
- Liberation of sufficient heat within the furnace to heat the stock and overcome all heat losses.
- Transfer of available part of that heat from the furnace gases to the surface of the heating stock.
- Equalization of the temperature within the stock.

- Reduction of heat losses from the furnace to the minimum possible extent.

8.3 Furnace Energy Supply

Since the products of flue gases directly contact the stock, type of fuel chosen is of importance. For example, some materials will not tolerate sulphur in the fuel. Also use of solid fuels will generate particulate matter, which will interfere the stock placed inside the furnace. Hence, vast majority of the furnaces use liquid fuel, gaseous fuel or electricity as energy input. Electricity is used in induction and arc furnaces for melting steel and cast iron. Non-ferrous melting utilizes oil as fuel.

8.4 Oil Fired Furnace

Furnace oil is the major fuel used in oil fired furnaces, especially for reheating and heat treatment of materials. LDO is used in furnaces where presence of sulphur is undesirable. The key to efficient furnace operation lies in complete combustion of fuel with minimum excess air.

Furnaces operate with efficiencies as low as 7% as against up to 90% achievable in other combustion equipment such as boiler. This is because of the high temperature at which the furnaces have to operate to meet the required demand. For example, a furnace heating the stock to 1200^{o}C will have its exhaust gases leaving at least at 1200^{o}C resulting in a huge heat loss through the stack. However, improvements in efficiencies have been brought about by methods such as preheating of stock, preheating of combustion air and other waste heat recovery systems.

8.5 Typical Furnace System

i. Forging Furnaces

The forging furnace is used for preheating billets and blooms to attain a 'forge' temperature. The furnace temperature is maintained at around 1200 to 1250 °C. Forging furnaces use an open fireplace system and most of the heat is transmitted by radiation.

The total operating cycle can be divided into (a) heat up time (b) soaking time and (c) forging time.

Normally, large pieces are soaked for 4 to 6 hrs inside the furnace to attain uniform temperature throughout the cross-section of the material. The actual soaking time varies with the type and thickness of the material. The completely soaked material is withdrawn from furnace to the hammer to be forged as required. Larger pieces may have to be reheated several times. A typical forging furnaces is illustrated in Figure 8.2.

Figure 8.2 Forging Furnace

The charging and discharging of the material is done manually and this results in significant heat loss during the forging operation. Specific fuel consumption depends upon the type of material and number of `reheats' required.

ii. Rerolling Mill Furnace

a) Batch type

A box type furnace is employed for batch type rerolling mill. The furnace is basically used for heating up scrap, small ingots and billets weighing 2 to 20 kg for rerolling. The charging and discharging of the `material' is done manually and the final product is in the form of rods, strips etc. The operating temperature is about 1200 °C. The total cycle time can be further categorized into heat-up time and rerolling time. During heat-up time the material gets heated up to the required temperature and is removed manually for rerolling. The average output from these furnaces varies from 10 to 15 tonnes / day.

b) Continuous Pusher Type

The process flow and operating cycles of a continuous pusher type is the same as that of the batch furnace. The operating temperature is about 1250 °C. Generally, these furnaces operate 8 to 10 hours with an output of 50 to 100 tons per day. The material or stock recovers a part of the heat in flue gases as it moves down the length of the furnace. Heat absorption by the material in the furnace is slow, steady and uniform throughout the cross-section compared with batch type.

iii. Continuous Steel Reheating Furnaces

The main function of a reheating furnace is to raise the temperature of a piece of steel, typically to between 900 °C and 1250 °C, until it is plastic enough to be pressed or rolled to the desired section, size or shape, The furnace must also meet specific requirements and objectives in terms of stock heating rates for metallurgical and productivity reasons. In continuous reheating, the steel stock forms a continuous flow of material and is heated to the desired temperature as it travels through the furnace.

All furnaces possess the features shown in Figure 8.3

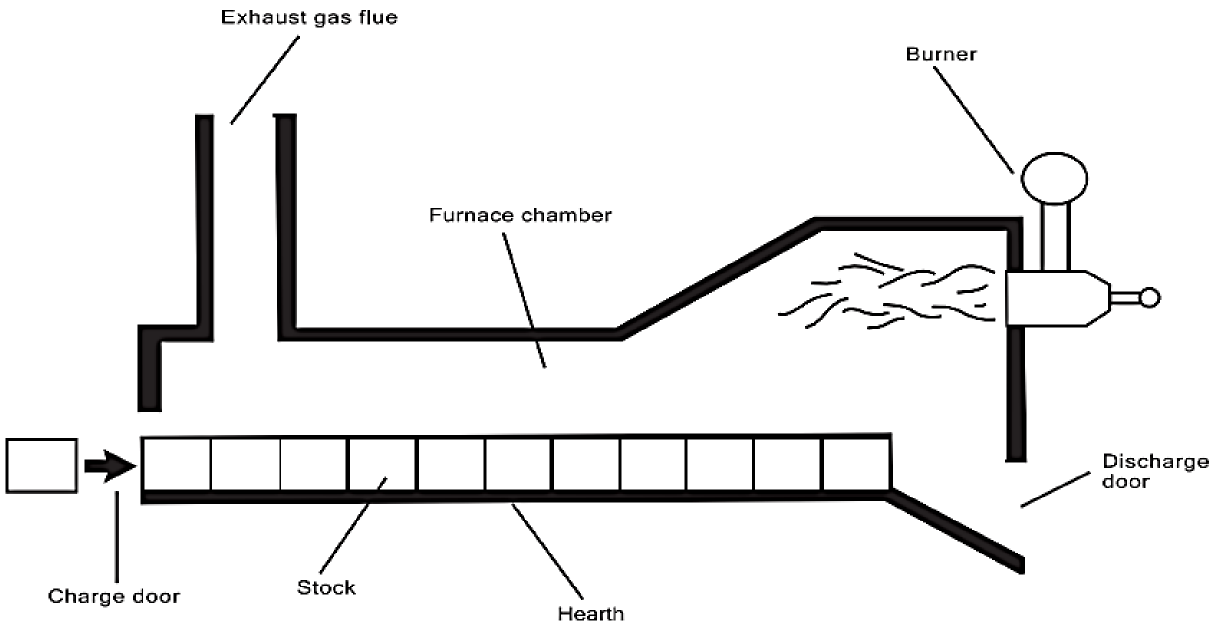


Figure 8.3 Furnace Feature

- A refractory chamber constructed of insulating materials for retaining heat at the high operating temperatures.
- A hearth to support or carry the steel. This can consist of refractory materials or an arrangement of metallic supports that may be water-cooled.
- Burners that use liquid or gaseous fuels to raise and maintain the temperature in the chamber. Coal or electricity can be used for reheating. A method of removing the combustion exhaust gases from the chamber
- A method of introducing and removing the steel from the chamber.
- These facilities depend on the size and type of furnace, the shape and size of the steel being processed, and the general layout of the rolling mill.
- Common systems include roller tables, conveyors, charging machines and furnace pushers.

8.6 Heat Transfer in Furnaces

The main ways in which heat is transferred to the steel in a reheating furnace are shown in Figure 8.4. In simple terms, heat is transferred to the stock by:

✓ Radiation from the flame, hot combustion products and the furnace walls and roof;

✓ Convection due to the movement of hot gases over the stock surface.

At the high temperatures employed in reheating furnaces, the dominant mode of heat transfer is wall radiation. Heat transfer by gas radiation is dependent on the gas composition (mainly the carbon dioxide and water vapour concentrations), the temperature and the geometry of the furnace.

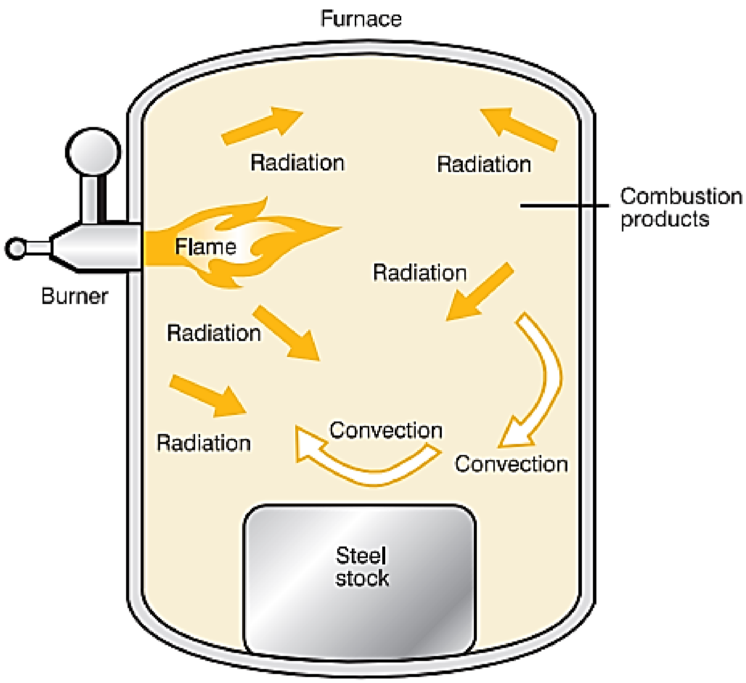


Figure 8.4: Heat Transfer in furnace

8.7 Types of Continuous Reheating Furnace

Continuous reheating furnaces are primarily categorised by the method by which stock is transported through the furnace. There are two basic methods:

- Stock is butted together to form a stream of material that is pushed through the furnace. Such furnaces are called pusher type furnaces.
- Stock is placed on a moving hearth or supporting structure which transports the steel through the furnace. Such types include walking beam, walking hearth, rotary hearth and continuous recirculating bogie furnaces.

The major consideration with respect to furnace energy use is that the inlet and outlet apertures should be minimal in size and designed to avoid air infiltration.

i. Pusher Type Furnaces

The pusher type furnace is popular in steel industry. It has relatively low installation and maintenance costs compared to moving hearth furnaces. The furnace may have a solid hearth, but it is also possible to push the stock along skids with water-cooled supports that allow both the top and bottom faces of the stock to the heated. The design of a typical pusher furnace design is shown schematically in Figure 4.5.

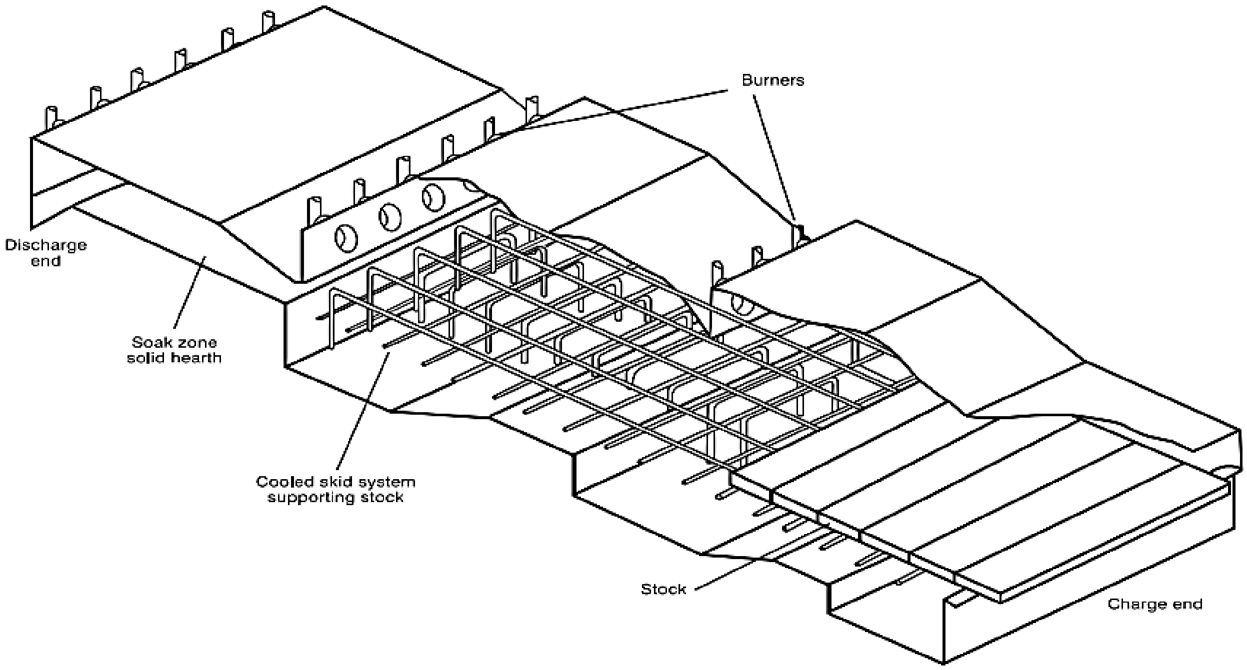


Figure 8.5: Pusher Type Furnace

Pusher type furnaces, however, do have some disadvantages, including:

✓ Frequent damage of refractory hearth and skid marks on material
✓ Water cooling energy losses from the skids and stock supporting structure in top and bottom fired furnaces have a detrimental effect on energy use;
✓ Discharge must be accompanied by charge:
✓ Stock sizes and weights and furnace length are limited by friction and the possibility of stock pile-ups.
✓ All-round heating of the stock is not possible.

ii. Walking Hearth Furnaces

The walking hearth furnace (Figure.8.6) allows the stock to be transported through the furnace in discrete steps. Such furnaces have several attractive features, including: simplicity of design, ease of construction, ability to cater for different stock sizes (within limits), negligible water cooling energy losses and minimal physical marking of the stock.

The main disadvantage of walking hearth furnaces is that the bottom face of the stock cannot be heated. This can be alleviated to some extent by maintaining large spaces between pieces of stock. Small spaces between the individual stock pieces limits the heating of the side faces and increases the potential for unacceptable temperature differences within the stock at discharge. Consequently, the stock residence time may be long, possibly several hours; this may have an adverse effect on furnace flexibility and the yield may be affected by scaling.

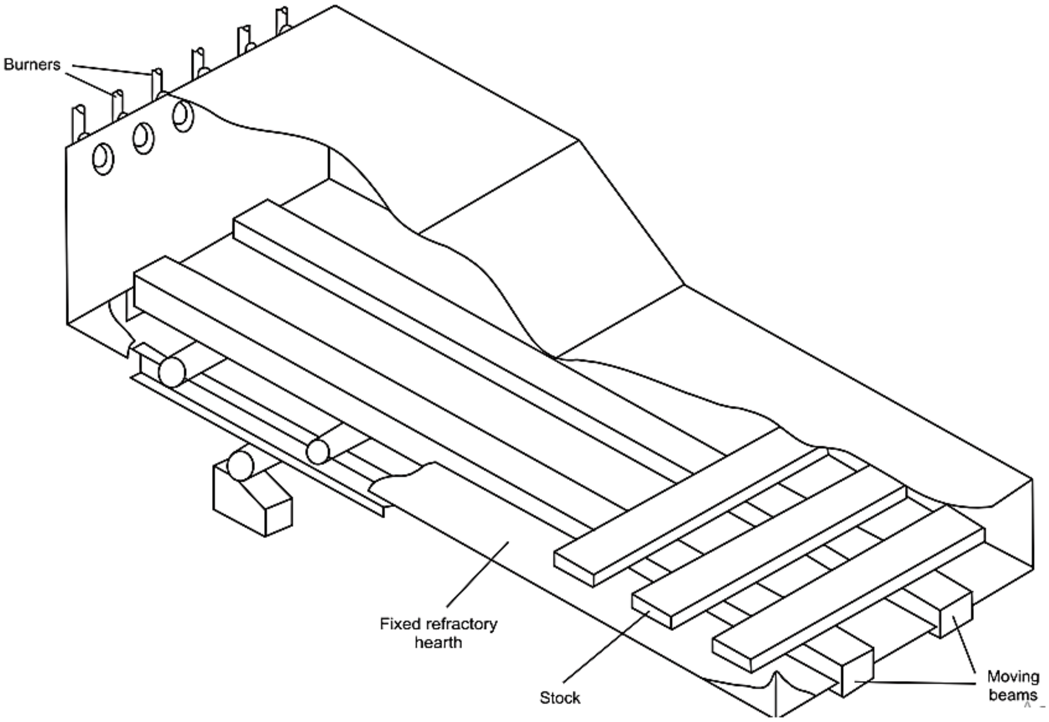


Figure 8.6 Walking Hearth Type Furnace

iii. Rotary hearth furnace

The rotary hearth furnace (Figure 8.7) has tended to supersede the re-circulating bogie type. The heating and cooling effects introduced by the bogies are eliminated, so heat storage losses are less. The rotary hearth has, however a more Burners complex design with an annular shape and revolving hearth.

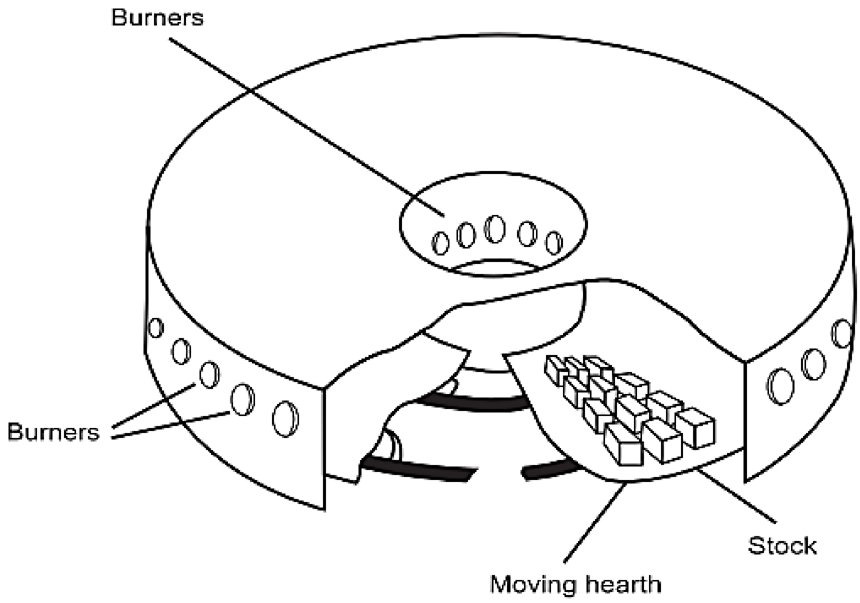


Figure 8.7 Rotary Hearth Furnace

iv. Continuous Recirculating Bogie type Furnaces

These types of moving hearth type furnaces tend to be used for compact stock of variable size and geometry. In bogie furnaces (Figure 8.8), the stock is placed on a bogie with a refractory hearth, which travels through the furnace with others in the form of a train. The entire furnace length is always occupied by bogies. Bogie furnaces tend to be long and narrow and to suffer from problems arising from inadequate sealing of the gap between the bogies and furnace shell, difficulties in removing scale, and difficulties in firing across a narrow hearth width.

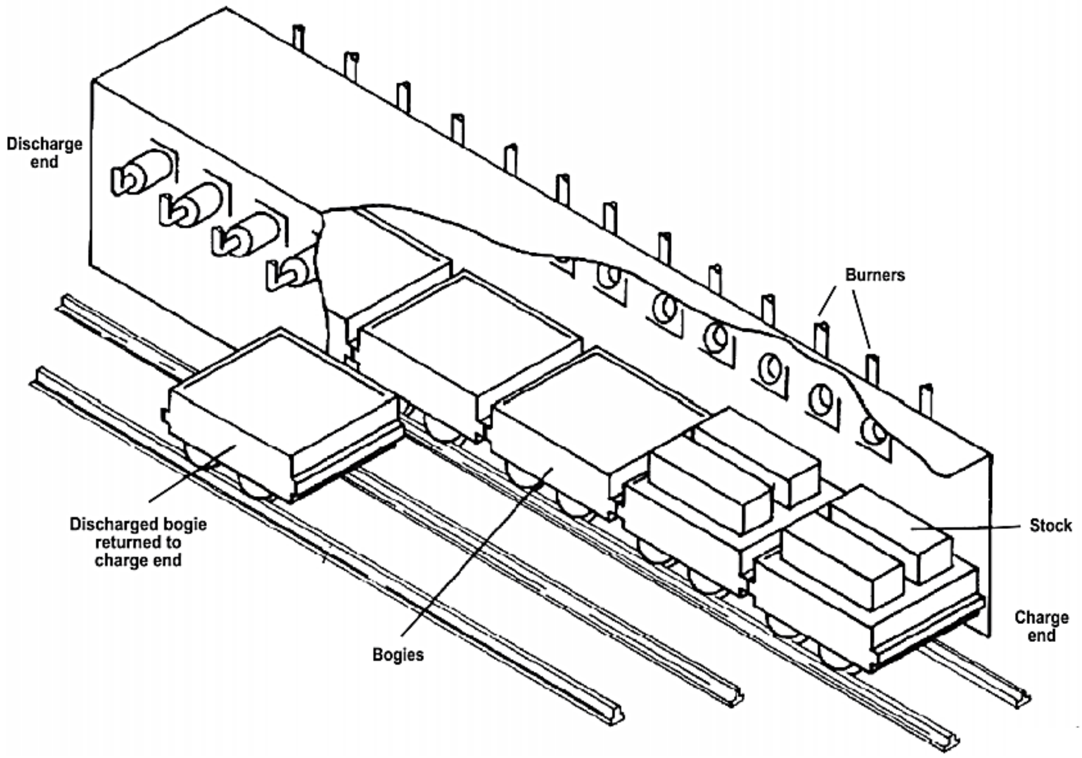


Figure 8.8 Continuous Circulating Bogie Type Furnace

v. Walking Beam Furnaces:

The walking beam furnace (Figure 8.9) overcomes many of the problems of pusher furnaces and permits heating of the bottom face of the stock. This allows shorter stock heating times and furnace lengths and thus better control of heating rates, uniform stock discharge temperatures and operational flexibility. In common with top and bottom fired pusher furnaces, however, much of the furnace is below the level of the mill; this may be a constraint in some applications.

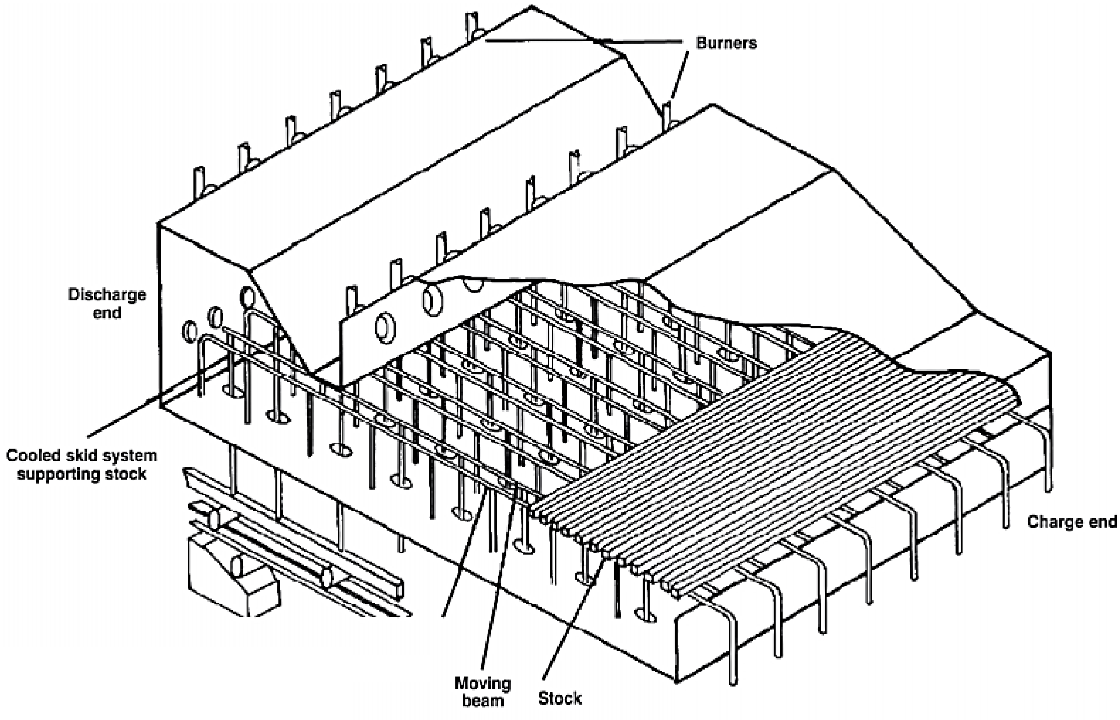


Figure 8.9 Walking Beam Furnace

vi. Cupola Furnace

A cupola furnace (Figure 8.10) is tall, cylindrical cast iron, foundry returns. The charge used in cupola furnace consists of alternate layers of coke, flux and metal (iron). These three components are continuously built into the cupola furnace. The most commonly used iron - to - coke ratio is 8:1. The flux may be limestone (CaCO3), fluorspar, sodium carbonate or calcium carbide. Limestone is the commonly employed flux. The total weight of the flux will be approximately 1/5th the weight of the coke charge. Sufficient air is passed through the tuyeres for proper combustion of coke.

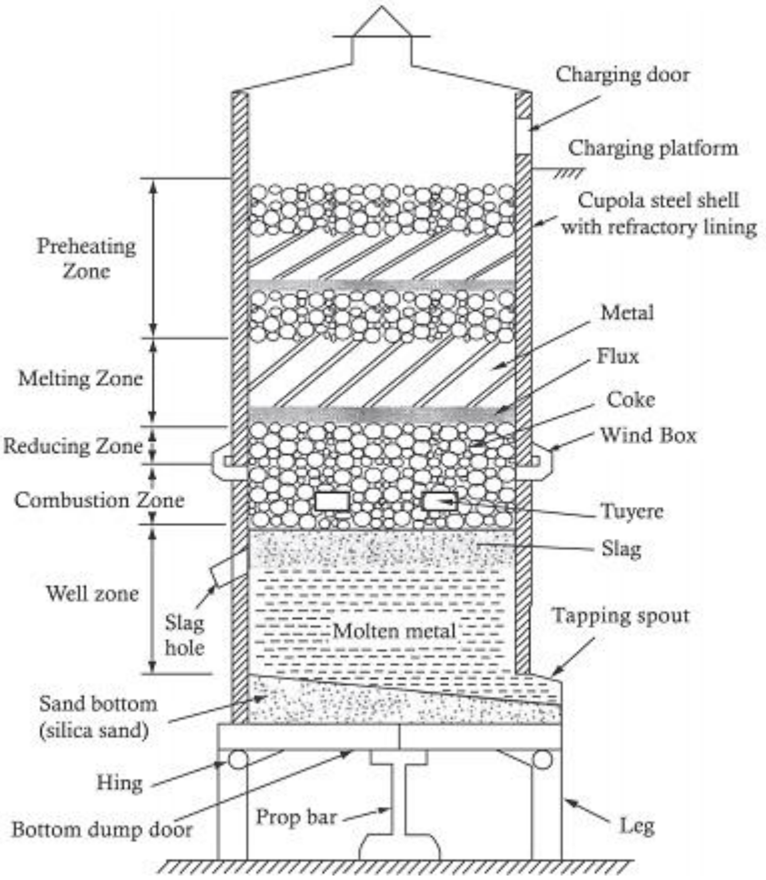


Figure 8.10 Induction Furnace

vii. Induction Furnaces

Induction furnaces are ideal for melting and alloying a wide variety of metals with minimum melt losses, however, little refining of the metal is possible. There are two main types of induction furnace: coreless and channel, the principle of operation of which are the same.

Coreless Induction Furnace

Coreless induction furnace (Figure 8.11) consists of: a water cooled helical coil made of a copper tube, a crucible installed within the coil and supporting shell equipped with trunnions on which the furnace may tilt. Alternating current passing through the coil induces alternating currents in the metal charge loaded to the crucible. These induced currents heat the charge.

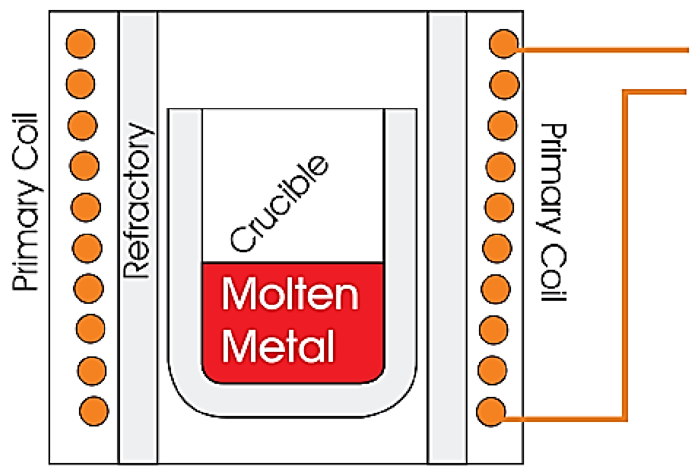


Figure 8.11 Induction Furnace

When the charge is molten, electromagnetic field produced by the coil interacts with the electromagnetic field produced by the induced current. The resulted force causes stirring effect helping homogenizing the melt composition and the temperature.

The frequency of the alternating current used in induction furnaces may vary from the line frequency (50 Hz or 60 Hz) to high frequency 10,000 Hz .

The total absolute energy required to melt one tonne of different metals at different molten temperature is given in table 8.1.

Table 8.1: Energy Required to Melt One Ton of Different Metals

Type of metal	Specific heat require	Latent heat require	Total require kWh/Ton
Mild steel @ 1650 °C Melting temp.	1000 x 0.682 x 1620 °C ÷ 3600 kWh ΔT = 1650°C-30°C Specific heat = 0.9 kJ/kg °C = 307 kWh	272 x 1000 ÷ 3600 kWh Latent Heat = 272 kJ/kg = 76 kWh	307 kWh + 76 kWh = 376 kWh
Aluminum @ 710 °C Melting temp.	1000 x 0.9 x 680 °C ÷ 3600 kWh ΔT= 710 °C-30 °C Specific heat = 0.9 kJ/kg °C = 170 kWh	396.9 x 1000 ÷ 3600 kWh Latent Heat = 396.9 kJ/kg = 110 kWh	170 kWh + 110 kWh = 180 kWh
Copper @ 1130 °C Melting temp.	1000 x 0.386 x 1100 °C ÷ 3600 kWh ΔT=1130 °C-30 °C Specific heat = 0.386 kJ/kg °C = 118 kWh	212 x 1000 ÷ 3600 kWh Latent Heat = 212 kJ/kg = 59 kWh	118 kWh + 59 kWh = 117 kWh
Gold @ 1130 °C Melting temp.	1000 x 0.131 x 1130°C ÷ 3600 kWh ΔT=1130 °C-30 °C Specific heat = 0.131 kJ/kg °C = 36.38 kWh	67.62 x 1000 ÷ 3600kWh Latent Heat = 67.62 kJ/kg = 18.78 kWh	36.38 kWh + 18.78 kWh = 56 kWh

Furnace Efficiency

$$Efficiency, \% = \frac{Theoretical\ total\ heat\ required\ for\ melting\ (H_T),\ kWh}{Actual\ Electricity\ consumed\ for\ melting\ (H_A),\ kWh} \times 100$$

Theoretical heat required for melting (H_T)

$$Heat\ required\ for\ melting\ metal, H_1, kWh = \frac{W_m \times \left(C_p \times (T_2 - T_1) + h\right)}{3600}$$

(3600 kJ = 1 kWh)

$$Heat\ required\ for\ melting\ slag, H_2, kWh = \frac{1.65 \times W_s}{3.6}$$

(3.6 MJ = 1 kWh)

Where,

W_m - Weight of the metal, kg
W_s - Weight of the slag, kg
C_p - Specific heat of metal, kJ/kg °C
T_2 - **Final temperature of the metal**
T_1 - Initial or charge temperature of the metal

Total theoretical heat required for melting, $H_T = H_1 + H_2$

Actual electricity consumed for melting (H_A)

The actual consumption of electricity for melting can be measured from the input busbar to the furnace. the difference between Actual and theoretical values will be loss due to conduction, radiation and other losses.

Example 8.1

Calculate the furnace efficiency from the data given below

Specific heat	- 0.682 kJ/kg ^{0}C
Latent heat	- 272 kJ/kg
Melting temperature	- 1650 ^{0}C

Charge temperature	- 30 ^{0}C
Quantity of metal	- 1000 kg
Quantity of slag	- 25 kg
Electricity consumed	- 625 kWh

Solution

$$Heat\ required\ for\ melting\ metal, H_1, kWh = \frac{1000\times(0.682\times(1650-30)+272)}{3600}$$
$$= 382.45\ \text{kWh}$$

$$Heat\ required\ for\ melting\ slag, H_2, kWh = \frac{1.65\times 25}{3.6}$$
$$= 11.45\ \text{kWh}$$

Total theoretical heat required for melting, $H_T = 382.45 + 11.45$
$= 394$ kWh

$$Efficiency, \% = \frac{394,\ kWh}{625,\ kWh}\times 100$$
$$= 63\ \%$$

8.8 Distribution of losses in induction furnace

Losses in induction furnace

The theoretical energy requires to melt one Ton of steel is 385 To 400 kWh/Ton. However, in actual practice, the specific energy consumption is remarkably higher to 550 - 950 kWh/ton.

1. Power loss in generator / panel = 2 - 4 %
2. Power loss in capacitor Bank = 1.0 - 3 %
3. Power loss in Crucible = 18 - 25 % (Water cooled cables, Bus bar, and change over switches)
4. Radiation loss = 7 - 9%

Factors affecting the furnace efficiency

The factors, which affect the furnace efficiency, are as under;

- Due to poor maintenance the total production stops sometimes. Higher breakdown results in increasing the' cost of production
- Due to low supply voltage the furnace draws less power, causes slow melting and inefficient operation resulting increase in production cost.
- Sometimes lining material selection is wrong with respect to metal. Basic lining is better conductor of heat compared to acidic lining. Wrong lining selection increases breakdown, Furnace down time and furnace losses, resulting in inefficient operation.
- Poor coordination between melting staff & contractor
- Absence of material handling equipment
- Poor moulding efficiency, so furnace on hold
- Poor quality scrap, reducing lining life, takes more time to melt.
- Absence of thermal insulation between lining & coil.

Hot Air Generator

Hot air at a wide range of temperatures and pressures is produced for applications like foundry sand drying, shell sand coating, core drying rooms or ovens, drying and processing of ores and minerals, food processing, tea drying, seed drying and paint drying. Furnace oil, HSD, LDO, LPG or natural gas may be used.

Hot air generators supply air heated to elevated temperature by mixing it with products of combustion from a burner. The hot air generator consists of an inner refractory chamber, venturi section where hot products of combustion mix with dilution air, and outlet section.

The combustion chamber is lined with firebrick, while the mixing chamber and the outlet section are lined with insulation brick. Air and oil pipelines required for combustion are included. The combustion equipment comprises of burner with burner block, mounting plate, isolating valve, and oil pumping and heating unit.

8.9 Performance Evaluation of a Fuel Fired Furnace

The fuel required for combustion is cleaned, preheated and burnt in the combustion zone of the furnace. Thermal efficiency of the furnaces is the ratio of heat delivered to a material stock and heat supplied to the heating equipment. The purpose of a heating process is to introduce a certain amount of thermal energy into a material stock / product, raising it to a certain temperature to prepare it for additional processing or change its properties.

This results in energy losses in different areas and forms as shown in Sankey diagram (Figure 4.2).

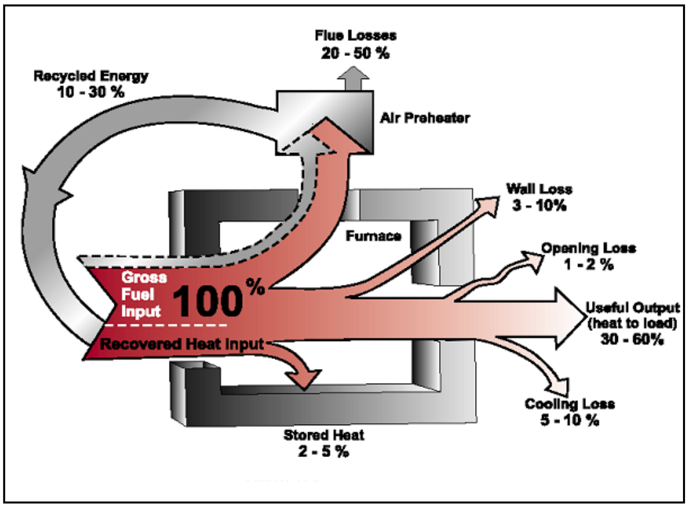


Figure 8.12 Fuel Fired Furnace

The major losses that occur in the fuel fired furnaces are listed below.

1. Heat lost through exhaust gases either as sensible heat or as incomplete combustion
2. Heat loss through furnace walls and hearth
3. Heat loss to the surroundings by radiation and convection from the outer surface of the walls
4. Heat loss through gases leaking through cracks, openings and doors.

Economy in fuel can be achieved if the total heat that can be passed on to the stock is as large as possible.

Furnace Efficiency

Thermal efficiency of a furnace is determined either by direct or indirect method of evaluation.

Direct method

The efficiency of furnace can be assessed by measuring the amount of heat added to the stock and the heat in the fuel consumed, on a batch/day basis as relevant.

$$\text{Thermal efficiency of the furnace} = \frac{\text{Heat in the stock}}{\text{Heat in the fuel consumed for heating the stock}} \times 100$$

The quantity of heat to be imparted (Q_s) to the stock can be found from the following relation;

$Q_s \quad = \quad m \times C_p \times (t_1 - t_2)$

where,

Q_s = Quantity of heat imparted to the stock in kCal
m = Weight of the stock in kg
C_p = Mean specific heat of stock in kCal/kg°C
t_1 = Final temperature of stock desired, °C
t_2 = Initial temperature of the stock before it enters the furnace, °C

Heat in fuel = Quantity of fuel (q) in kg/hX GCV in kCal/kg

Example 8.2

The following are the operating parameters of rerolling mill furnace

Weight of input material	- 10 T/hr
Furnace oil consumption	- 600 litres/hr
Specific gravity of oil	- 0.92
Final material temperature	- 1200 °C
Initial material temperature	- 40 °C
Outlet flue gas temperature	- 650 °C
Specific heat of the material	- 0.12 kcal/kg°C
GCV of oil	- 10,000 kCal/kg
Percentage yield	- 92 %

a. Calculate furnace efficiency by direct method
b. Calculate Specific fuel consumption on finished product basis

Solution

a) Furnace efficiency by direct method

Heat input 600 lit/hr x 0.92 x 10000 =55,20,000 kcal/hr
Heat output 10,000 x 0.12 x (1200 – 40) = 1,39,2000 kcal/hr

Efficiency	1,39,2000 /55,20,000 = 25.2 %

b) Specific fuel consumption on finished product basis

Weight of finished products	10 x 0.92 = 9.2 T/hr
Furnace oil consumption	600 litres/hr
Specific fuel consumption	600/9.2 = 65.2 litres/ton

Indirect Method

Similar to the method of evaluating boiler efficiency by indirect method, furnace efficiency can also be calculated by indirect methods. Furnace efficiency is calculated after subtracting sensible heat loss in flue gas, loss due to moisture in flue gas, heat loss due to openings in furnace, heat loss through furnace skin and other unaccounted losses.

In order to find out furnace efficiency using indirect method, various parameters that are required are hourly furnace oil consumption, material output, excess air quantity, temperature of flue gas, temperature of furnace at various zones, skin temperature and hot combustion air temperature. Instruments like infrared thermometer, fuel consumption monitor, surface thermocouple and other measuring devices are required to measure the above parameters.

Typical thermal efficiencies for common industrial furnaces are given in Table4.1.

Table 8.2: Thermal efficiencies for common industrial furnaces

Furnace Type	Typical thermal efficiency (%)
1) Low Temperature furnaces	
a. 540 – 980 ºC (Batch type)	20-30
b. 540 – 980 ºC (Continuous type)	15-25
c. Coil Anneal (Bell) radiant type	4-7
d. Strip Anneal Muffle	7-12
2) High temperature furnaces	
Slot forge	5-12
b. Pusher, Roll down or Rotary	7-14
c. Batch forge	5-10
d. Car Bottom	7-12
3) Continuous Kiln	
a. Hoffman	25-93
b. Tunnel	21-82
c. Transverse-arch Annular	26-96
4) Ovens	
a. Indirect fired ovens (20ºC-370ºC)	35-40
b. Direct fired ovens (20ºC-370ºC)	35-40

Energy Balance in a Typical Reheating Furnace

The heat inputs and outputs are calculated (as per JIS GO702)on the basis of per tonne of stock or product output and simplified.

Heat balance table

Heat Input			Heat output		
Item	kcal/t	%	Item	kcal/t	%
Combustion heat of fuel (Q_1)			Heat carried away by 1 tonne of billet (Q_3)		
Sensible heat of fuel (Q_2)			Heat loss in dry flue gas per tonne of billet (Q_4)		
			Heat loss due to formation of water vapour from fuel per tonne of billet (Q_5)		
			Heat loss due to moisture in combustion air (Q_6)		
			% Heat loss due to partial conversion of C to CO (Q_7)		
			Amount of heat loss from the furnace body and other sections (Q_8)		
			Radiation heat loss through furnace openings (Q_9)		
			Unaccounted losses (Q_{10})		
Total					

Efficiency of furnace (by direct method)

$$\eta_{furnace} = \frac{\text{Heat carried away by billet, kCal/hr}}{\text{Combustion heat of fuel, kCal/hr}} \times 100$$

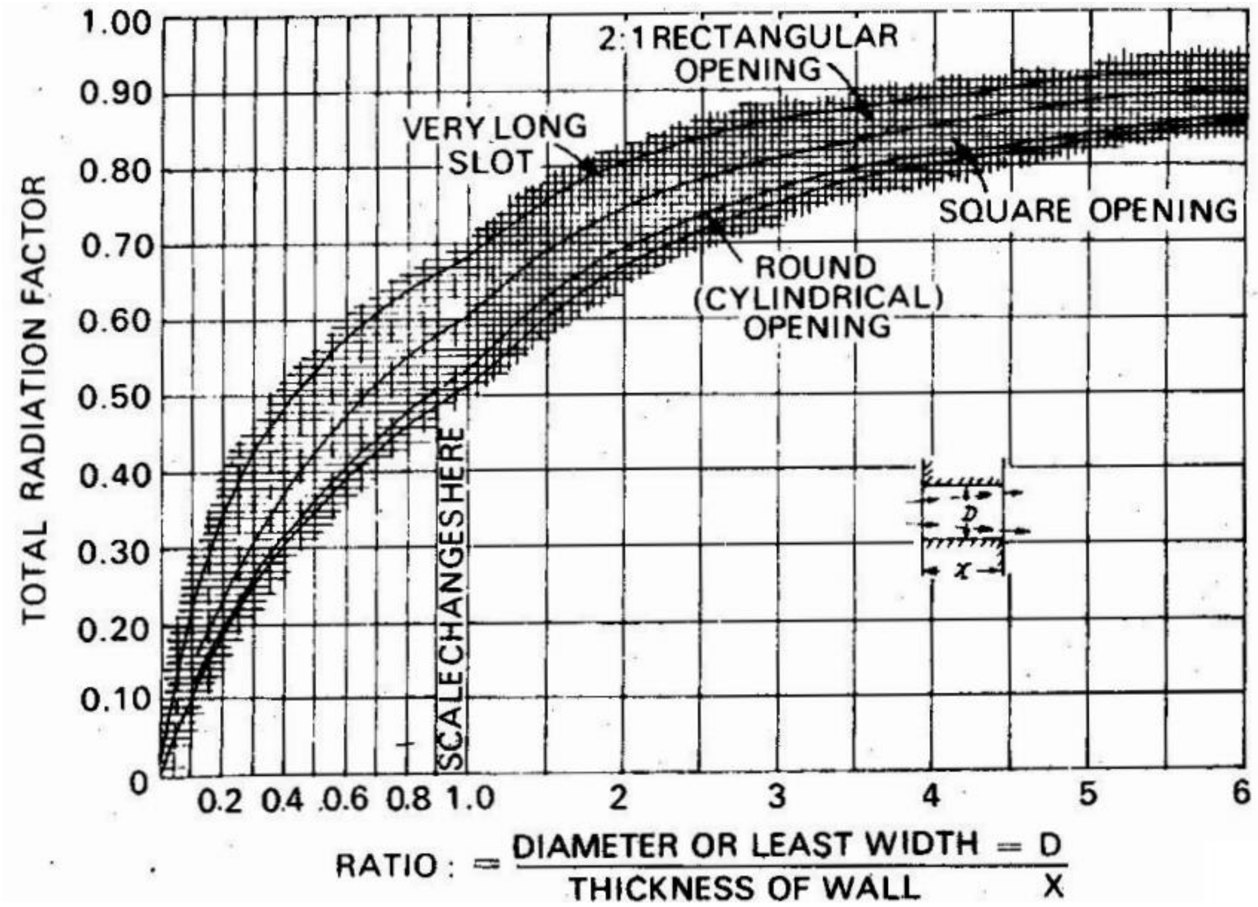


Figure 8.13: Factor for determining the equivalent of heat release from openings to the quality of heat release from perfect black body

The instruments required for carrying out performance evaluation in a furnace is given in the Table 8.2.

Table 8.3 Furnace Instrumentation

Sl. No.	Measuring Parameters	Location of Measurement	Instrument Required	Required Value
1.	Furnace soaking zone temperature (reheating furnaces)	Soaking zone side wall	Pt/Pt-Rh thermocouple with indicator and recorder	1200-1300°C
2.	Flue gas	Flue gas exit from furnace and entry to recuperator	Chromel Alummel Thermocouple with indicator	700°C max.
3.	Flue gas	After recuperator	Hg in steel thermometer	300°C (max)
4.	Furnace hearth pressure in the heating zone	Near charging end side wall over hearth level	Low pressure ring gauge	+0.1 mm of Wg
5.	Flue gas analyser	Near charging end side wall	Fuel efficiency monitor for oxygen & temperature.	O_2% = 5 t = 700°C (max)
6.	Billet temperature	Portable	Infrared Pyrometer or optical pyrometer	----

8.10 General Fuel Economy Measures in Furnaces

Typical energy efficiency measures for an industry with furnace are:

a) Complete combustion with minimum excess air
b) Correct heat distribution
c) Operating at the desired temperature
d) Reducing heat losses from furnace openings
e) Maintaining correct amount of furnace draught
f) Optimum capacity utilization
g) Waste heat recovery from the flue gases
h) Minimum refractory losses
i) Use of Ceramic Coatings

a) Complete Combustion with Minimum Excess Air:

The amount of heat lost in the flue gases (stack losses) depends upon amount of excess air. In the case of a furnace carrying away flue gases at 900ºC, % heat lost is shown in table 8.3.

Table 8.3: Heat Loss in Flue Gas Based on Excess Air Level

Excess Air	% of total heat in the fuel carried away by waste gases (flue gas temp. 900 ºC)
25	48
50	55
75	63
100	71

To obtain complete combustion of fuel with the minimum amount of air, it is necessary to control air infiltration, maintain pressure of combustion air, fuel quality and excess air monitoring.

Higher excess air will reduce flame temperature, furnace temperature and heating rate. On the other hand, if the excess air is less, then unburnt components in flue gases will increase and would be carried away in the flue gases through stack. The figure 8.14 also indicates relation between air ratio and exhaust gas loss.

The optimization of combustion air is the most attractive and economical measure for energy conservation. The impact of this measure is higher when the temperature of furnace is high. Air ratio is the value that is given by dividing the actual air amount by the theoretical combustion air amount, and it represents the extent of excess of air.

If a reheating furnace is not equipped with an automatic air/fuel ratio controller, it is necessary to periodically sample gas in the furnace and measure its oxygen contents by a gas analyzer. The Figure 8.15 shows a typical example of a reheating furnace equipped with an automatic air/fuel ratio controller.

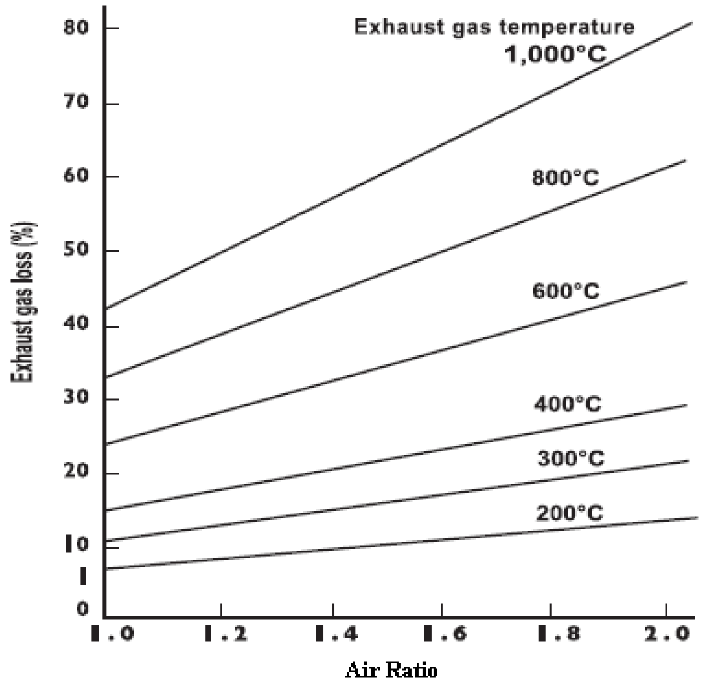


Figure 8.14: Relation between air ratio and exhaust gas loss

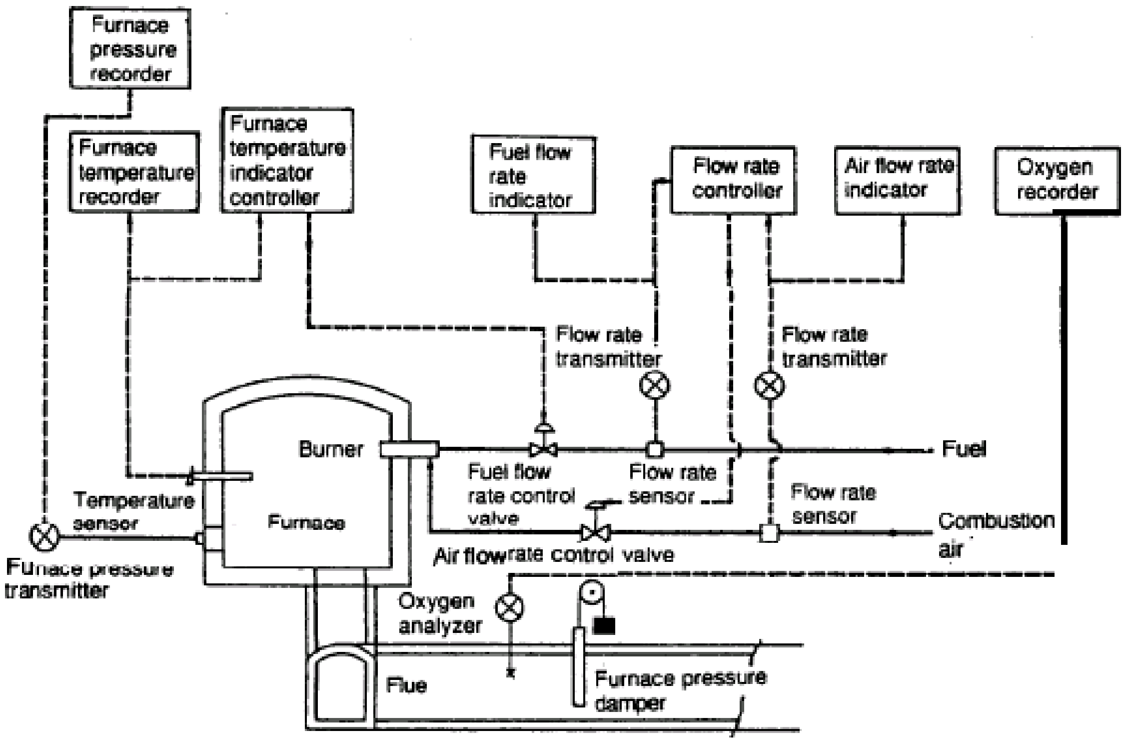


Figure 8.15: Air/fuel ratio control system with flow rate controller

More excess air also means more scale losses, which is equally a big loss in terms of money.

b) Proper Heat Distribution:

Furnace design should be such that in a given time, as much of the stock could be heated uniformly to a desired temperature with minimum fuel firing rate.

Following care should be taken when using burners, for proper heat distribution:

i. The flame should not touch any solid object and should propagate clear of any solid object. Any obstruction will de atomise the fuel particles thus affecting combustion and create black smoke. If flame impinges on the stock, there would be increase in scale losses (Refer Figures 8.16 and 8.17).

ii. If the flames impinge on refractories, the incomplete combustion products can settle and react with the refractory constituents at high flame temperatures.

iii. The flames of different burners in the furnace should stay clear of each other. If they intersect, inefficient combustion would occur. It is desirable to stagger the burners on the opposite sides.

iv. The burner flame has a tendency to travel freely in the combustion space just above the material. In small furnaces, the axis of the burner is never placed parallel to the hearth but always at an upward angle. Flame should not hit the roof.

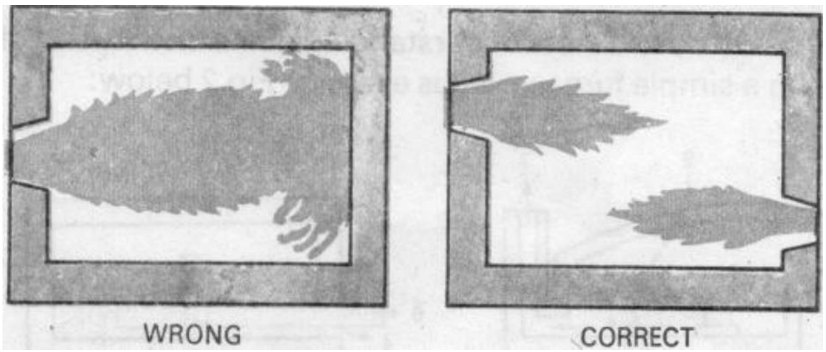


Figure 8.16: Heat Distribution in Furnace

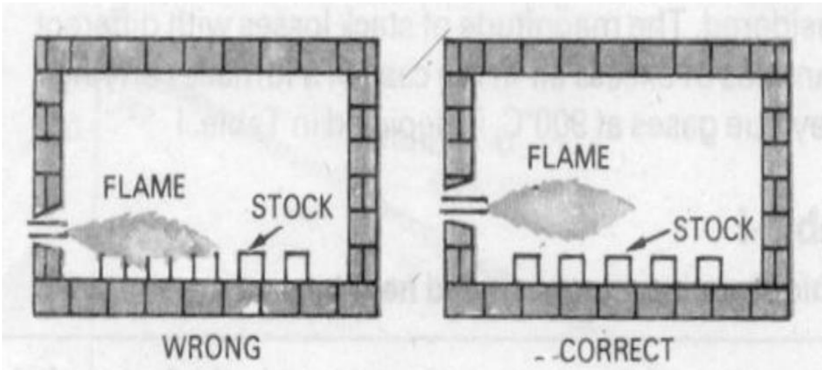


Figure 8.17: Alignment of Burners in Furnace

v. The larger burners produce a long flame, which may be difficult to contain within the furnace walls. More burners of less capacity give better heat distribution in the furnace and also increase furnace life.

vi. For small furnaces, it is desirable to have a long flame with golden yellow colour while firing furnace oil for uniform heating. The flame should not be too long that it enters the chimney or comes out through the furnace top or through doors. In such cases, major portion of additional fuel is carried away from the furnace.

c) Maintaining Optimum Operating Temperature of Furnace:

It is important to operate the furnace at optimum temperature. The operating temperatures of various furnaces are given in table 8.4.

Table 8.4 Operating Temperature of Various Furnaces

Slab Reheating furnaces	1200 ºC
Rolling Mill furnaces	1200 ºC
Bar furnace for Sheet Mill	800 ºC
Bogey type annealing furnaces	650 ºC -750 ºC

Operating at too high temperatures than optimum causes heat loss, excessive oxidation, de-carbonization as well as over-stressing of the refractories. These controls are normally left to operator judgment, which is not desirable. To avoid human error, on/off controls should be provided.

d) Prevention of Heat Loss through Openings:

Heat loss through openings consists of the heat loss by direct radiation through openings and the heat loss caused by combustion gas that leaks through openings.

The heat loss from an opening can also be calculated using the following formula:

$$Q = 4.88 x \left(\frac{T}{100}\right)^4 x a x A x H$$

where,

T: absolute temperature (K)
a: factor for total radiation
A: area of opening, m^2
H: time (Hr)

This is explained by an example as follows.

Example 8.3

A reheating furnace with walls 460 mm thick (X) has a billet extraction outlet, which is 1 m high (D)and 1 m wide. When the furnace temperature is 1,340°C the quantity (Q) of radiation heat loss from this opening is evaluated as follows.
The shape of opening is square, and D/X = l/O.46 = 2.17. Thus, the factor for total radiation is 0.71 (refer Figure 4.13) and we get,

$Q=4.88x((1340+273)/100)^4x0.71x1= 234,500$ kcal/hr.

If the furnace pressure is slightly higher than outside air pressure (as in case of reheating furnace) during its operation, the combustion gas inside may blow off through openings and heat is lost with that. But damage is more, if outside air intrudes into the furnace, making temperature distribution uneven and oxidizing billets. This heat loss is about 1% of the total quantity of heat generated in the furnace, if furnace pressure is controlled properly.

e) Control of furnace draft:

If negative pressures exist in the furnace, air infiltration is liable to occur through the cracks and openings thereby affecting air-fuel ratio control. Tests conducted on apparently airtight furnaces have shown air infiltration up to the extent of 40%.

Neglecting furnaces pressure could mean problems of cold metal and non-uniform metal temperatures, which could affect subsequent operations like forging and rolling and result in increased fuel consumption. For optimum fuel consumption, slight positive pressure should be maintained in the furnace as shown in Figure 8.18.

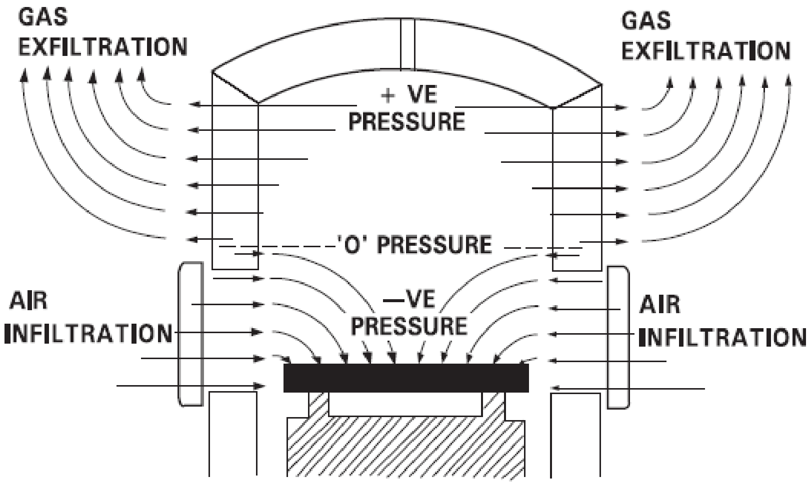


Figure 8.18: Effect of pressure on the location of zero level and infiltration of air

Ex-filtration is less serious than infiltration. Some of the associated problems with ex filtration are leaping out of flames, overheating of the furnace refractories leading to reduced brick life, increased furnace maintenance, burning out of ducts and equipment attached to the furnace, etc.

In addition to the proper control on furnace pressure, it is important to keep the openings as small as possible and to seal them in order to prevent the release of high temperature gas and intrusion of outside air through openings such as the charging inlet, extracting outlet and peephole on furnace walls or the ceiling.

f) Optimum Capacity Utilization:

One of the most vital factors affecting efficiency is loading. There is a particular loading at which the furnace will operate at maximum thermal efficiency. If the furnace is under loaded a smaller fraction of the available heat in the working chamber will be taken up by the load and therefore efficiency will be low.

The best method of loading is generally obtained by trial-noting the weight of material put in at each charge, the time it takes to reach temperature and the amount of fuel used. Every endeavour should be made to load a furnace at the rate associated with optimum efficiency although it must be realised that `limitations to achieving this are sometimes imposed by work availability or other factors beyond control.

The loading of the charge on the furnace hearth should be arranged so that,

- It receives the maximum amount of radiation from the hot surfaces of the heating chambers and the flames produced.
- The hot gases are efficiently circulated around the heat receiving surfaces

Stock should not be placed in the following position

- In the direct path of the burners or where impingement of flame is likely to occur.
- In an area which is likely to cause a blockage or restriction of the flue system of the furnace.
- Close to any door openings where cold spots are likely to develop.

The other reason for not operating the furnace at optimum loading is the mismatching of furnace dimension with respect to charge and production schedule.
In the interests of economy and work quality the materials comprising the load should only remain in the furnace for the minimum time to obtain the required physical and metallurgical requirements. When the materials attain these properties they should be removed from the furnace to avoid damage and fuel wastage. The higher the working temperature, higher is the loss per unit time. The effect on the materials by excessive residence time will be an increase in surface defects due to oxidation. The rate of oxidation is dependent upon time, temperature, as well as free oxygen content. The possible increase in surface defects can lead to rejection of the product. It is therefore essential that coordination between the furnace operator, production and planning personnel be maintained.

Optimum utilization of furnace can be planned at design stage. Correct furnace for the jobs should be selected considering whether continuous or batch type furnace would be more suitable. For a continuous type furnace, the overall efficiency will increase with heat recuperation from the waste gas stream. If only batch type furnace is used, careful planning of the loads is important. Furnace should be recharged as soon as possible to enable use of residual furnace heat.

g) Waste Heat Recovery from Furnace Flue Gases:

In any industrial furnace the products of combustion leave the furnace at a temperature higher than the stock temperature. Sensible heat losses in the flue gases, while leaving the chimney, carry 35 to 55 percent of the heat input to the furnace. The higher the quantum of excess air and flue gas temperature, the higher would be the waste heat availability.

Waste heat recovery should be considered after all other energy conservation measures have been taken. Minimizing the generation of waste heat should be the primary objective.

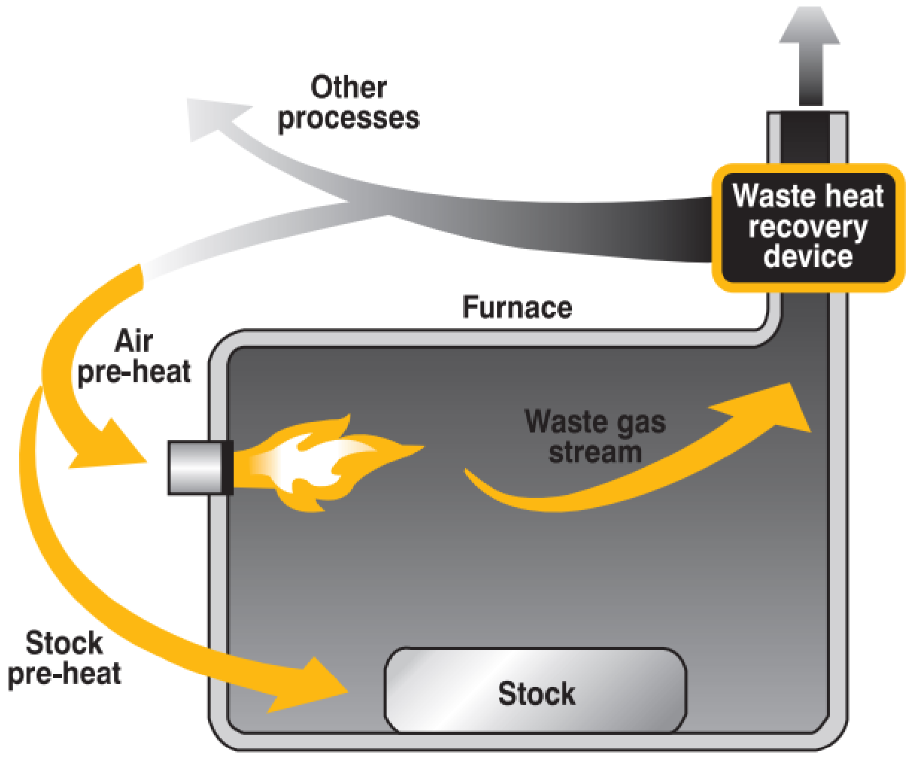


Figure 8.19: Waste Heat Recovery

The sensible heat in flue gases can be generally salvaged by the following methods:

- Charge preheating
- Preheating of combustion air
- Utilizing waste heat for other process (to generate steam or hot water by a waste heat boiler)

Charge Pre-heating

When raw materials are preheated by exhaust gases before being placed in a heating furnace, the amount of fuel necessary to heat them in the furnace is reduced. Since raw materials are usually at room temperature, they can be heated sufficiently using high-temperature gas to reduce fuel consumption rate.

Preheating of Combustion Air

For a long time, the preheating of combustion air using heat from exhaust gas was not used except for large boilers, metal-heating furnaces and high-temperature kilns. This method is now being employed in compact boilers and compact industrial furnaces as well. (Refer Figure 8.20).
A recuperator is a device that recovers heat from exhaust gas exhausted from a furnace. A metallic recuperator has heat transfer surface made of metal, and a ceramic recuperator has heat transfer surface made of ceramics. When the exhaust gas temperature is lower than1,000°C and air for combustion is preheated, a metallic recuperator is used in general.

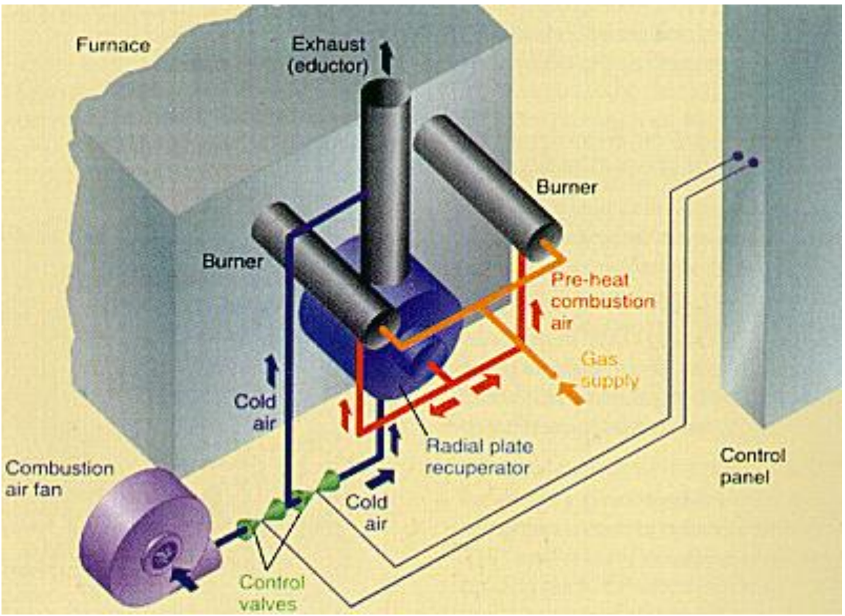


Figure 8.20: Preheating the air for combustion by a recuperator

External Recuperators

There are two main types of external recuperators:

✓ radiation recuperators;
✓ convection recuperators

Radiation recuperators generally take the form of concentric cylinders, in which the combustion air passes through the annulus and the exhaust gases from the furnace pass through the centre, see Figure 8.21 (a). The simple construction means that such recuperators are suitable for use with dirty gases, have a negligible resistance to flow, and can replace the flue or chimney if space is limited. The annulus can be replaced by a ring of vertical tubes, but this design is more difficult to install and maintain. Radiation recuperators rely on radiation from high temperature exhaust gases and should not he employed with exhaust gases at less than about 800°C.

Convection recuperators consist essentially of bundles of drawn or cast tubes; see Figure 8.21 (b). Internal and/or external fins can be added to assist heat transfer. The combustion air normally passes through the tubes and the exhaust gases outside the tubes, but there are some applications where this is reversed. For example, with dirty gases, it is easier to keep the tubes clean if the air flows on the outside. Design variations include 'IP tube and double pass systems. Convection recuperators are more suitable for exhaust gas temperatures of less than about 900°C.

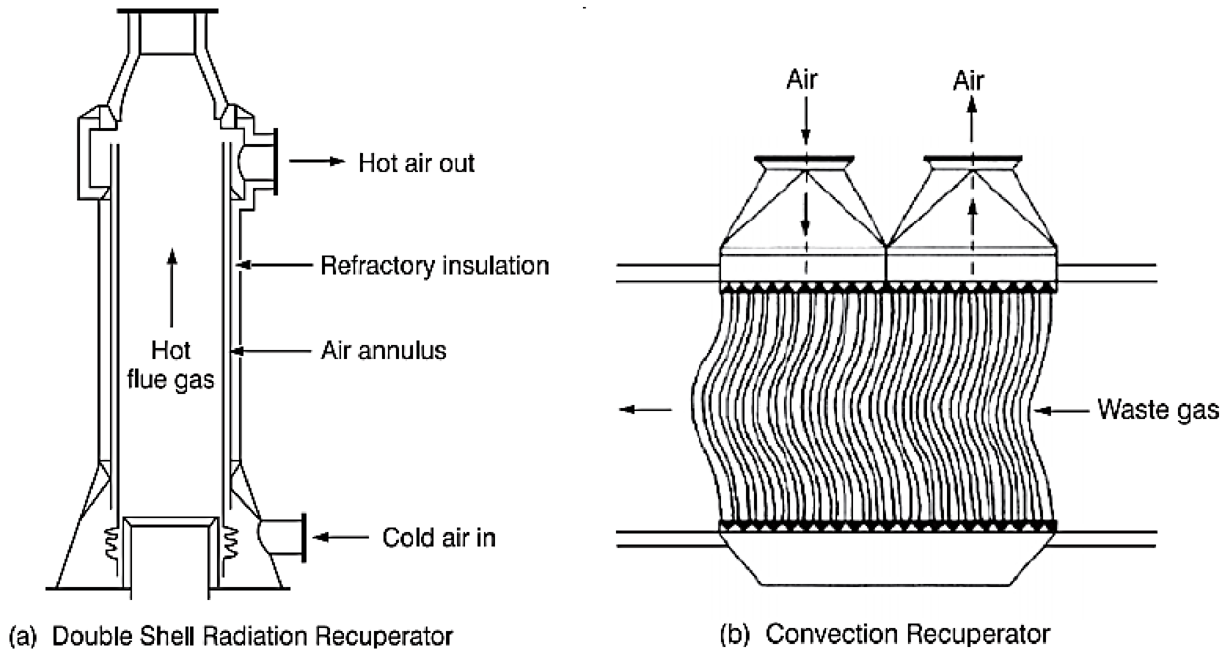


Figure 8.21: Metallic Recuperators

Self-Recuperative Burners

Self-recuperative burners (SRBs) are based on traditional heat recovery techniques in that the products of combustion are drawn through a concentric tube recuperator around the burner body and used to pre-heat the combustion air (Figure 8.22)

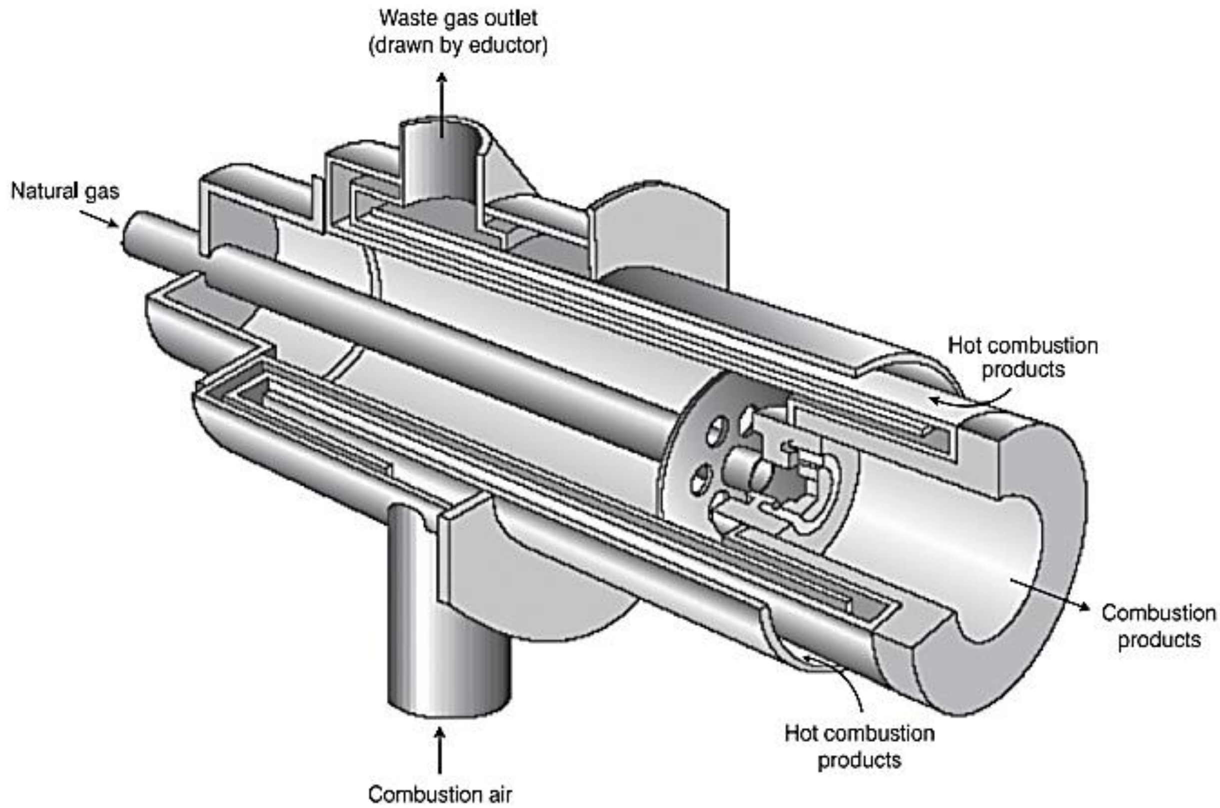


Figure 4.22: Self-Recuperative Burners

A major advantage of this type of system is that it can be retro-fitted to an existing furnace structure to increase production capability without having to alter the existing exhaust gas ducting arrangements. SRBs are generally more suited to heat treatment furnaces where exhaust gas temperatures are lower and there are no stock recuperation facilities.

Estimation of fuel savings

By using preheated air for combustion, fuel can be saved. The fuel saving rate is given by the following formula:

$$S = \frac{P}{F + P - Q} x100(\%)$$

Where,

S: Fuel saving rate
F: Calorific value of fuel (kcal/kgfuel)
P: Quantity of heat brought in by preheated air (kcal/kgfuel)
Q: Quantity of heat taken away by exhaust gas (kcal/kgfuel)

By this formula, fuel saving rates for heavy oil and natural gas were calculated for various temperatures of exhaust gas and preheated air. The results are shown in the following Figure 8.23 and Figure 8.24.

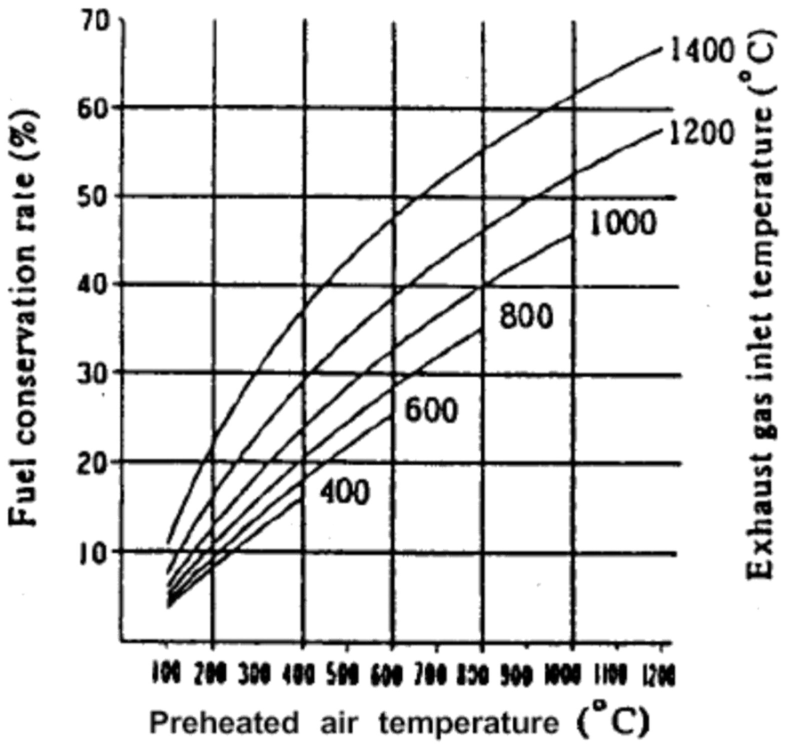


Figure 8.23: Fuel conservation rate when oil is used

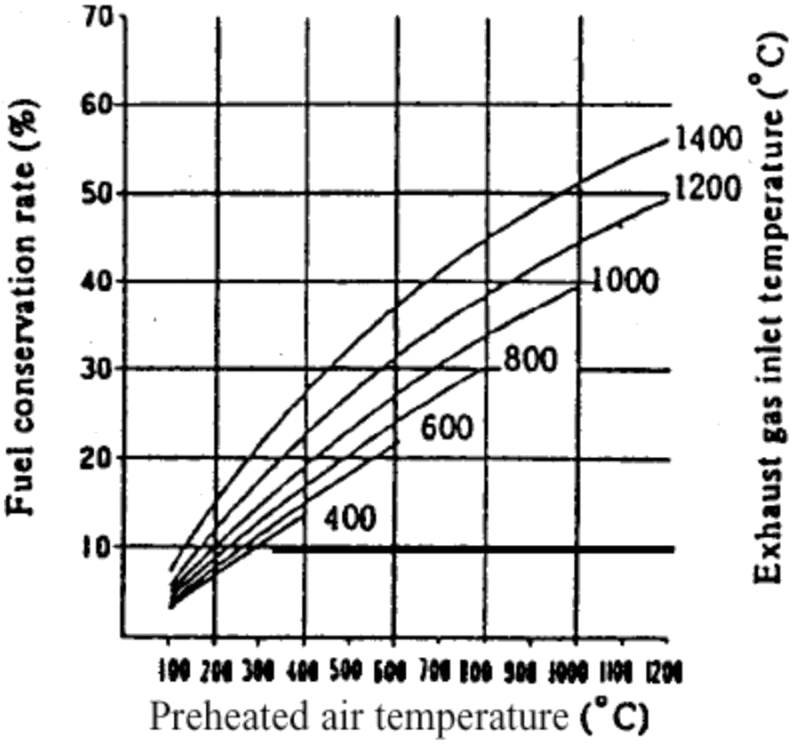


Figure 8.24: Fuel conservation rate when natural gas is used

For example, when combustion air for heavy oil is preheated to 400°C by a heat exchanger with an inlet temperature of 800°C, the fuel conservation rate is estimated to be about 20 percent. When installing a recuperator in a continuous steel reheating furnace, it is important to choose a preheated air temperature that will balance the fuel saving effect and the invested cost for the equipment.
Also, the following points should be checked:

- Draft of exhaust gas: When exhaust gas goes through a recuperator, its draft resistance usually causes a pressure loss of 5-10 mm H_2O. Thus, the draft of stack should be checked.
- Air blower for combustion air: While the air for combustion goes through a recuperator, usually 100-200 mm H_2O pressure is lost. Thus, the discharge pressure of air blower should be checked, and the necessary pressure should be provided by burners.

Since the volume of air is increased owing to its preheating, it is necessary to be careful about the modification of air-duct diameters and blowers. As for the use of combustion gases resulting from high-density oils with a high sulphur content, care must be taken to avoid problems such as clogging with dust or sulphides, corrosion or increases in nitrogen oxides.

Table 4.5 gives details of various air preheaters. In addition, heat-pipe-type heat exchangers and high temperature gas or gas-plate heat exchangers can serve as air preheaters.

Table 8.5: Details of air preheaters

Type	Exhaust Gas Temperature, ^0C	Preheated Air Temperature, ^0C	Object Furnace

Recuperative	Metallic recuperator	Flue installation	Convective: multitubular, other	1000 or below	300 – 600	Heating furnace, heat treatment furnace and other industrial furnaces
		Chimney installation	Radiative and convective	1000 – 1300	-do-	-do-
	Ceramic (tile) recuperator			1200 – 1400	400 – 700	Soaking pit and glass
Regenerative	General			1000 – 1600	600 – 1300	Coke oven, hot blast stove & glass kiln
	Rotary regenerative			600	100 - 300	Boiler, hot blast stove

a. Utilizing Waste Heat as a Heat Source for Other Processes

The temperature of heating-furnace exhaust gas can be as high as 400 –600°C, even after heath has been recovered from it.

When a large amount of steam or hot water is needed in a plant, installing a waste heat boiler to produce the steam or hot water using the exhaust gas heat is preferred. If the exhaust gas heat is suitable for equipment in terms of heat quantity, temperature range, operation time etc., the fuel consumption can be greatly reduced. In one case, exhaust gas from a quenching furnace was used as a heat source in a tempering furnace so as to obviate the need to use fuel for the tempering furnace itself.

h) Minimizing Wall Losses

About 30-40% of the fuel input to the furnace generally goes to make up for heat losses in intermittent or continuous furnaces. The appropriate choice of refractory and insulation materials goes a long way in achieving fairly high fuel savings in industrial furnaces.

The heat losses from furnace walls affect the fuel economy considerably. The extent of wall losses depends on:

- Emissivity of wall
- Thermal conductivity of refractories
- Wall thickness
- Whether furnace is operated continuously or intermittently

Heat losses can be reduced by increasing the wall thickness, or through the application of insulating bricks. Outside wall temperatures and heat losses of a composite wall of a certain thickness of fire brick and insulation brick are much lower, due to lesser conductivity of insulating brick as compared to a refractory brick of similar thickness. In the actual operation in most of the small furnaces the operating periods alternate with the idle periods. During the off period, the heat stored in the refractories during the on period is gradually dissipated, mainly through radiation and convection from the cold face. In addition, some heat is abstracted by air flowing through the furnace. Dissipation of stored heat is a loss, because the lost heat is again imparted to the refractories during the heat "on" period, thus consuming extra fuel to generate that heat. If a furnace is operated 24 hours, every third day, practically all the heat stored in the refractories is lost. But if the furnace is operated 8 hours per day all the heat stored in the refractories is not dissipated. For a furnace with a fire brick wall of 350mm thickness, it is estimated that 55percent of the heats to red in the refractories is dissipated from the cold surface during the 16 hours idle period. Furnace walls built of insulating refractories and cased in a shell reduce the flow of heat to the surroundings.

Prevention of Radiation Heat Loss from Surface of Furnace

The quantity of heat release from surface of furnace body is the sum of natural convection and thermal radiation. This quantity can be calculated from surface temperatures of furnace. The temperatures on furnace surface should be measured at as many points as possible, and their average should be used. If the number of measuring points is too small, the error becomes large.

The quantity (Q)of heat release from are heating furnace is calculated with the following formula:

$$Q = a \text{ x } (t_1 - t_2)^{5/4} + 4.88 \text{ E x} \left(\left(\frac{t_1 + 273}{100} \right)^4 - \left(\frac{t_2 + 273}{100} \right)^4 \right)$$

Where,

Q : Quantity of heat released (kcal/hr/m^2)
a : Factor regarding direction of the surface of natural convection ceiling = 2.8, side walls = 2.2, hearth = 1.5
t_1 : Temperature of external wall surface of the furnace (°C)
t_2 : Temperature of air around the furnace (°C)
E : Emissivity of external wall surface of the furnace

The first term of the formula above represents the quantity of heat release by natural convection, and the second term represents the quantity of heat release by radiation. The following Figure 8.25 shows the relation between the temperature of external wall surface and the quantity of heat release calculated with this formula.

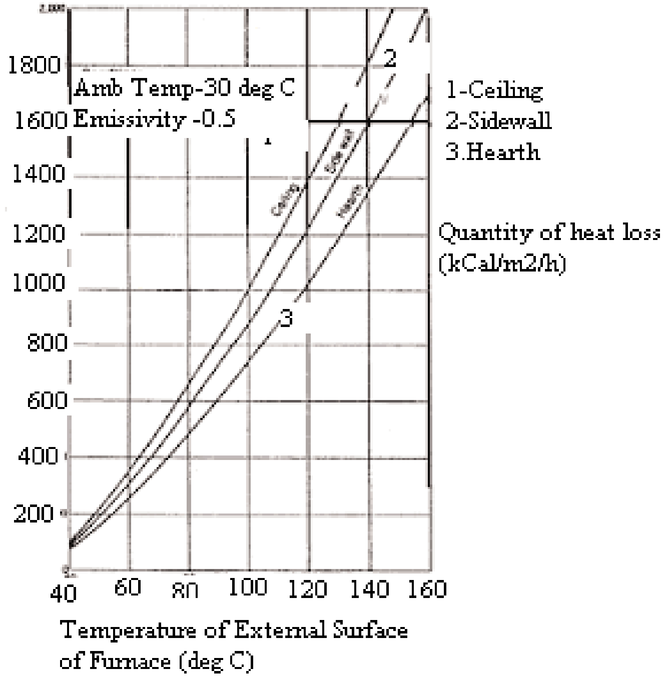


Figure 8.25: Quantity of heat release at various temperature

This is explained with an example as follows:

Example 8.4

There is a reheating furnace whose ceiling, side walls and hearth has 20 m^2, 50 m^2, and 20 m^2 of surface area respectively. Their surface temperatures are measured and the averages are 80ºC, 90ºC and 100ºC respectively. Evaluate the quantity of heat release from the whole surface of the furnace.

From the above figure 4.25, the quantities of heat release from ceiling, side walls and hearth per unit area are respectively 650 kcal/m^2h, 720 kcal/m^2h, and 730 kcal/m^2h.

Therefore, the total quantity of heat release is,
Q = (650x20) + (720x50) + (730x20) = 13000 + 36000 +14600= 63,600kcal/hr.

Use of Ceramic Fiber

Ceramic fibre is a low thermal mass refractory used in the hot face of the furnace and fastened to the refractory walls. Due to its low thermal mass the storage losses are minimized. This results in faster heating up of furnace and also faster cooling. Energy savings by this application is possible only in intermittent furnaces.

i) Use of Ceramic Coatings

Ceramic coatings in furnace chamber promote rapid and efficient transfer of heat, uniform heating and extended life of refractories. The emissivity of conventional refractories decreases with increase in temperature whereas for ceramic coatings it increases. This outstanding property has been exploited for use in hot face insulation.

Ceramic coatings are high emissivity coatings which when applied has a long life at temperatures up to 1350ºC. The coatings fall into two general categories-those used for coating metal substrates, and those used for coating refractory substrates. The coatings are non-toxic, non-flammable and water based. Applied at room temperatures, they are sprayed and air dried in less than five minutes. The coatings allow the substrate to maintain its designed metallurgical properties and mechanical strength. Installation is quick and can be completed during shut down. Energy savings of the order of 8-20% have been reported depending on the type of furnace and operating conditions.

Fish Bone Diagram for Energy Conservation Analysis in Furnaces

All the possible measures discussed can be incorporated in furnace design and operation. The figure 8.26 shows characteristics diagram of energy conservation for a fuel-fired furnace.

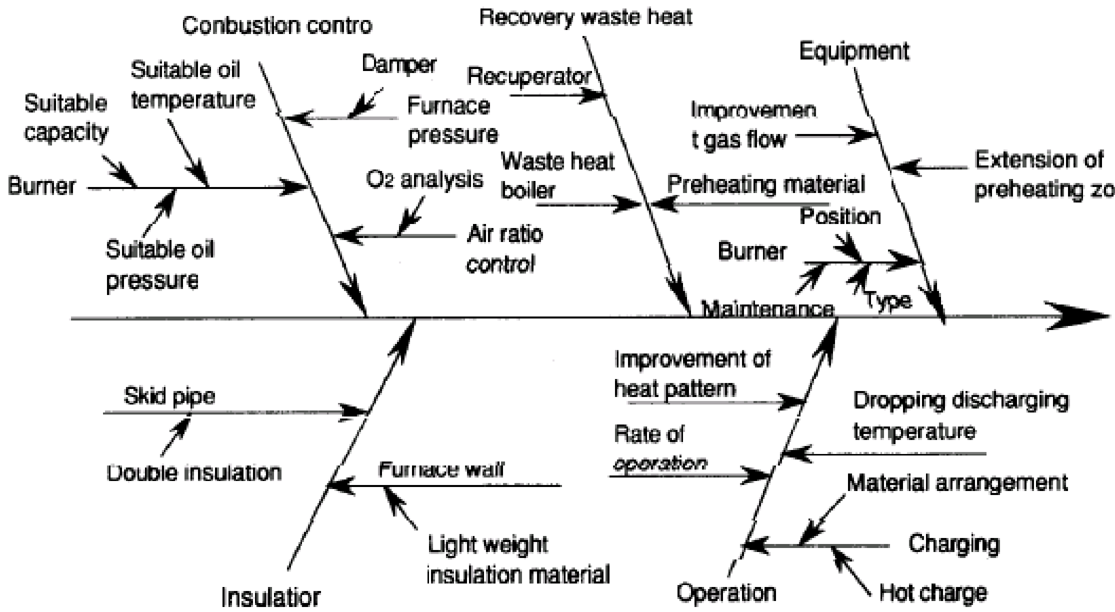


Figure 8.26 Characteristic Diagram of Energy Conservation for Reheating Furnace

8.11 Case Study

In are rolling mill, following energy conservation measures have been implemented and savings achieved are explained below:

Saving by Installing a Recuperator

This plant had a continuous pusher type billet reheating furnace. The furnace consists of two burners at the heating zone. The furnace is having a length of 40 ft. Annual furnace oil consumption is 620 KL. The furnace did not have any waste heat recovery device. The flue gas temperature is found to be 650 ^{0}C. To tap this potential heat, the unit has installed a recuperator device. It was possible to preheat the combustion air to 325 ^{0}C. By resorting to this measure, there was 15% fuel saving which is 93 KL of oil per annum.

During start up the furnace is already filled up with billets of previous day and has a temperature of about 700oC. During initial starting of furnace only the billets in the soaking zone are heated up as there is no movement of billets. Further the flow of heat is from soaking zone to heating zone. Therefore, during starting the soaking zone burners are switched on first and heating zone burners are started only after the mill starts operating.

Similarly, prior to mill stoppage billets lying in soaking zone have already attained re-rolling temperature and the incoming billets from heating zone will not be rolled and hence there is no need to heat those billets. As a result the burners in heating zone are stopped at least 30 to 60 minutes before the stoppage of mill.

The company has saved about 32.4 kL of furnace oil per annum.

b.

Calculations:

a. During Starting:

Savings by operating 2 nos. of LAP 4 A Wesman burners
30 minutes after starting up = 54 litres

b. During Shutdown:

Savings by switching off 2 Nos. of LAP Wesman burners
Before 30 minutes of furnace shut down = 54 litres

Total savings per day = 108 litres

Annual Savings = 32.4 KL

Example 8.5

Calculate the induction melting furnace efficiency from the following melt cycle data

Mild steel (MS) scrap charged : 1500 kg
Specific heat of MS : 0.682 kJ/kg ^{0}C
Latent heat of MS : 272 kJ/kg
MS melting temperature : 1650 ^{0}C
Inlet MS charge temperature : 40 ^{0}C
Electricity consumed during cycle : 1020 kWh

Solution

Theoretical energy required for melting = 1500 (0.682 x (1650 – 40) + 272)/3600 kWh
= 570.8 kWh

Actual input = 1020 kWh

Furnace efficiency = 570.8 x 100 / 1020
= 56%

Example 8.6

In a crude distillation unit of a refinery, furnace is operated to heat 500 m^3/hr of crude oil from 255°C to 360°C by firing 3.4 tons/hr of fuel oil having GCV of 9850 kcal/kg. As an energy conservation measure, the management has installed an air pre heater (APH) to reduce the flue gas heat loss. The APH is designed to pre-heat 57 tonnes/hr of combustion air to 195°C.

Calculate the efficiency of the furnace before & after the installation of APH.

Consider the following data:

- Specific heat of crude oil = 0.6 kcal/kg°C
- Specific heat of air = 0.24 kcal/kg°C
- Specific gravity of Crude oil = 0.85
- Ambient temperature = 28°C.

Solution

Before the installation of APH

Heat gain by the crude = 500 x 1000 x 0.85 x 0.6 x (360-255)
= 26775000 kCal/hr

Heat input to the furnace = 3.4 x1000x 9850
= 33490000 kCal/hr

Efficiency of the furnace = 26775000 / 33490000
= 80 %

After the installation of APH

Heat gain by the crude = 500 x 1000 x 0.85 x 0.6 x (360-255)
= 26775000 kCal/hr

Heat gain by Air-preheater = 57 x 1000 x 0.24 x (195-28)
= 2284560 kCal/hr

Heat reduction in the furnace input = Heat gain by Air-preheater

New Heat input to the furnace = 33490000 – 2284560
= 31,205,440 kCal/hr

Efficiency of furnace after installation of APH = 26775000 / 31,205,440
= 85.8 %

CHAPTER 9: INSULATION AND REFRACTORIES

9.1 Insulation

9.1.1 Purpose of Insulation

Insulation is used to prevent heat loss or heat gain to enable less energy consumption while meeting the demands of heating and cooling. A thermal insulator is a poor conductor of heat and has a low thermal conductivity and hence is used in buildings and in manufacturing processes to prevent heat loss or heat gain. Thermal insulation delivers the following benefits:

- Reduces over-all energy consumption
- Offers better process control by maintaining process temperature.
- Prevents corrosion by keeping the exposed surface of a refrigerated system above dew point
- Provides fire protection to equipment
- Absorbs vibration

Insulating materials are porous, containing large number of dormant air cells. Insulation for heating system should be fire proof, be vermin proof, have lasting quality, be mechanically strong, be compact and be light in weight.

9.1.2 Types and Application

The Insulation can be classified into three groups according to the temperature ranges for which they are used. They are

Low Temperature Insulations (up to 90°C)

This range covers insulating materials for refrigerators, cold and hot water systems, storage tanks, etc. The commonly used materials are Cork, Wood, 85% magnesia, Mineral Fibres, Polyurethane and expanded Polystyrene, etc

Medium Temperature Insulations (90 - 325°C)

Insulators in this range are used in low temperature, heating and steam raising equipment, steam lines, flue ducts etc. The types of materials used in this temperatures range include 85% Magnesia, Asbestos, Calcium Silicate and Mineral Fibres etc.

High Temperature Insulations (325° C - above)

Typical uses of such materials are super-heated steam system, oven dryer and furnaces etc. The most extensively used materials in this range are Asbestos, Calcium Silicate, Mineral Fibre, Mica and Vermiculite based insulation, Fireclay or Silica based insulation and Ceramic Fibre.

The Table 9.1 describes the characteristics and applications of various insulating materials.

Table 9.1: Characteristics & Applications of various insulating materials

S. No.	Type of Insulation	Application	Characteristics
1	Polystyrene An organic form made by polymerizing styrene	Suitable for low temperatures (-167 °C to 82 °C). Mainly used in • Cool rooms, • refrigeration piping and • concrete retaining structures	Rigid and light weight. Combustible, has a low melting point, is UV degradable, and susceptible to attacks by solvents
2	Polyurethane Made by reacting isocyanates and alcohols. Made in continuous slab or foamed in situ.	Suitable for low temperatures (-178°C to 4 °C). Mainly used in • cool rooms, • refrigerated transports, • deep freezing cabinets, • refrigeration piping, • floor and foundation insulation.	Closed cell structure, low density and high mechanical strength Combustible, produces toxic vapours and has a tendency to smoulder.
3	Rockwool (mineral fibre) Manufactured by melting basalt and coke in a cupola at about 1500 °C. Phenolic binders used.	Suitable for temperatures up to 820 °C. Mainly used to insulate • industrial ovens, • heat exchangers, • driers, • boilers and high temperature pipes	Has a wide density range and is available in matts, blankets, loose form or preformed for pipe insulation. It is chemically inert, non-corrosive and maintains Mechanical strength during handling
4	Fibre Glass Formed by bonding long glass fibres with a thermo setting resin to form blankets and batts, semi-rigid boards, high density rigid boards and preformed pipe sections	Suitable for temperatures up to 540 °C. Mainly used to insulate • industrial ovens, • heat exchangers, • driers, boilers and pipe works	Will not settle or disintegrate with ageing. Fibre glass products are slightly alkaline pH9 (neutral is pH7). It should not promote or accelerate the corrosion of steel. Hence, it is protected from external contamination.
5	Calcium Silicate Made from anhydrous calcium silicate material reinforced with a non-asbestos binder. Available in slab form of various sizes.	Suitable for temperatures up to 1050 °C. Mainly used to • insulate furnace walls, • fire boxes, • back-up refractory, • flue lining and boilers	Has a minute air cell structure, has a low thermal conductivity and will retain its size and shape in its useable temperature range. It is light weight, but has good structural strength so it can withstand mechanical abrasion. It will not burn or rot, is moisture resistant and non-corrosive.
6	Ceramic Fibre Made from high purity alumina and silica grains, melted in an electric furnace and blasted by high velocity gases into light fluffy fibres. Made in a variety of forms	Suitable for temperatures up to 1430 °C. Mainly used to insulate • furnace and kiln back-up refractory, • fire boxes, • glass feeder bowls,	Suitable for many applications because of the variety of forms. These include cloth, felt, tape, coating cements and variform castable (fire brick)

		• furnace repair, induction • coil insulation, • high temperature gaskets and • wrapping material	

Classification of insulating materials based on their forms

- **Powdered:** It is mixed with water used to cover odd shapes such as pipe unions, elbows, valves etc.
- **Sheet:** applied to flat areas such as ceilings, ducts, etc.
- **Block and brick:** used to cover outside surfaces of boilers.
- **Blanket:** used to cover ducts, pipes.
- **Tube:** used to insulate steam and hot water pipes.
- **Roll:** used to cover cold and warm-air ducts for furnace castings in hot-air heating systems.
- **Custom Moulded Insulation:** Lagging materials can be obtained in bulk, in the form of moulded sections; semi - cylindrical for pipes, slabs for vessels, flanges, valves etc. The main advantage of the moulded sections is the ease of application and replacement when undertaking repairs for damaged lagging.

9.1.3 Thermal Resistance (R)

The effectiveness of insulation is measured in terms of thermal resistance, called R-value, which indicates the resistance of heat flow. The higher the R-value, the greater the insulating power. The actual R-value of thermal insulation depends on the type of material, its thickness and density. In calculating the R-value of insulation, the R-values of the individual layers are added. The amount of insulation depends on:

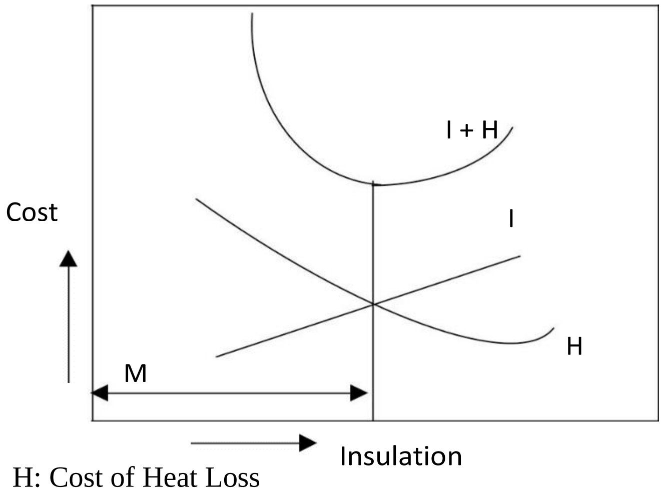
- Climate
- Type of fuel used
- The section the requires insulation

Once the type of insulation material that is required is finalized based on temperature of process and the average ambient temperature, the thickness of insulating material required needs to be evaluated.

9.1.4 Economic Thickness of Insulation (ETI)

The effectiveness of insulation follows the law of decreasing returns. Hence, there is a definite economic limit to the amount of insulation, which is justified. An increased thickness is uneconomical and cannot be recovered through small heat savings. This limiting value is termed as economic thickness of insulation. An illustrative case is given in Figure 9.1. Each industry has different fuel cost and boiler efficiency. These values can be used for calculating economic thickness of insulation. This shows that thickness for a given set of circumstances results in the lowest overall cost of insulation and heat loss combined over a given period of time. The following figure 9.1 and 9.2 illustrates the principle of economic thickness of insulation.

Figure 9.1: Illustration of optimal insulation



I: Cost of Insulation H: Cost of Heat Loss
I + H: Total Cost M: Economic Thickness

Figure 9.2: Determination of economic thickness of insulation

Heat loss from a surface is expressed as

$$\mathbf{H} = \mathbf{h} \times \mathbf{A} \times (\mathbf{Th} - \mathbf{Ta})$$

Where,

h is Heat transfer coefficient, W/m2 K (2000 W/ m^2 K)
H is Heat loss, Watts
Ta is Average ambient temperature, °C
Th is Hot surface temperature (for hot fluid piping) in °C & Cold surface temperature (for cold fluids piping) in °C

The point where the amount of insulation gives the greatest return on investment is called as **"economic thickness of insulation (ETI)".** The determination of economic thickness requires the attention to the following factors.

- Cost of fuel
- Annual hours of operation
- Heat content of fuel
- Boiler efficiency
- Operating surface temperature

- Pipe diameter/thickness of surface
- Estimated cost of insulation.
- Average exposure ambient still air temperature.

The cost of insulation depends not only on the thickness of insulating material but also on the material itself. Materials with higher thermal resistance will require insulating material of less thickness compared to insulating material with lower thermal resistance. At the same time cost of higher thermal resistance for same thickness may be higher compare to insulating material with lower thermal resistance.

9.1.5 Heat Savings and Application Criteria

Various charts, graphs and references are available for heat loss computation. The surface heat loss can be computed with the help of a simple relation as given below. This equation can be used up to 200 °C surface temperature. Factors like wind velocities, conductivity of insulating material etc. has not been considered in the equation.

$$S = \left[10 + \frac{T_s - T_a}{20}\right](T_s - T_a)$$

Where

S =Surface heat loss in Kcal/hr m^2

Ts =Hot surface temperature in °C

Ta =Ambient temperature in °C

$$Total\ heat\ loss/hr\ (Hs) = S\ \times A$$

Where,

A = Surface area inm^2

Based on the cost of heat energy, the quantification of heat loss in BDT can be worked out as under:

$$\text{Equivalent fuel loss (Hf)}\left(\frac{\text{kg}}{\text{yr}}\right) = \frac{\text{H}_\text{s} \times \text{Yearly hours of operation}}{\text{GCV} \times \eta_\text{b}}$$

$$\text{Annual heat loss in monetary terms (BDT)} = \text{Hf} \times \text{Fuel cost (BDT/kg)}$$

Where

GCV = Gross Calorific value of fuel Kcal/Kg

η_b= Boiler efficiency in %

Methodology for calculating Economic Thickness of Insulation:

- Step 1: Calculate the surface area of pipe
- Step 2: Calculate unit heat loss and using surface area calculate total surface heat loss with and without insulation.
- Step 3: Convert heat loss to fuel loss using calorific value of fuel used in boiler. Adjust fuel usage to boiler efficiency. Convert hourly loss to yearly loss.
- Step 4: Using unit fuel cost data estimate fuel loss in cost terms for the entire life of insulating material i.e. 5 years.
- Step 5: Using given insulating material costs estimate cost of insulation for varying thickness of the insulating material.
- Step 6: Calculate the total cost of insulation and fuel loss cost.
- Step 7: Plot graph of Insulation thickness v/s Cost of insulating material, Cost of fuel loss and total cost.
- Step 8: Identify the economic thickness of insulating material by drawing a vertical line at the point of intersection of cost of insulating material and cost of fuel loss lines.

9.1.6 Cold Insulation

Cold Insulation Features

Cold Insulation should be considered and where operating temperature are below ambient where protection is required against heat gain, condensation or freezing. Condensation will occur whenever moist air comes into contact with the surface that is at a temperature lower than the dew point of the vapour. In addition, heat gained by uninsulated chilled water lines can adversely affect the efficiency of the cooling system. The most important characteristics of a suitable Cold insulation material have following features:

- Low thermal conductivity
- High water resistance, and
- Durability at low temperature

Other properties like easy workability, negligible capillary absorption should also be taken into consideration while making a selection. The insulation system is only as good as its vapour barrier and the care with which it is installed.

Material Selection for Cold Insulation

Selection of insulation materials should be carefully considered where the possibility of steam purging of the equipment is required or for other reasons which may cause the temperature to be increased to a level that exceeds the maximum limiting temperature of the insulation materials, i.e., material then deteriorate. Examples of cold insulation include Urethane Foam, Expanded Polystyrene, Resin bonded glass wool, Resin Bonded Glass wool, and Phenolic Foam.

Economics of Cold Insulation:

Unlike hot insulation system, the concern area in Cold Insulation is the heat gain into the refrigerated space, which leads to increase in the refrigeration load (TR) & energy consumption as a consequence. The cost of heat gain can thus be assessed & evaluated against cost of additional cold insulation thickness, to optimize overall energy consumption & cost in refrigeration system.

9.2 Refractories

Refractories are non-metallic materials have insulating and other chemical and physical properties that make them able to contain the heat generated by burning of the fuel in the furnace and to minimise heat losses, withstand high temperatures and make them applicable for structures, or as components of systems, that are exposed to environments above 1,000 °F (811 K; 538 °C) and should not contaminate the material with which it is in contact. Refractory materials are used in furnaces, kilns, incinerators, and reactors.

The various combinations of operating conditions under which refractories are used, make it necessary to manufacture a range of refractory materials with different properties and accordingly are made in varying combinations and shapes for different applications. A furnace designer should have a clear idea of the service conditions of different refractory and for which the refractory is being used and needs to consider the following points, before selecting a refractory.

- Area of application
- Working temperatures
- Extent of abrasion and impact
- Structural load of the furnace

- Stress due to temperature gradient in the structures and temperatures fluctuations
- Chemical compatibility with the furnace environment
- Heat transfer and fuel conservation
- Cost consideration

Properties of Refractories

Some of the important properties of refractories are:

Size: The size and shape of the refractories is a part of the design feature. It is an important feature in design since it affects the stability of any structure. Accuracy and size is extremely important to enable proper fitting of the refractory shape and to minimize the thickness and joints in construction.

Bulk density: A useful property of refractories is bulk density, which defines the material present in a given volume. An increase in bulk density of a given refractory increases its volume stability, its heat capacity, as well as resistance to slag penetration.

Porosity: The apparent porosity is a measure of the volume of the open pores, into which a liquid can penetrate, as a percentage of the total volume. This is an important property in cases where the refractory is in contact with molten charge and slags. A low apparent porosity is desirable since it would prevent easy penetration of the refractory size and continuity of pores will have important influences on refractory behaviour. A large number of small pores is generally preferable to an equivalent number of large pores.

Cold crushing strength: The cold crushing strength, which is considered by some to be of doubtful relevance as a useful property, other than that it reveals little more than the ability to withstand the rigors of transport, can be used as a useful indicator to the adequacy of firing and abrasion resistance in consonance with other properties such as bulk density and porosity.

Pyrometric cone equivalent (PCE): Temperature at which a refractory will deform under its own weight is known as its softening temperature which is indicated by PCE. Refractories, due to their chemical complexity, melt progressively over a range of temperature. Hence refractoriness or fusion point is ideally assessed by the cone fusion method. The equivalent standard cone which melts to the same extent as the test cone is known as the pyrometric cone equivalent.

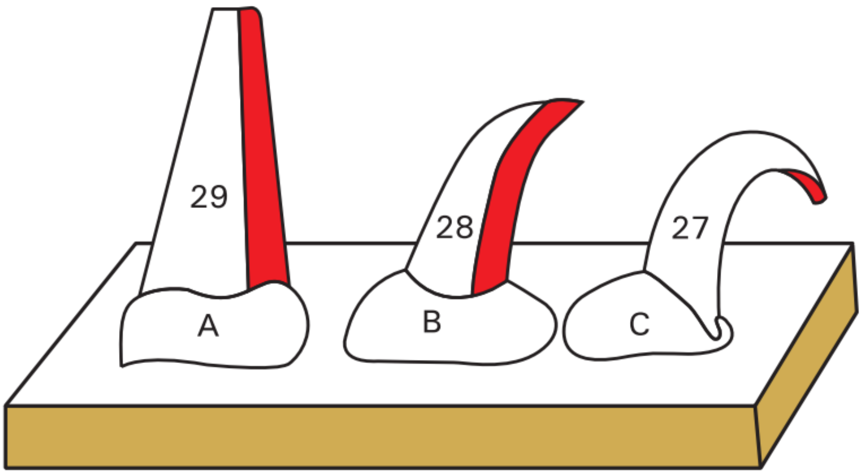


Figure 9.3: Pyrometric Cones

Thus in the Figure 9.3 refractoriness of Sample A is much higher than B and C. The pyrometric cone equivalent indicates only the softening temperature. But, in service the refractory is subjected to loads which would deform the refractory at a much lower temperature than that indicated by PCE. With change in the environmental conditions, such as reducing atmosphere, the P.C.E. value changes drastically.

Refractoriness under load (RUL): The refractoriness under load test (RUL test) gives an indication of the temperature at which the bricks will collapse, in service conditions with similar load.

Creep at high temperature: Creep is a time dependent property which determines the deformation in a given time and at a given temperature by a material under stress.

Volume stability, expansion, and shrinkage at high temperatures: The contraction or expansion of the refractories can take place during service. Such permanent changes in dimensions may be due to several operational factors.

Reversible thermal expansion: Any material when heated, expands, and contracts on cooling. The reversible thermal expansion is a reflection on the phase transformations that occur during heating and cooling.

Thermal conductivity: Thermal conductivity depends upon the chemical and mineralogical compositions as well as the glassy phase contained in the refractory and the application temperature. The conductivity usually changes with rise in temperature. In cases where heat transfer is required though the brick work, for example in recuperators, regenerators, muffles, etc. the refractory should have high conductivity. Low thermal conductivity is desirable for conservation of heat by providing adequate insulation.

The provisions for back-up insulation, conserves heat but at the same time it increases the hot face temperature and hence the demand on the refractory quality increases.
Light weight refractories of low thermal conductivity find wider applications in the moderately low temperature heat treatment furnaces, where its primary function is usually conservation of energy. It is more so in case of batch type furnaces where the low heat capacity of the refractory structure would minimize the heat storage during the intermittent heating and cooling cycles.

9.2.1 Selection of Refractories

The selection of refractories for any particular application is made with a view to achieve the best performance of the equipment furnace, kiln or boiler and depends on their properties. Further, the choice of a refractory material for a given application will be determined by the type of furnace or heating unit and the prevailing conditions e.g., the gaseous atmosphere, the presence of slags, the type metal charges etc. It is, therefore, clear that temperature is by no means the only criterion for selection of refractories. Important physical properties of some insulating refractories that are considered in selecting them are shown in the following Table 5.2.

Table 9.2: Physical properties of some insulating refractories

Type/grade	Thermal Conductivity at 400 °C	Max. safe Temp °C	Cold Crushing Strength Kg/cm^2	Porosity %	Bulk Density Kg/m^2
Diatomite Solid	0.025	1000	270	52	1090
Diatomite Porous	0.014	800	110	77	540
Clay	0.030	1500	260	68	560
High Alumina	0.028	1500-1600	300	66	910
Silica	0.040	1400	400	65	830

Beside the physical properties chemical properties and the working atmosphere where these are used also influence their selection. Considering these factors refractories are classified based on the refractory constituents, behaviour of the refractory constituents in their working atmosphere, and the form of refractory application

9.2.2 Classification of Refractories

Refractories are classified based on their refractoriness, based on chemical composition of refractories, their form and operating temperatures.

Classification based on refractoriness

Based on the property of refractoriness, they are usually classified into four classes using their PCE[1] (pyrometric cone equivalent) value as given in table 9.3.

Table 9.3: Classification of Refractories based on PCE Value

Class of Refractory	PCE value
Super duty refractories	33 - 38
High duty refractories	30 - 33
Intermediate duty refractories	28 - 30
Low duty refractories	19 - 28

Classification based on composition of Refractories

Refractories can be classified on the basis of chemical composition and method of manufacture. The constituents, characteristics and applications of these refractories are summarized in table 9.4.

Table 9.4: Classification of Refractories based on Materials, their characteristics and applications

Refractory Type	General Characteristics	Application
Acid Bricks: Used in areas where both slag and atmosphere are acidic and are attacked by alkalis (basic slags).		
Silica	High strength at high temperatures, residual expansion, low specific gravity, high expansion coefficient at low temperatures, low expansion coefficient at high temperatures	Glass tank crown, copper refining furnace, electric arc furnace roof
Fused silica	Low thermal expansion coefficient, high thermal shock resistance, low thermal conductivity, low specific gravity, low specific heat	Coke over, hot stove, soaking pit, glass tank crown
Fireclay (Chamotte)	Consists of kaolinite ($Al_2O_3.2SiO_2.2H_2O$) and minor amounts of other clay materials. Low thermal expansion coefficient. Low thermal conductivity, low specific gravity, low specific heat, low strength at high temperatures, less slag penetration	Ladle, runner, sleeve, coke oven, annealing furnace, blast furnace hot stove, reheating furnace, soaking pit
Alumina	High refractoriness, high mechanical strength, high slag resistance, high specific gravity, relatively high thermal conductivity	Hot stove, stopper head, sleeve, soaking pit cover, reheating furnace, glass tank, high-temperature kiln.
High alumina	Composed of bauxite or other raw materials that contain 50 to 87.5 percent alumina. High refractoriness, high mechanical strength, high slag resistance, high specific gravity, relatively	Slide gate, aluminium melting furnace, skid rail, ladle, incinerator, reheating furnace hearth.

[1]*The pyrometric cone is "A pyramid with a triangular base and of a defined shape and size; the "cone" is shaped from a carefully proportioned and uniformly mixed batch of ceramic materials so that when it is heated under stated conditions, it will bend due to softening, the tip of the cone becoming level with the base at a definitive temperature. Pyrometric cones are made in series, the temperature interval between the successive cones usually being 20 degrees Celsius.* ***The number of that standard pyrometric cone whose tip would touch the supporting plaque simultaneously with a cone of the refractory material being investigated when tested in accordance with ASTM Test Method C-24.***

Refractory Type	General Characteristics	Application
	high thermal conductivity	
Roeske	Low thermal expansion coefficient, high thermal shock resistance, low thermal conductivity, low specific gravity, low specific heat	Ladle, runner, sleeve, coke oven, hot stove, soaking pit, annealing, blast and reheating furnace.
Zircon	Containing Zirconium silicate (ZrO_2SiO_2). Maintains good volume stability for extended periods, has high thermal shock resistance, high slag resistance, high specific gravity	Ladle, nozzle, stopper head, sleeve
Zirconia	High melting point, low wet ability against molten metal, low thermal conductivity, high corrosion resistance, high specific gravity	Nozzle for continuous casting, glass tank, high-temperature furnace, crucible.
Alumina zirconia silica	High slag resistance, high corrosion resistance against molten glass	Glass tank, incinerator, ladle, nozzle for continuous casting
Mullite	Made from kyanite, sillimanite, andalusite, bauxite or mixtures of alumina silicate materials; mullite refractories are about 70% alumina. They maintain a low level of impurities and high resistance to loading in high temperatures and offers good thermal shock resistance, excellent thermal stability, resistance to most chemical attack, resistance to abrasion and good electrical resistivity.	Steel ladles, lances, reheat furnaces and slide gates are examples of mullite aggregate based products with various alumina contents. In kiln areas such as kiln setter slabs and posts for supporting ceramic ware during firing
Basic Bricks: Are stable to alkaline slags, dusts and fumes at high temperatures and are attacked by acid slags.		
Lime	High slag resistance, low hydration resistance	Special refining surface
Magnesia	High refractoriness, relatively low strength at high temperature, high basic slag resistance, low thermal shock resistance, low durability at high humidity	Hot-metal mixer, secondary refining vessel, rotary kiln, checker chamber of glass tank, electric arc furnace
Magnesia-chrome	High refractoriness, High refractoriness under load, high basic slag resistance, relatively good thermal shock resistance (low MgO bricks), high strength at high temperature (direct bonded and fusion cast)	Hot-metal mixer, electric arc furnace, secondary refining vessel, nonferrous refining furnace, rotary cement kiln, lime and dolomite kiln, copper furnace, ladle, checker chamber of glass tank, slag line of electric arc furnace, degasser for copper, non-ferrous smelter.
Dolomite	High refractoriness under load, high basic slag resistance, low durability in high humidity, high thermal expansion coefficient	Basic oxygen furnace, electric arc furnace, secondary refining vessel, rotary cement kiln.
Spinel	High thermal shock resistance, high strength at high temperatures, high slag resistance	Rotary cement kiln, ladle.
Neutral Non-oxide Bricks : are chemically stable to both acids and bases and are used in areas where slag and atmosphere are either acidic or basic		
Chrome	High refractoriness, low strength at high temperature, low thermal resistance	Buffer brick between acid and base brick
Silicon carbide	They are produced by the reaction of sand and coke in an electric furnace. High refractoriness, high strength at high temperature, high thermal conductivity, high thermal shock resistance, reduced oxidation resistance at high temperature, high slag resistance	Kiln furniture, incinerator, blast furnace

Refractory Type	General Characteristics	Application
Silicon carbide-graphite	High refractoriness, high strength at high temperature, high thermal conductivity, high thermal shock resistance	Incinerator
Silicon nitride	High strength, high thermal shock resistance, relatively high oxidation resistance	Kiln furniture, blast furnace
Composite		
Silicon carbide	Containing High corrosion resistance against low iron oxide, high strength at high temperatures, high thermal shock resistance	Ladle, blast furnace, electric arc, torpedo ladle, iron ladle
Magnesia-carbon	High slag resistance, high thermal shock resistance	Basic oxygen furnace, electric arc furnace, ladle
Alumina-carbon	High refractoriness, high thermal shock resistance, high corrosion resistance	Submerged entry nozzle, slide gate

Classification based on Form of Refractories

Refractories and refractory materials are used in various forms depending on the requirements. Table 9.5 gives different forms in which these are produced.

Table 9.5: Forms of Refractories

Kind	Definition
Shaped Refractories	
Bricks	Refractories that have shapes and are used to line furnaces, kilns, glass tanks, incinerators, etc.
Insulating firebrick	Low thermal conductivity firebrick.
Unshaped Refractories (Monolithic)	
Mortar	Materials for bonding bricks in a lining. The three types of mortar – heat-setting; air-setting; and hydraulic-setting – have different setting mechanisms.
Castables	Refractory materials are mixed with hydraulic-setting cement (either Portland or a high-alumina cement) and casted. Used to line furnaces, kilns, formation of the bases of tunnel kiln cars used in the ceramic industry etc.
Plastics	Refractories in which raw materials and plastic materials are mixed with water. Plastic refractories are roughly formed, sometimes with chemical additives.
Gunning mixes	Refractories that are sprayed on the surface by a gun.
Ramming mixes	Granular refractories that are strengthened by gunning formulation of a ceramic bond after heating. Ramming mixes have less plasticity and are installed by air rammer.
Slinger mixes	Refractories installed by a slinger machine.
Patching materials/ coating materials	Refractories with properties similar to refractory mortar. However, patching materials have controlled grain size for easy patching or coating.
Light weight castables	These are porous lightweight materials which are mixed with hydraulic cement and water and formed by casting. Lightweight castables are used to line furnaces, kilns, etc.
Fibrous Materials	
Ceramic fibre	Ceramic fibre is analumino silicate or ZrO_2 added alumino silicate material manufactured by blending and melting alumina and silica at temperature of 1800–2000 °Cand fibre made by blowing compressed air or dropping the melt on spinning disc. There are produced as in blanket, felt, module, vacuum, rope, or loose fibre form.

Recommended operating temperatures for continuous operations are given in the Table 9.6.

Table 9.6: Recommended operating temperature for Continuous Operation

	Al_2O_3 %	SiO_2 %	ZrO_2 %
1150 °C	43-47	53-57	-
1250 °C	52-56	44-48	-
1325 °C	33-35	47-50	17-20

9.3 High Emissivity Coatings

Emissivity is the measure of a material's ability to both absorb and radiate heat. The high emissivity materials when coated increases the surface emissivity of materials, with resultant benefits in heat transfer efficiency and in the service life of heat transfer components like refractories and metallic components such as radiant tubes and heating elements. High emissivity coatings are applied in the interior surface of furnaces or where rapid heating is required. The use of such coatings was found to reduce fuel or power to tune of 25-45%. The Figure 9.4 shows emissivity of various insulating materials including high emissivity coatings. High emissivity coating shows a constant value over varying process temperatures.

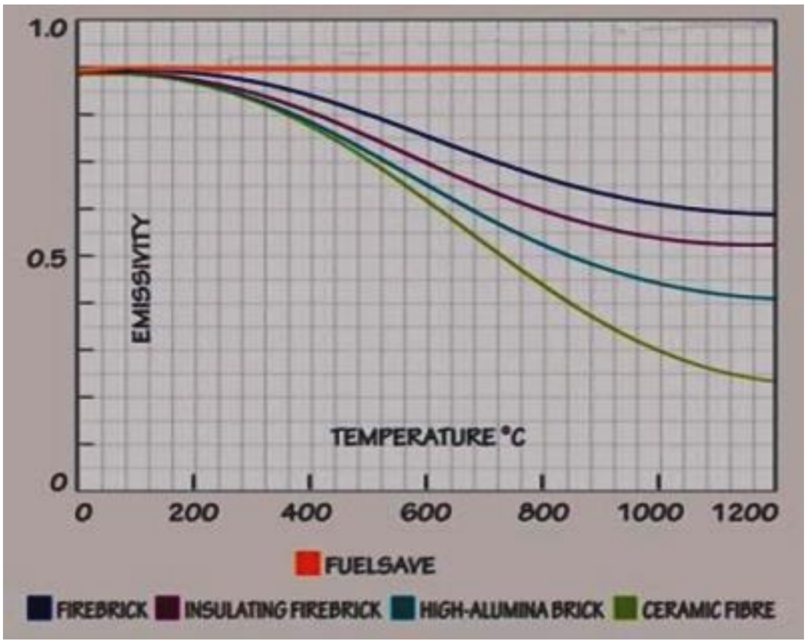


Figure 9.4: Emissivity of refractory materials at different temperatures

Furnaces, which operate at high temperature, have emissivity of 0.3. By using high emissivity coatings this can go up to 0.8 thus effectively increasing the radiative heat transfer.

CHAPTER 10: COGENERATION/TRIGENERATION

10.1 Introduction– Definition and Need

In conventional power plant when steam or gas expands through a turbine, nearly 60 to 70% of the input energy escapes with the exhaust steam or gas yielding only 30-40% efficiency. Also further losses of around 10-15% are associated with the transmission and distribution of electricity in the electrical grid. These losses are greatest when electricity is delivered to the smallest consumers.

If this energy in the exhaust steam or gas is utilized for meeting the process heat requirements, the efficiency of utilization of the fuel will increase and corresponding GHG emissions will reduce. Such an application, where the electrical power and process heat requirements are met from the fuel, is termed as “Cogeneration” or combined heat and power (CHP). The concept of CHP is illustrated in figure 10.1. Since, most of the industries need both heat and electrical energy, cogeneration can be a sensible investment for industries.

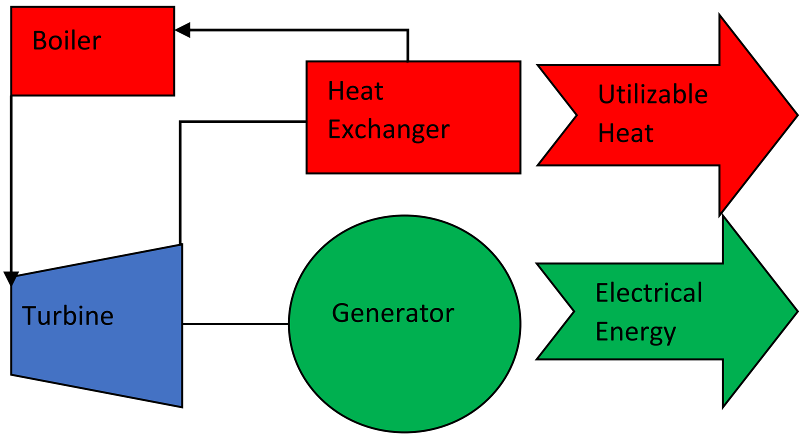
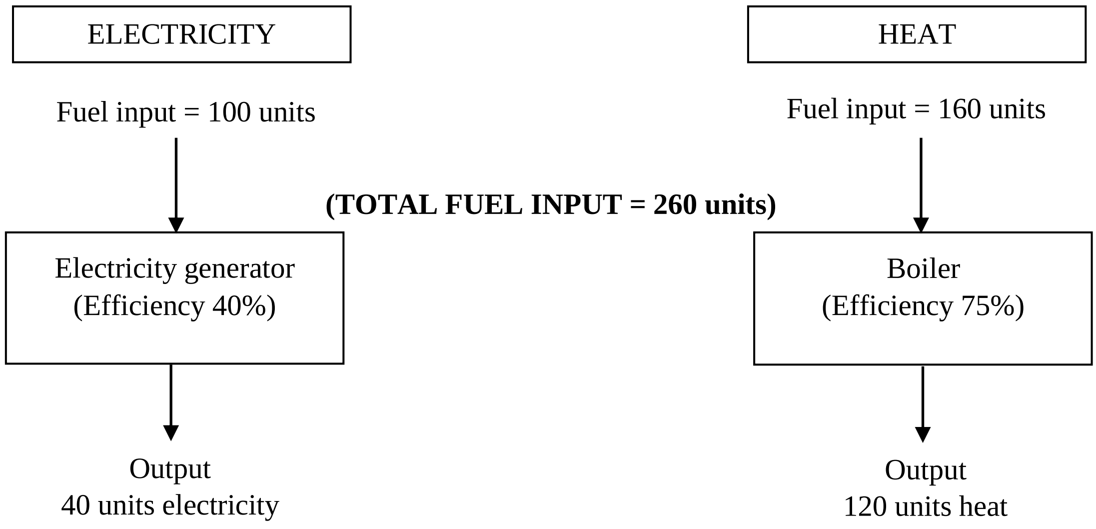


Figure 10.1: Cogeneration System

In cogeneration system efficiencies can go up to 90% and above providing energy savings ranging between 15-40% when compared against the supply of electricity and heat from conventional power stations and boilers. Since, electricity generated by cogeneration plant is normally used locally the transmission and distribution losses are negligible.

As an illustrative case, a plant needs 40 units of electric power and 120 units of thermal energy for its operation. Initially the plant met its requirement by having separate source for the electric power and thermal energy. In this process the total input required is 260 units. After installing a cogeneration system to meet both the loads, the plant is able to increase the overall efficiency of the system and bring down the input from 260 units to 200 units. Figure 10.2 gives comparison between Separate Heat and Power and Cogeneration System.

Case A: Separate Heat and Power



Case B: Combined Heat and Power

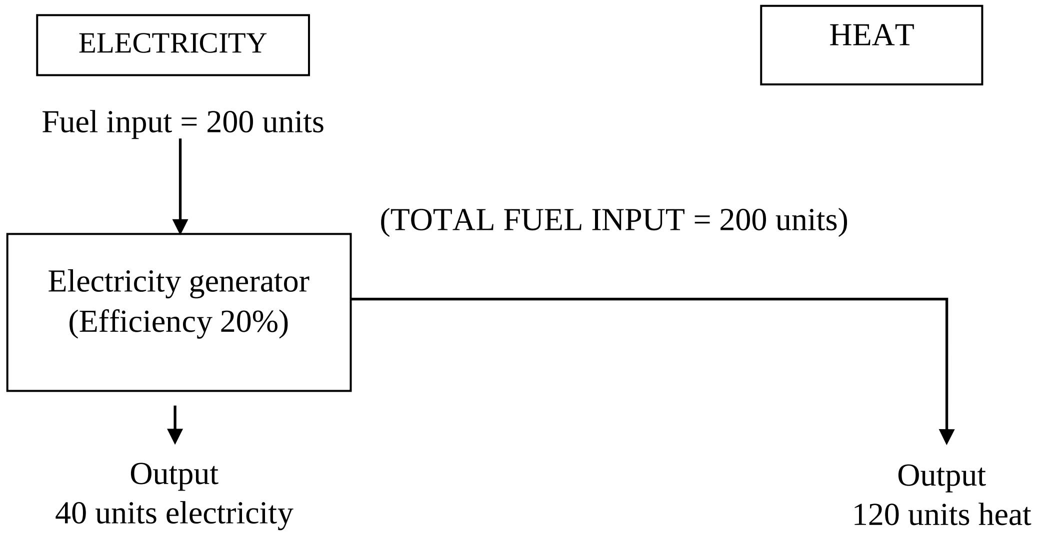


Figure 10.2: Comparison between energy inputs without and with cogeneration

In a cogeneration system, if less electricity is generated than needed, it will be necessary to buy extra. However, when the scheme is sized according to the heat demand, normally, more electricity than needed is generated. The surplus electricity can be sold to the grid. It can also be supplied to another customer via the distribution system, which is called the wheeling of power. As a rough guide.

If there is constant heat demand for at least 4,500 hours per year- Cogeneration is likely to be suitable

10.2 Classification of Cogeneration Systems

There are two main types of cogeneration concepts: “Topping Cycle” plants, and “Bottoming Cycle” plants.

10.2.1 Topping Cycle

A topping cycle plant generates electricity or mechanical power first. There are four types of topping cycle cogeneration systems. They are:

Topping cycle cogeneration systems are of four types:

1) **Combined- cycle topping system**: Fuel burnt directly in gas turbine or diesel engine to produce electrical or mechanical power and the exhaust is used to provide process heat or process steam. The process is shown in figure 10.3.

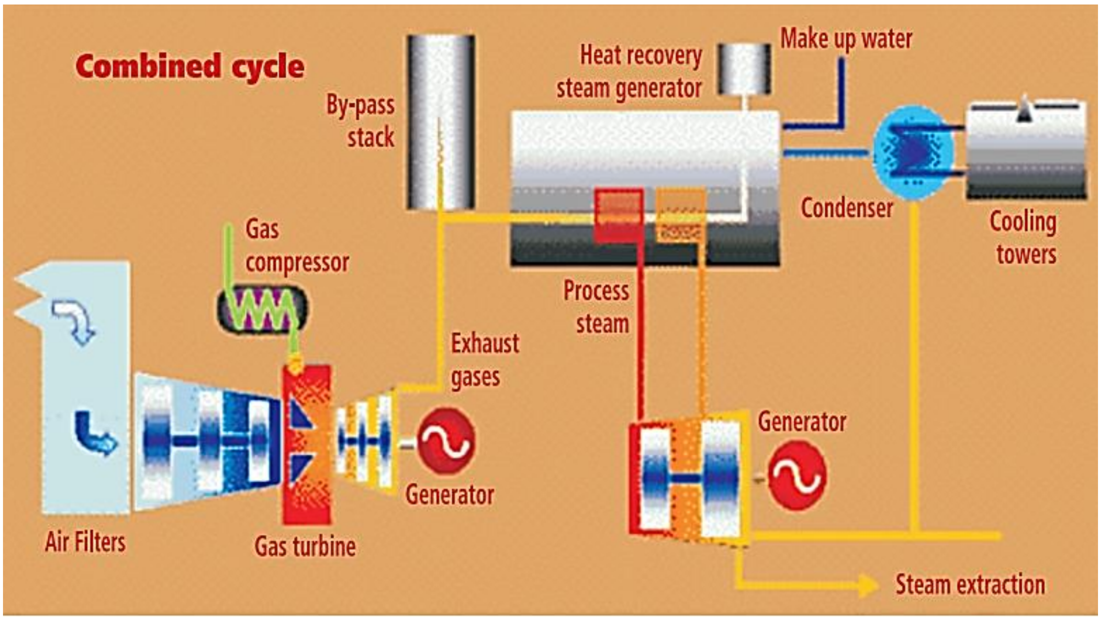


Figure 10.3: Steam turbine topping systems

2) **Steam-turbine topping system:** Fuel burnt to produce high-pressure steam to run a steam turbine to produce power, and the exhaust is used as process steam.

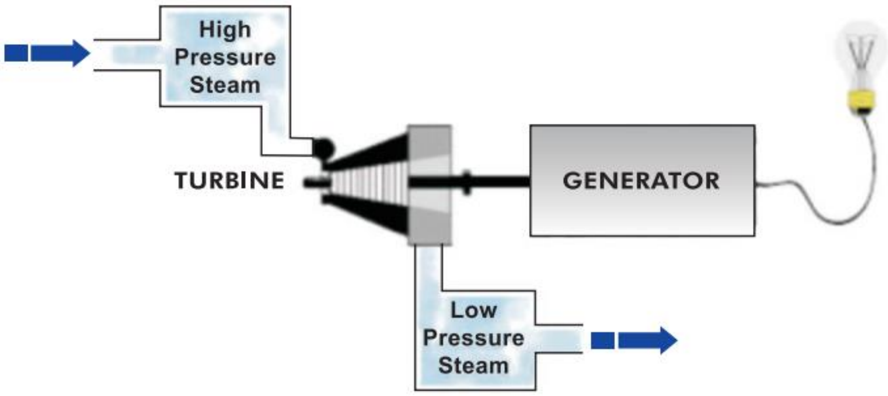


Figure 10.4: Steam turbine topping systems

3) **Diesel or gas engine topping systems:** A third type employs hot water from an engine jacket cooling system flowing to a heat recovery boiler, where it is converted to process steam and hot water for space heating.

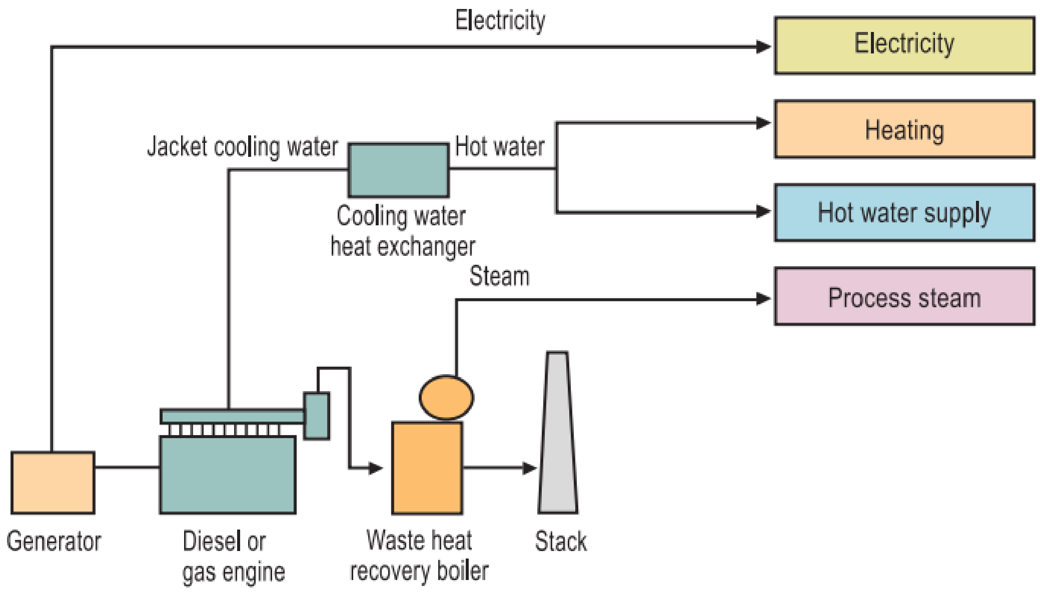


Figure 10.5: Diesel or gas engine topping systems

4) **Gas-turbine topping system**: A natural gas turbine drives a generator. The exhaust gas goes to a heat recovery boiler that makes process steam and process heat.

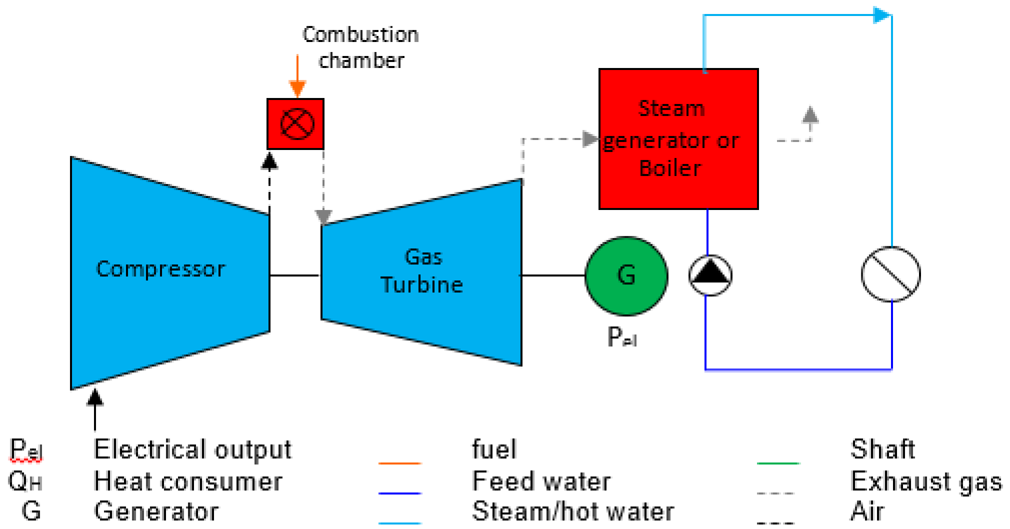


Figure 10.6: Gas turbine topping systems

10.2.2 Bottoming Cycle:

A bottoming cycle plant generates heat first. Bottoming cycle plants are much less common than topping cycle plants. These plants exist in heavy industries such as glass or metals manufacturing where very high temperature furnaces are used. The Figure 10.7 illustrates the bottoming cycle where fuel is burnt in a furnace to produce synthetic rutile. The waste gases coming out of the furnace is utilized in a boiler to generate steam, which drives the turbine to produce electricity.

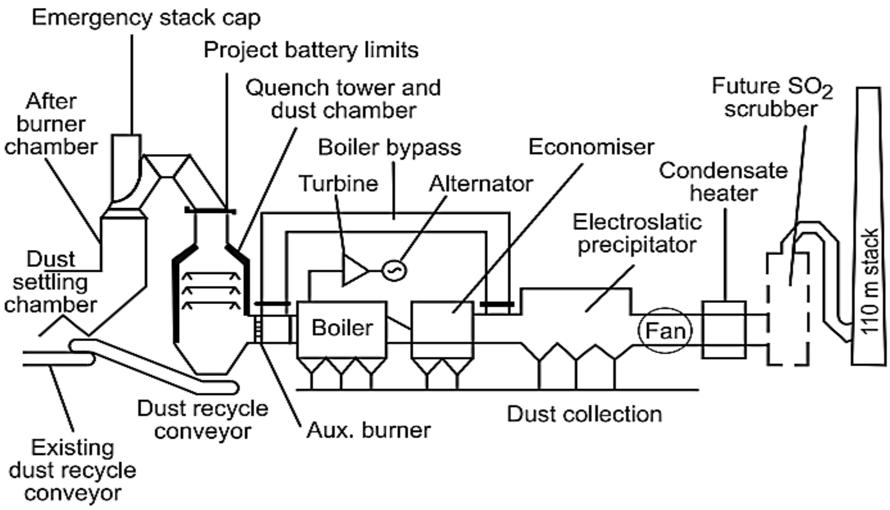


Figure 10.7: Bottoming cycle

10.3 Types of Cogeneration Systems

- Steam turbine
- Gas turbine
- Diesel engine

10.3.1 Steam Turbine

Steam turbines are the most commonly employed prime movers for cogeneration applications. In the steam turbine, high pressure steam generated in a boiler or heat recovery steam generator (HRSG) is expanded to a lower pressure level, converting the thermal energy of high-pressure steam to kinetic energy through nozzles and then to mechanical power through rotating blades. Boiler fuels can include fossil fuels such as coal, oil and natural gas or renewable fuels like wood or municipal waste.

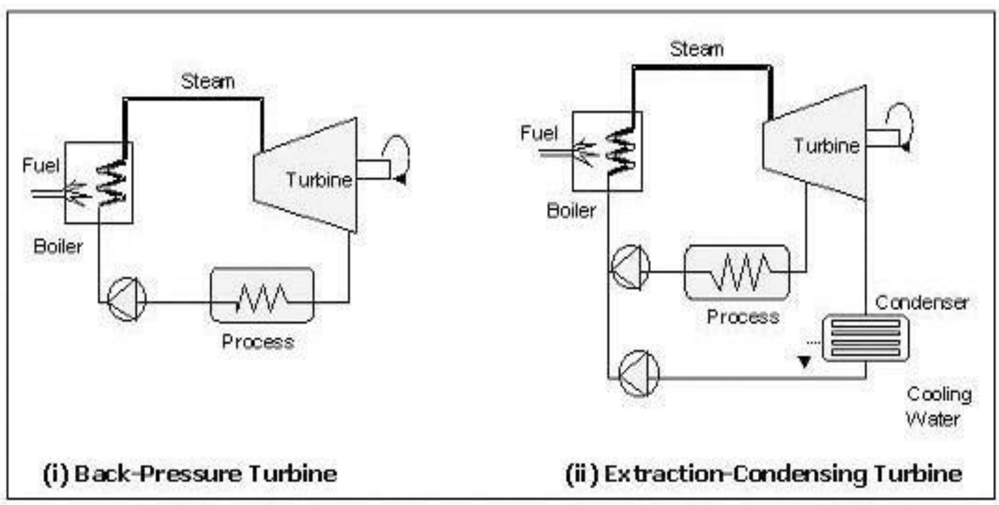


Figure 10.8: Steam turbine cogeneration system

The thermodynamic cycle for the steam turbine is the Rankine cycle, although a number of different cycles are also used, such as the Reheat, the Regenerative and the combined cycle. The Rankine cycle is the basis for conventional power generating stations and consists of a heat source (boiler) that converts water to high- pressure steam. The steam flows through the turbine to produce power and may

be wet, dry saturated or superheated.
Depending on the pressure (or temperature) levels at which process steam is required, back-pressure steam turbines can have different configurations. In extraction and double extraction back-pressure turbines, some amount of steam is extracted from the turbine after being expanded to a certain pressure level. The extracted steam meets the heat demands at pressure levels higher than the exhaust pressure of the steam turbine.

The efficiency of a back-pressure steam turbine cogeneration system is the highest. In cases where 100 per cent back-pressure exhaust steam is used, the only inefficiencies are gear drive and electric generator losses, and the inefficiency of steam generation. Therefore, with an efficient boiler, the overall thermal efficiency of the system could reach as much as 90 percent.

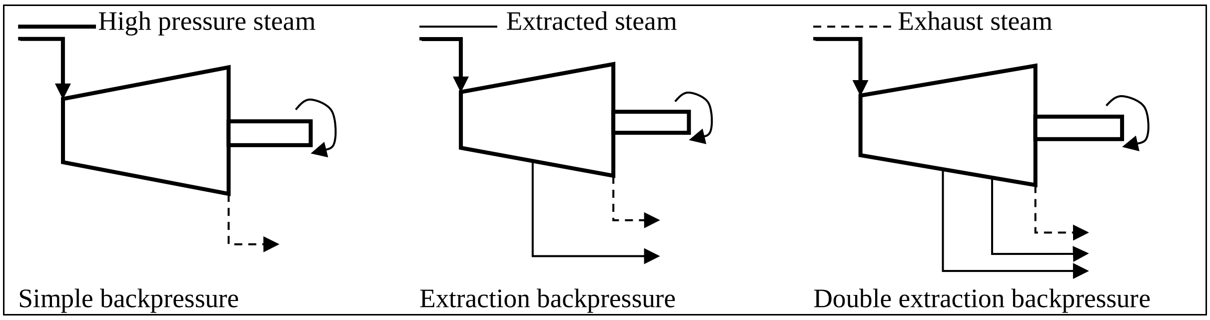


Figure 10.9: Configurations for back pressure steam turbines

Back-Pressure turbine: In this type steam enters the turbine chamber at **High Pressure** and expands to **Low or Medium Pressure**. Enthalpy difference is used for generating power /work.

Total Condensing turbine: In this type, steam entering at High / Medium Pressure condenses in a surface condenser and work is done till it reaches the Condensing pressure (vacuum).

Extraction cum Condensing steam turbine: In this high Pressure steam enters the turbine and passes out from the turbine chamber in stages. The Figure 7.9 shows a two stage extraction cum condensing turbine. In this MP steam and LP steam pass out to meet the process needs. Balance quantity condenses in the surface condenser. The Energy difference is used for generating Power. This configuration meets the heat-power requirement of the process.

The extraction condensing turbines: These turbines have higher power to heat ratio in comparison with back-pressure turbines. Although condensing systems need more auxiliary equipment such as the condenser and cooling towers, better matching of electrical power and heat demand can be obtained where electricity demand is much higher than the steam demand and the load patterns are highly fluctuating.

The overall thermal efficiency of an extraction condensing turbine cogeneration system is lower than that of back pressure turbine system, basically because the exhaust heat cannot be utilized (it is normally lost in the cooling water circuit). However, extraction condensing cogeneration systems have higher electricity generation efficiencies.

10.3.2 Gas Turbine

In gas turbines fuel is burnt in a pressurized combustion chamber using combustion air supplied by a compressor. These hot gases expand through the blades on the turbine rotor causing them to move generating mechanical energy.

In conventional Gas turbine, gases enter the turbine at 900 to 1000°C and leave at 400 to 500 °C. Residual energy in the form of hot exhaust gases can be used to generate wholly or partly, the thermal (steam) demand of the site.

The available mechanical energy can be applied in the following ways:

- to produce electricity with a generator (most applications);
- to drive pumps, compressors, blowers, etc.

A gas turbine operates under exacting conditions of high speed and high temperature. The hot gases supplied to it must be free of particulates which would erode the blades and contain no more than minimal amounts of contaminants, which would cause corrosion under operating conditions. High-premium fuels are therefore most often used, particularly natural gas. Distillate oils such as gas oil LPGs and Naphtha are suitable.

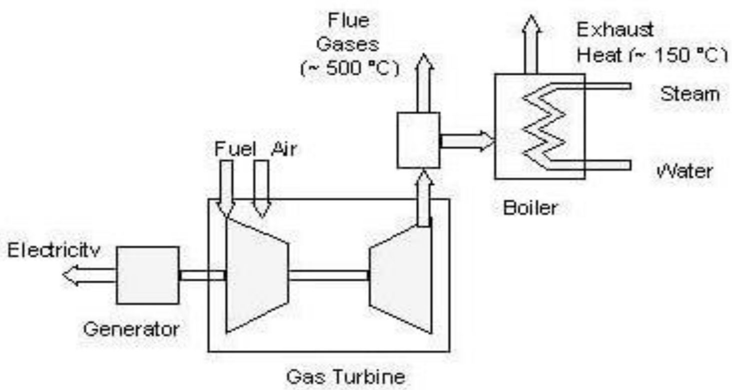


Figure 10.10: Gas turbine

Gas Turbine Efficiency

Turbine Efficiency is the ratio of actual work output of the turbine to the net input energy supplied in the form of fuel. For stand-alone Gas Turbines, without any heat recovery system the efficiency will be as low as 35 to 40%. This is attributed to the blade efficiency of the rotor, leakage through clearance spaces, friction, irreversible turbulence etc.

Increasing Overall Efficiency

Since Exhaust gas from the Gas Turbine is high, it is possible to recover energy from the hot gas by a Heat Recovery Steam Generator and use the steam for process.

Net Turbine Efficiency

Above efficiency figures did not include the energy consumed by air compressors, fuel pump and other auxiliaries.

Air compressor alone consumes about 50 to 60 % of energy generated by the turbine. Hence net turbine efficiency, which is the actual energy output available will be less than what has been calculated. In most Gas Turbine plants, air compressor is an integral part of Turbine plant.

10.3.3 Diesel Engine Systems

This system provides process heat or steam from engine exhaust. The engine jacket cooling water heat exchanger and lube oil cooler may also be used to provide hot water or hot air. There are, however, limited applications for this. As these engines can use only fuels like HSD, distillate, residual oils, natural gas, LPG etc. and as they are not economically better than steam/gas turbine, their use is not widespread for co-generation. One more reason for this is the engine maintenance requirement.

10.4 7.4 Methods for Calculating CHP System Efficiency

Two efficiency metrics namely Total system efficiency and Effective electric efficiency are used to compare CHP systems with SHP systems:

Total system efficiency refers to the sum of the useful power output (in MWh expressed in Btu/hr) and useful thermal outputs (in Btu/hr) divided by the total fuel input (in Btu/hr) and is the more commonly cited efficiency metric.

Effective electric efficiency refers to the electricity output divided by the additional fuel the CHP system uses over and above what would have been used by a conventional system to meet the facility's thermal energy load.

Both efficiency metrics consider all the outputs of CHP systems and reflect the benefits of CHP. Since each metric measures a different performance characteristic, the purpose and calculated value of each type of efficiency metric differs. For example, the total system efficiency is typically most appropriate for comparing CHP system energy efficiency with the efficiency of a site's SHP options. The effective electric efficiency is typically used to compare the CHP system with conventional electricity production (i.e., the grid).

In general, a CHP system's total system efficiency differs from its effective electric efficiency by 5% to 15%.

10.5 Typical Cogeneration Performance Parameters

The following Table 10.1 gives typical Cogeneration Performance Parameters for different Cogeneration Packages giving heat rate, overall efficiencies etc.

Table 10.1: Typical Cogeneration Performance Parameters

Prime Mover in Cogen. Package	Nominal Range (Electrical)	Electrical Generation to Heat Rate (kcal / kWh)	Efficiencies, %		
			Electrical Conversion	Thermal Recovery	Overall Cogeneration
Smaller Reciprocating Engines	10 – 500 kW	2650 - 6300	20-32	50	74-82
Larger Reciprocating Engines	500 – 3000 kW	2400 - 3275	26-36	50	76-86
Diesel Engines	10-3000 kW	2770 - 3775	23-38	50	73-88
Smaller Gas Turbines	800-10000 kW	2770-3525	24-31	50	74-81
Larger Gas Turbines	10-20 MW	2770-3275	26-31	50	78-81
Steam Turbines	10-100 MW	2520-5040	17-34	-	-

Note: Adapted from Cogeneration Handbook California Energy Commission, 1982

10.6 Heat: Power Ratio

Cogeneration is likely to be most attractive when the demand for both steam and power is balanced i.e. consistent with the range of steam (Heat) to power output ratios that can be obtained from a suitable cogeneration plant.

Heat-to-power ratio is defined as the ratio of thermal energy to electricity required by the energy consuming facility and expressed in different units such as Btu/kWh, kcal/kWh, kW/kW, etc. It is one of the most important technical parameters influencing the selection of the type of cogeneration system. The proportions of heat and power needed (heat to power ratio) vary from site to site, so the type of plant selected should match demands as closely as possible. The plant may therefore be set up to supply part or all of the site heat and electricity loads, or an excess of either may be exported if a suitable customer is available.

Heat-to-power ratios of different cogeneration systems and for certain energy intensive industries are shown in Table 10.2 & 10.3.

The electrical output is the useful power generation from the turbine and the thermal output is the useful extraction from turbine for process heating. The fuel heat input is the fuel flow rate multiplied by its calorific value.

Table 10.2: Heat-to-power ratios & key parameters of cogeneration systems

Cogeneration System	Heat-to- Power ratio (KW/KW)	Power Output (as % of fuel input)	Overall efficiency %
Back-pressure steam turbine	4.0-14.3	14-28	84-92
Extraction-condensing steam turbine	2.0-10	22-40	60-80
Gas turbine	1.3-2.0	24-35	70-85
Combined Cycle	1.0-1.7	34-40	69-83
Reciprocating Engine	1.1-2.5	33-53	75-85

Table 10.3: Typical Heat: Power ratios for certain energy intensive industries

Industry	Minimum	Maximum	Average
Breweries	1.1	4.5	3.1
Pharmaceuticals	1.5	2.5	2.0
Fertilizer	0.8	3.0	2.0
Food	0.8	2.5	1.2
Paper	1.5	2.5	1.9

10.7 Factors for selection of cogeneration system

Following factors should be given due consideration in selecting the most appropriate cogeneration system for a particular industry.

- Normal as well as maximum/minimum power load and steam load in the plant, and duration for which the process can tolerate without these utilities, i.e. criticality and essentiality of inputs.
- What is more critical - whether power or steam, to decide about emergency back-up availability of power or steam.
- Anticipated fluctuations in power and steam load and pattern of fluctuation, sudden rise and

fall in demand with their time duration and response time required to meet the same.

- Under normal process conditions, the step-by-step rate of increase in drawl of power and steam as the process picks up - whether the rise in demand of one utility is rapid than the other, same or vice-versa.
- Type of fuel available - whether clean fuel like natural gas, naphtha or high-speed diesel or high ash bearing fuels like furnace oil, LSHS, etc or worst fuels like coal, lignite, etc., long term availability of fuels and fuel pricing.
- Commercial availability of various system alternatives, life span of various systems and corresponding outlay for maintenance.
- In general, simultaneous demands for heat and power must be present for at least 4,500 h/year, although there are applications where CHP systems may be cost effective with fewer hours. For example, when electricity rates are high or when the local power provider offers incentives, this operating period could be as low as 2,200 h/year.
- Power-to-heat ratio for the plant should not fluctuate more than 10%.
- Influence exerted by local conditions at plant site, i.e. space available, soil conditions, raw water availability, infrastructure and environment.
- Project completion time.
- Project cost and long-term benefits.

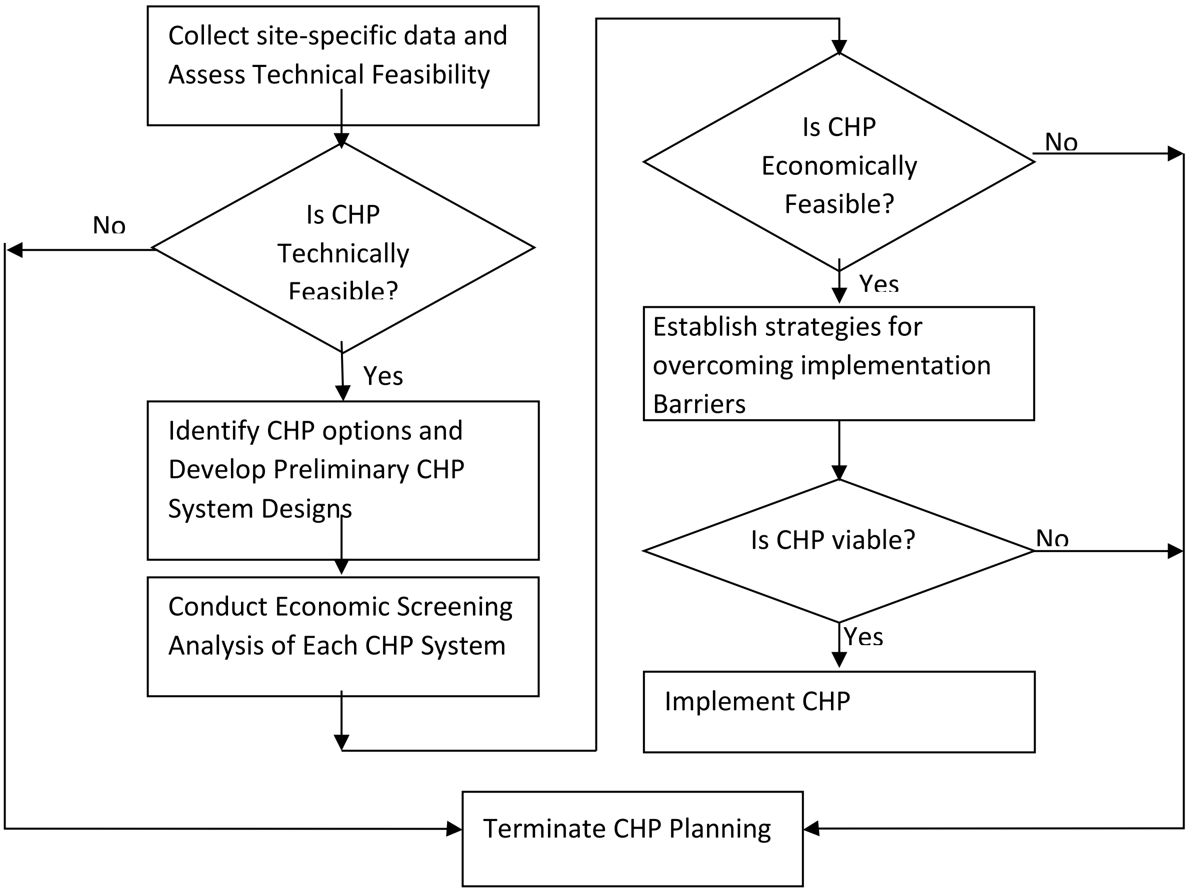


Figure 10.11: Framework for Evaluating CHP viability

10.8 Operating Strategies for Cogeneration Plant

For cogeneration plant there are three main operating regimes:

- The unit is operated to provide base load electrical and thermal output. Any shortfall is supplemented with electricity from external public/private utility and heat from stand-by boilers or boost (thermic fluid) heaters;
- The unit is operated to provide electricity in excess of the site's requirements, for export, whilst all the thermal output is used on site;
- The unit is operated to provide electricity for site, with or without export, and the heat produced is used on site with the surplus being exported to off-site customers.

Table 10.4: Characteristics of Prime Movers for CHP Applications [a]

Prime Mover Characteristic	Steam Turbine	Gas turbine	Micro turbine	Reciprocating Engine	
				Compression Ignition	Spark Ignition
Capacity, MW	0.05 to > 250	0.5 to 250	0.03-0.35	0.03 to 4	0.05 to 5
Power-to-heat ratio	0.05 to 0.2	0.5 to 2	0.4 to 0.7	0.5 to 1	0.5 to 1
Fuels	All types of fuel can be burned to produce steam	Natural gas, bio gas, propane and distillate fuel oil	Natural gas, Waste and sour gases, gasoline, kerosene, diesel and distillate fuel oil	Natural gas, diesel and residual oil	Natural gas, bio gas, propane, land fill gas and gasoline
Installed cost, $/KW	200 -1000	400 -1800	1300 -2500	900 - 1500	901 - 1500
Maintenance cost, $/kWh	≤ 0.002	0.003 - 0.01	≤ 0.018	0.005 - 0.015	0.007 - 0.02
Overhaul period, h	> 50000	12000 - 50000	5000 - 40000	25000 - 30000	24000 - 60000
Start-up time	Hours	Minutes	Minutes	Seconds	Seconds
Total CHP efficiency (HHV) [b]	70 - 85 %	70 - 75 %	65 - 75 %	70 - 80 %	70 - 80 %
CHP electrical efficiency (HHV) [c]	20 - 40 %	22 - 36 %	18 - 29 %	27 - 45 %	22 - 40 %
Availability	Nearly 100%	90 - 98 %	90 - 98 %	90 - 95 %	92 - 97 %
Noise	High	High	High	Moderate	High
Service life	30 years or more	30000 - 100000 hrs	40000 - 80000 hrs	15 - 25 years	15 - 25 years
Part-load operation	Good	Poor	Satisfactory	Good	Satisfactory
NOx control options	Unnecessary but may be required as part of steam supply system.	Steam or water injection, lean premixed combustion, SCR, SNCR and SCONOXTM	Lean premixed combustion, SCR, SNCR and SCONOXTM	Lean air-fuel mixture, SCR, SNCR and SCONOXTM	Lean air-fuel mixture, staged ignition, catalytic 3-way conversion(TWC), SCR, SNCR and SCONOXTM

Prime Mover Characteristic	Steam Turbine	Gas turbine	Micro turbine	Reciprocating Engine	
				Compression Ignition	Spark Ignition
Preferred uses for recovered heat	Process heat, hot water and low-pressure to high pressure steam	Process heat, hot water and low-pressure to high pressure steam	Process heat, hot water and low-pressure steam	Hot water and low-pressure steam	Hot water and low-pressure steam
Temperature of rejected heat, °F	Varies depending on extraction conditions	500 -1100	400 - 600	180 - 900	180 - 1200
Operating mode	Load-tracking and continuous base-loaded operation	Base-loaded, load-tracking, and peak shaving operations	Base-loaded, load-tracking, and peak shaving operations	Base-loaded, load-tracking, emergency and peak shaving operations	Base-loaded, load-tracking, emergency and peak shaving operations
Potential applications	Topping-cycle, bottoming-cycle, combined-cycle, and trigeneration CHP systems	Topping-cycle, combined-cycle, and trigeneration CHP systems	Topping-cycle, combined-cycle, and trigeneration CHP systems	Topping-cycle, combined-cycle, and trigeneration CHP systems	Topping-cycle, combined-cycle, and trigeneration CHP systems
a Based on CHP systems that operate at least 8000 hrs/year					
b Total CHP efficiency is a measure of (the net electricity generated plus the net heat supplied to the process), divided by the total fuel input					
c CHP electrical efficiency is a function of the net electricity generated, divided by the total fuel input					

Table 10.5: Sources of Information for decision making

Required information	**Sources of Information**								
	Energy Audit	**Utility Company**	**Fuel Suppliers**	**Equipment Suppliers**	**Management**	**Legal authorities**	**Air -water quality authority**	**Special authorities[b]**	**Financial Institutions**
Total thermal loads, magnitude and profile	X								
Total electrical loads, magnitude and profile	X								
Cooling Loads	X								

Required information	Sources of Information								
	Energy Audit	**Utility Company**	**Fuel Suppliers**	**Equipment Suppliers**	**Management**	**Legal authorities**	**Air -water quality authority**	**Special authorities[b]**	**Financial Institutions**
Major load centres and energy consumers	X								
Anticipated load changers, Mission or Function changes	X								
Waste heat sources	X								
Waste fuel sources	X								
Complimentary off-site loads	X								
Present Electrical Energy Costs and Rate Formats	X	X							
Projected Electrical Energy Rate structure		X							
Policies towards parallel generation		X							
Ownership/Operation policies and preferences		X			X				
Cogenerator rate structure, Standby charges, Reliability Requirements, Payment for Power to Grid		X							
Environmental and Siting Constraint Overview		X							
Tax and Investment Incentives		X				X			
Regulations Related to Cogeneration		X				X			
Present Fuel Costs	X		X						
Projected fuel costs		X	X						
Projected fuel availability		X	X						
Fuel Characteristics and Properties			X						
Performance Data, Design and Off Design Conditions				X					
Fuel Consumption				X					
Fuel Flexibility				X					
Emissions Data and Specifications				X					
Air Emission Regulations				X			X		
Other Emission Regulations				X				X	

Required information	Sources of Information								
	Energy Audit	**Utility Company**	**Fuel Suppliers**	**Equipment Suppliers**	**Management**	**Legal authorities**	**Air -water quality authority**	**Special authorities[b]**	**Financial Institutions**
Fiscal Policies					X				
Funding Sources					X				X
Cost and Conditions of financing									X
Siting restrictions						X	X	X	

an Oil, Natural gas or Coal

b For example, Zoning, airport, Coastal

(Source : Cogeneration Systems- Technical Report by E Cooper 1980)

10.9 Relative Merits of Co-Generation Systems

The following Table 10.6 gives the advantages and disadvantages of various co-generation systems:

Table 10.6: Advantages and disadvantages of various cogeneration systems

Variant	Advantages	Disadvantages
Back-pressure	- High fuel efficiency rating	Little flexibility in design and operation
Steam turbine & fuel firing in boiler	• Simple plant • Well-suited to low quality fuels	• More capital investment • Low fuel efficiency rating • High cooling water demand • More impact on environment • High civil const. cost due • to complicated foundations
Gas turbine with waste heat recovery boiler	• Good fuel efficiency • Simple plant • Low civil const. Cost • Less delivery period • Less impact on environment • High flexibility in operation	• Moderate part load efficiency • Limited suitability for low quality fuels
Combined gas & steam turbine with waste heat recovery boiler	• Optimum fuel efficiency rating • Low relative capital cost • Less gestation period • Quick start up & stoppage • Less impact on environment • High flexibility in operation	• Average to moderate part-load efficiency • Limited suitability for low quality fuels
Diesel Engine & waste heat recovery Boiler & cooling water heat exchanger	• Low civil const. Cost due to block foundations & least no. of auxiliaries • High Power efficiency • Better suitability as standby power source	• Low overall efficiency • Limited suitability for low quality fuels • Availability of low temperature steam • Highly maintenance prone.

10.10 Case Study

Economics of a Gas Turbine based Cogeneration System

Alternative I: Gas Turbine based Cogeneration.		
Gas Turbine Parameters	Units	Quantity
Capacity of gas turbine generator	KW	4000
Plant operating hours per annum	hrs/ year	8000
Plant load factor (PLF)	%	90%
Heat rate as per standard given by gas turbine suppliers	KCal/KWH	3049.77
Waste heat boiler parameters- unfired steam output	TPH	10
Steam temperature	°C	200

Steam pressure	Kg/ Sq.cm	8.5
Steam enthalpy	Kcal/Kg	676.44
Fuel used		Natural Gas
Calorific Value - LCV	Kcal/ S cCum	9500
Price of gas	BDT/1000 S cum	3000
Capital investment for Cogeneration plant	BDT	1,300,000.00
Cost Estimation of Power & Steam from Cogeneration Plant		
Power generated = PLF x Plant Capacity x Operating hrs	KWH/ Year	28,800,000.00
Heat input = Power generated x Heat rate given by turbine supplier	Kcal	87,833,376,000
Natural gas(NG) required per annum = Heat input/ LCV of NG	S cum	9,245,619
Annual cost of fuel = Gas consumed x price	BDT	27,736,856.00
Annualised Cost of capital and operation charges	BDT	29,863,000.00
Overall cost of power from cogeneration plant (Alternative -I Cost)	BDT	57,599,856.00
Cost of power	BDT/KWH	2

Alternative-II Electric Power from State Grid & Steam from Natural Gas (NG) Fired Boiler		
Boiler installed in plant	TPH	10
Cost of electric power from grid	BDT/KWH	3
Capital investment for 10TPH, 8.5 kg/cm2 @ 200°C NG fired fire tube boiler & all auxiliaries	BDT	8,000,000.00
Hours of operation	hrs/ year	8000
Cost Estimation of Power & Steam from Grid and Steam from direct Conventional fired boiler		
Cost of power from state grid for 28,800,000 KWH	BDT/ year	86,400,000.00
	Fuel cost for steam by separate boiler	
Heat output in form of 10TPH steam per annum = Boiler capacity x steam Enthalpy x Hrs of operation	Kcal/ year	54,115,200,000
Heat input required to generate 10TPH steam per annum @ 90% efficiency	Kcal/ year	60,128,000,000

Natural gas(NG) required per annum = Heat input/ LCV of NG	S cum/ year	6,329,263
Annual cost of fuel = Gas consumed x price	BDT	18,987,789.00
Total cost for alternative II= Cost of grid power + fuel cost for steam	BDT	105,387,790.00
Alternative -I total cost	BDT	57,599,856.00
Alternative -II total cost	BDT	105,387,790.00
Differential cost	BDT	47,787,934.00

(Note: In case of alternative II, there will be some additional impact on cost of steam due to capital cost required for a separate boiler)

In the above case it can be seen that Alternative I is economical compared to Alternative II.

10.11 Trigeneration

Trigeneration refers to simultaneous generation of steam (heat), power and refrigeration through integrated systems. Industries requiring electricity, steam and cooling such as food processing and cold storages find the concepts of tri-generation very attractive.

A combined cycle trigeneration plant could typically consist of a gas turbine generator, waste heat recovery boiler, steam turbine, generator, and absorption chiller, to meet 100% of the facility energy needs. Whenever the power is surplus, it is sold to the grid.

An illustrative trigeneration system schematic is presented in Figure 10.12.

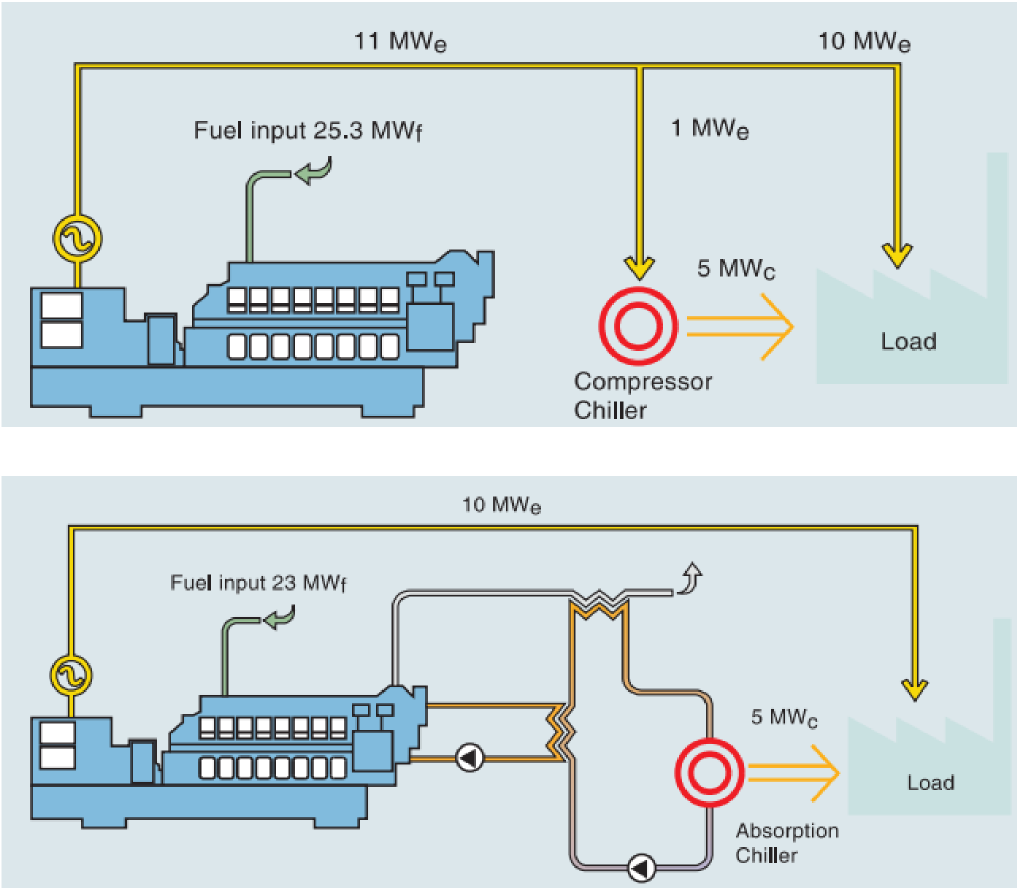


Figure 10.12: Trigeneration: Power, Heating and Cooling

10.12 Microturbine

The Micro steam Turbine Power System is a compact, efficient power system that generates electricity from pressure energy previously wasted in the steam pressure reducing valves.

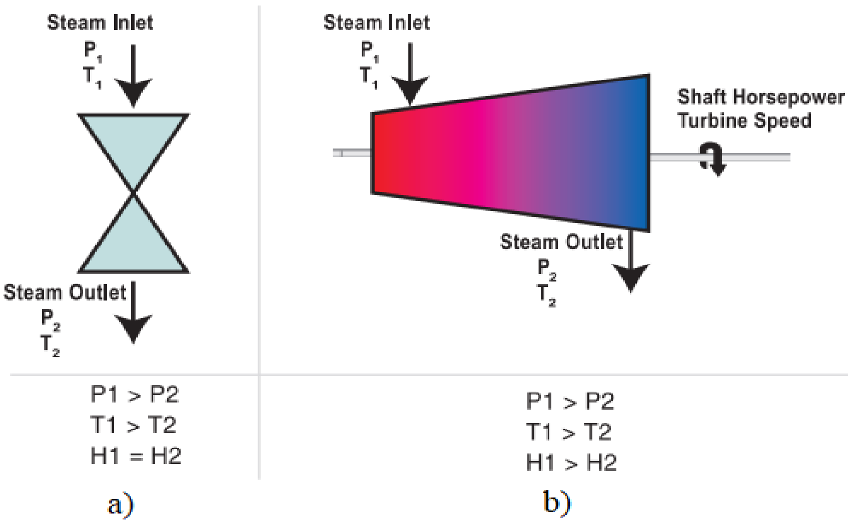


Figure 10.13 a) PRV, b) Micro turbine

In a typical steam system, a Pressure Reducing Valve (PRV) reduces the steam pressure from P1 to P2 (Figure 10.13a). This pressure reduction happens in such a manner that the total energy content (enthalpy) does not change (H1 = H2) and no shaft work is done.

On the other hand, when steam goes through a steam turbine, it expands and the steam pressure reduces from P1 to P2 (Figure 10.13b). The steam turbine produces shaft horsepower and as a result, the steam exit energy content (enthalpy) is lower when compared to the PRV case.

Steam is used for heating purposes in the plant. The process heat duty is fixed by the plant demand. Since the steam supplied to the process has a lower enthalpy, an additional amount of steam is required to ensure the same available heat duty. This additional amount of steam has an associated cost. Hence, power generated from a backpressure steam turbine is not free.
Nevertheless, using a backpressure steam turbine can improve the overall plant and global energy efficiency and more importantly, it can reduce total operating costs.

CHAPTER 11: WASTE HEAT RECOVERY

11.1 Introduction

Industrial waste heat refers to the heat energy that is generated but not fully utilized in the industrial processes and leaves the boundaries of a plant or building into the surrounding environment. Waste heat is generally associated with waste streams of air, exhaust gases, water, or other liquids. Waste heat losses arises both from equipment inefficiencies and due to equipment and process requirements. These losses can be reduced by improving equipment efficiency and installing waste heat recovery technologies.

Waste heat recovery (WHR) equipment is defined as any mechanical apparatus which usefully recovers thermal energy from process waste streams that are above ambient temperatures. The recovered heat is used to produce heat, generate power and in some cases for cooling applications. The aim of this chapter is to provide an understanding of why, when and how to recover waste heat and will cover the following aspects of WHR.

- Opportunities and benefits of WHR
- factors effecting waste heat recovery
- applications of waste heat
- WHR methods and technologies
- Industry/sector specific applications of WHR technologies
- Formulae for calculating heat losses
- Case examples of WHR implemented

11.2 Opportunities and benefits of WHR

The best waste heat-recovery opportunities are those that have the following characteristics:

- The waste heat supply is constant.
- The need is co-located with the waste heat supply.
- The need is synchronized with the available waste heat.
- The waste heat supply is higher in temperature than the need or
- The need and the waste heat stream temperatures match the capabilities of available heat-pumping equipment.
- The size of the waste heat stream and the need are large enough to justify the custom engineering required.

Benefits of 'waste heat recovery' can be broadly classified in two categories:

9.3.1

9.3.2 Direct Benefits:

Recovery of waste heat has a direct effect on the efficiency of the process. This is reflected by reduction in the utility consumption and process cost.

9.3.3 Indirect Benefits:

a) Reduction in equipment sizes: Waste heat recovery reduces the fuel consumption, which leads to reduction in the flue gas produced. If WHR systems are considered and incorporated at design stage it may result in reduction in equipment sizes of all flue gas handling equipment such as fans, stacks, ducts, burners, etc. In other modification and retrofit cases possibility exists to reduce the size of equipment.

b) Reduction in auxiliary energy consumption: Reduction in equipment sizes gives additional benefits in the form of reduction in auxiliary energy consumption like electricity for fans, pumps etc.

c) Reduction in pollution: A number of toxic combustible wastes such as carbon monoxide gas, sour gas, carbon black off gases, oil sludge, Acrylonitrile and other plastic chemicals etc., when combusted/burnt in the thermal oxidation or incinerators serves dual purpose of heat recovery and mitigation of the environmental pollution levels.

11.3 Factors affecting waste heat recovery

Before considering waste heat recovery it is important to consider why, when and how to recover this waste heat to gain benefits. The following factors influence the selection of a heat exchanger.

- Source of the waste heat stream.

In few cases it is difficult to access and recover heat from unconventional sources such as hot solid product streams (e.g., ingots) and hot equipment surfaces (e.g., sidewalls of primary aluminium cells).

- Amount of waste heat available

Once you find suitable waste heat source, it is important to establish that the source is capable of supplying sufficient 'quantity' of heat, and that the heat is of a good enough 'quality' (i.e. temperature) to promote good heat transfer.

- Characteristics of the waste heat stream

Essential considerations in making optional choice of waste heat recovery device:

1) Temperature of waste heat. (Temperature is a measure of quality of waste heat)
2) Flow rate of the fluid
3) Chemical composition of waste fluid
4) Properties of waste fluid (C_p, μ, ρ, κ)
5) Allowable pressure drop
6) Minimum temperature to which waste heat can be cooled
7) Corrosive elements in the exhaust fluid
8) Temperature to which the designed fluid is to be heated

The quality of the heat is based on the waste stream temperature and it is divided into three grades as mentioned in table 11.1 below. Higher the grade, the greater the potential value for heat recovery.

Table 11.1: Different grades of heat

High Grade	Medium Grade	Low Grade
1100°F – 3000°F (593°C – 1649°C)	400°F – 1100°F (204°C – 593°C)	80°F – 400°F (27°C – 204°C)

- Waste heat use.

It is important to have a use for any waste heat which may be recovered. In many applications there may be no demand for the heat that is available, with the result the excess heat energy is dumped into the environment. In other situations there may be a long time lag between waste heat production and the demand for heat. Waste heat therefore cannot be used unless there is some use of waste heat and/or some form of thermal storage is available.

Waste heat can be used in various ways, but the major uses include the following:

1) preheating combustion air
2) generating electrical and mechanical power

3) generating process steam
4) preheating boiler water
5) heating general process liquids and solids
6) heating viscous, corrosive, and difficult liquids
7) heating, ventilation and refrigeration applications.

The source of heat for applications 1 through 4 is usually hot gases, most frequently from combustion processes. The source of heat for applications 5 through 7 is usually process steam, process liquids/solids or exhaust air.

Table 11.2: Major Applications of Waste Heat Recovery

Application / Heat Exchanger Type	Pre-heat combustion air	Generate power	Generate Process steam	Pre-heat boiler water	Heat process liquids	Corrosive and viscous fluids	Heating and ventilation
Tube in tube	✓				✓		
Shell in tube		✓	✓	✓	✓		
Direct Contact	✓						
Solid plate fin	✓						✓
Heat pipes							✓
Run-around coils					✓	✓	✓
Spiral				✓	✓	✓	
Coils					✓		✓
Plate and frame					✓	✓	✓
Finned tube							✓
Panel coil					✓		
Cartridge					✓	✓	
Screw conveyor					✓	✓	

- Adequate space availability to install heat recovery system

Many facilities have limited physical space to access waste heat streams and to install waste heat recovery systems (e.g., limited floor or overhead space). In such cases it may not be feasible to install the heat recovery system.

- Primary energy saving possibility

Often the insertion of a heat exchange system increases the resistance of the fluid streams, resulting in higher fan or pump energy consumption. Heat energy is therefore replaced by electrical energy with no net energy savings.

- Economic viability or cost effectiveness of WHR technology

Heat recovery devices can be expensive to install. It is therefore essential that the economic payback period be determined before any investment is undertaken. If proper planning and analysis is not carried out at the concept and design stage, impact of installation of a waste heat recovery device is minimal or may even increase energy cost.

WHR technologies are similar to heat exchangers. The heat exchangers considered unviable are now being considered for heat recovery for the following reasons

- Heat exchange equipment costs came down making them viable

- Fuel costs increased making an economic case for waste heat recovery
- Regulatory requirements might have made it mandatory to install the same.

11.4 Overview of Waste Heat Recovery Methods and Technologies

Once the need and feasibility to install WHR equipment is established the next logical step is to select the appropriate method for utilization of waste heat and the equipment required.
The common methods by which waste heat is utilized are as follows.

- Direct utilization (e.g.: for drying or process heating)
- Energy Cascading (Using energy for high temperature application first followed by using the rejected heat for low temperature applications. For example after using high temperature and pressure steam for power generation low temperature and pressure steam can be used for other processes or space heating).
- Cogeneration (Producing electrical power and process heat simultaneously)
- Recuperators (Shell and tube, plate, coil, spiral heat exchangers)
- Regenerators (stationary or rotating type)
- Waste heat boilers

WHR can be classified based on the maximum outlet temperature of recovered waste heat. Accordingly based on waste heat stream temperatures WHR equipment is classified as follows.

1) Gas-to-gas heat exchanger (Graphite heat exchangers, stack-type recuperators, direct contact recuperator, plate fin (ceramic and metal) heat exchangers and ceramic tubes)
2) Gas-to-liquid heat exchanger (waste heat boilers, economizers and power generators)
3) Liquid-to-liquid heat exchanger (shell-and-tube, spiral, coil, finned-tube, plate-and-frame (plate), and run-around heat exchangers)
4) Other low-temperature WHR equipment (heat pumps, and heat pipes)

At higher temperature, only gas-to-gas heat transfer is used because of the difficulties encountered at these temperatures. At moderate temperatures (up to ~1000°F), gas-to-liquid transfer is used (steam boilers). At lower temperatures, the dominant mode is liquid-to-liquid heat recovery.

A brief description of commonly encountered heat exchangers is given in sections below.

11.4.1 Gas-to-gas Heat Exchanger

Graphite heat exchangers

Graphite heat exchangers have high thermal conductivity and frequently used for heating or cooling of ultra-corrosive liquid chemicals. This specific design allows for heat recovery between two ultra-corrosive fluids.

Figure 11.1: Graphite heat exchangers

(*Source: GAB Neumann's Annular Grove graphite heat exchangers*)

Recuperators

This is the most common type of equipment used for waste heat recovery. In this heat transfer is affected by bringing hot and cold streams adjacently where in heat from hot fluid is transferred through the fluid separation barrier by means of convection and conduction. The radiation recuperator gets its name from the fact that a substantial portion of the heat transfer from the hot gases to the surface of the inner tube takes place by radiative heat transfer. The cold air in the annuals, however, is almost transparent to infrared radiation so that only convection heat transfer takes place to the incoming air.

Based on type of heat transfer they are classified as stack-type or direct contact recuperators. Based on material of construction the direct contact recuperators are further classified as metallic recuperator (used to recover heat from gases at about 1000^{o}C) and ceramic recuperator (used to recover heat from gases at about 1550^{o}C).

Stack-type Recuperators

Stack type recuperators are used when the stack gas temperatures are high and heat transfer dominantly occurs by radiation rather than convection. These are generally co-current heat exchangers and are used for air preheating and is considered cost effective. It has an advantage that hot gases do not have to be rerouted and fans are not required to produce a draft. A major disadvantage is it required substantial heat difference between exhaust gas and preheat air.

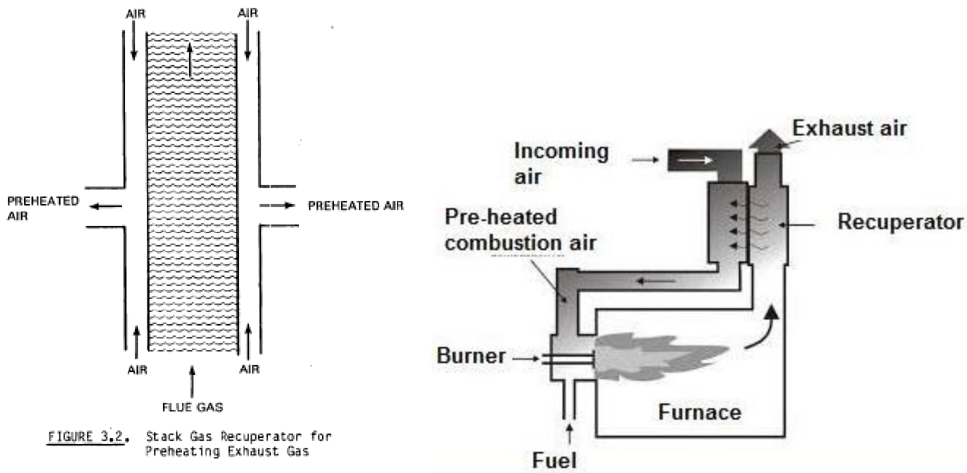


Figure 11.2: Preheating Combustion Air using a Recuperator in Furnace

Direct contact recuperator (ceramic and metal) heat exchangers

Direct contact recuperators provide highest air preheat temperature. These recuperators are also called "checkers". In this heat exchanger exhaust and air streams are alternated between two sets of checkers. The exhaust stream heats the checkers in one set while the air is being heated by the other. These are considered expensive and require considerable space for duct work and damper arrangements.

Metallic recuperator

The simplest configuration for a recuperator is the metallic radiation recuperator, which consists of two concentric lengths of metal tubing as shown in Figure 11.3.

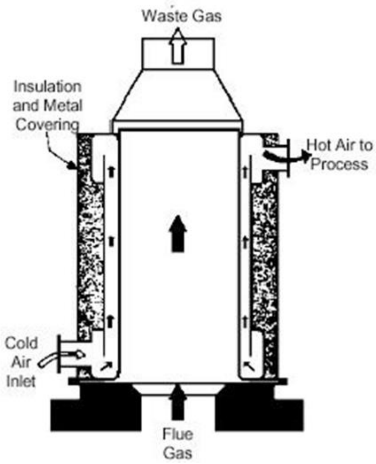


Figure 11.3: Metallic radiation recuperator

The inner tube carries the hot exhaust gases while the external annulus carries the ambient air from the atmosphere which recovers the heat from hot exhaust gases. The heated ambient air is supplied via air inlets of the furnace burners. This equivalent energy of hot combustion air does not have to be supplied by the fuel. So, less fuel is burned for a given furnace loading. The saving in fuel also means a decrease in combustion air requirements and therefore lesser quantities of exhaust gas.

The principal limitation of metal recuperators is the reduced life of the liner at inlet temperatures exceeding 1100°C.

Ceramic Recuperator

In order to overcome the temperature limitation of metallic recuperators, ceramic tube recuperators have been developed. The materials of ceramic recuperators allow operation on the gas side up to 1550°C and on the preheated air side up to 850°C. Early ceramic recuperators were built of tile and joined with furnace cement, and thermal cycling caused cracking of joints and rapid deterioration of the tubes. Later developments introduced various kinds of short silicon carbide tubes which can be joined by flexible seals located in the air headers.

Although the design of this heat exchanger may change with its particular application, three types are widely used.

Flat plate recuperator

Flat plate recuperator (Figure 11.4) consists of a series of metal (usually aluminium) plates separating ‘hot’ and ‘cold’ air or gas flows sandwiched in a box-like structure. The plates are sealed in order to prevent intermixing of the two fluid flows. They are often used in ducted air-conditioning installations to reclaim heat from the exhaust air stream without cross contamination.

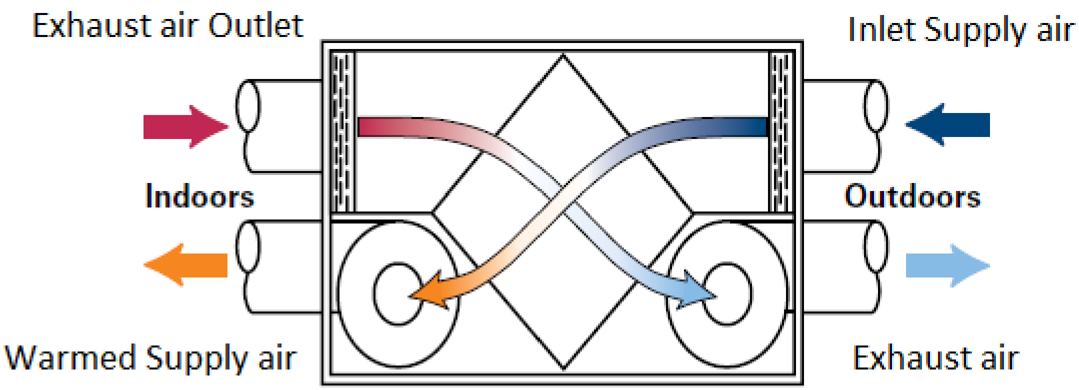


Figure 11.4: Flat Plate Recuperator

Plate fin (ceramic and metal) heat exchangers

Plate fin heat exchangers overcomes the problems associated with direct contact types and for high temperature applications (> 1360°F discharge air and > 1500 °F for flue gas) are available in both metal and ceramic designs

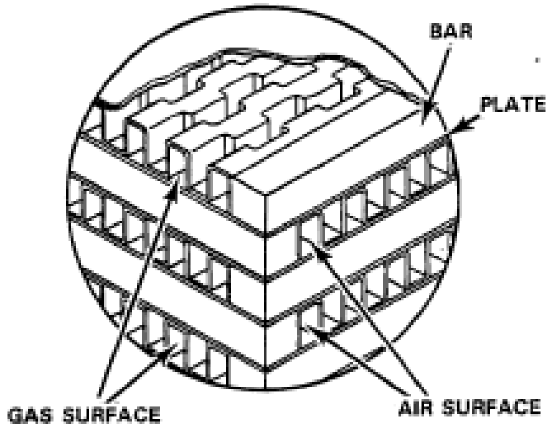


Figure 11.5: Plate Fin Heat Exchanger

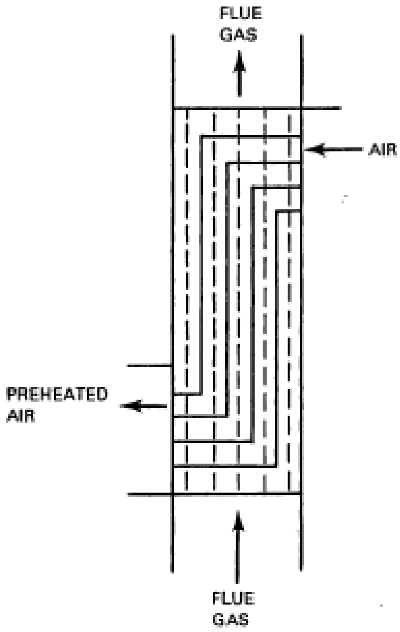


Figure 11.6: Metallic Recuperator with cross-counter flow design

Ceramic tubes

These are tubular heat exchangers made of ceramic tubes. They have problems of differential thermal expansion of the ceramic tubes and related hardware which can cause cracking and sealing problems.

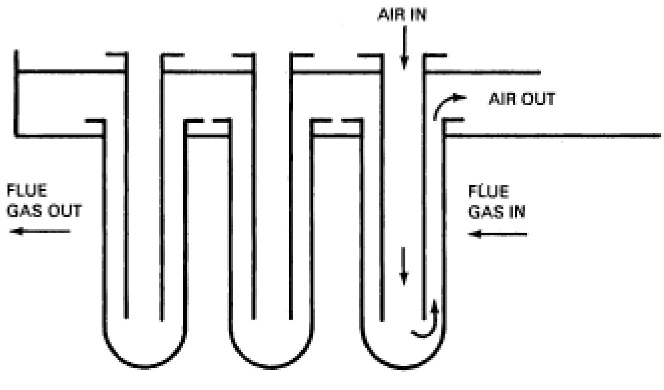


Figure 11.7: Ceramic Re-entrant Tube Heat Exchanger

11.4.2 Gas-to-liquid heat exchanger

Waste Heat Boilers

Waste heat boilers are available with fire-tube or water-tube designs in both extended surface and smooth tube models.

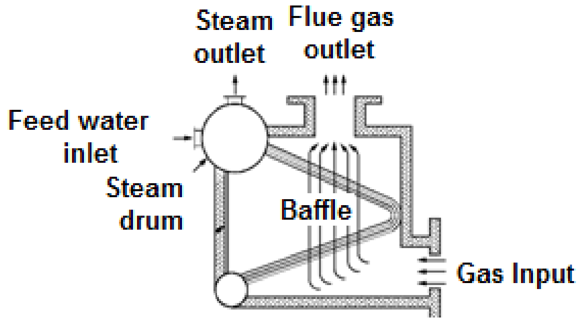


Figure 11.8: Generating Steam using Waste Heat Boiler

Economizers

Economizers operate on exhaust gas that already passed through either recuperators or waste heat boilers and are intended to operate waste heat from other heat utilization or recovery equipment. The dew point condensation of exhaust gases sets the lower operating limit for conventional economisers. Direct contact economisers using liquid spray etc. captures the latent heat (~ 1000 BTU/lb of water vapor contained) as well as the remaining sensible heat.

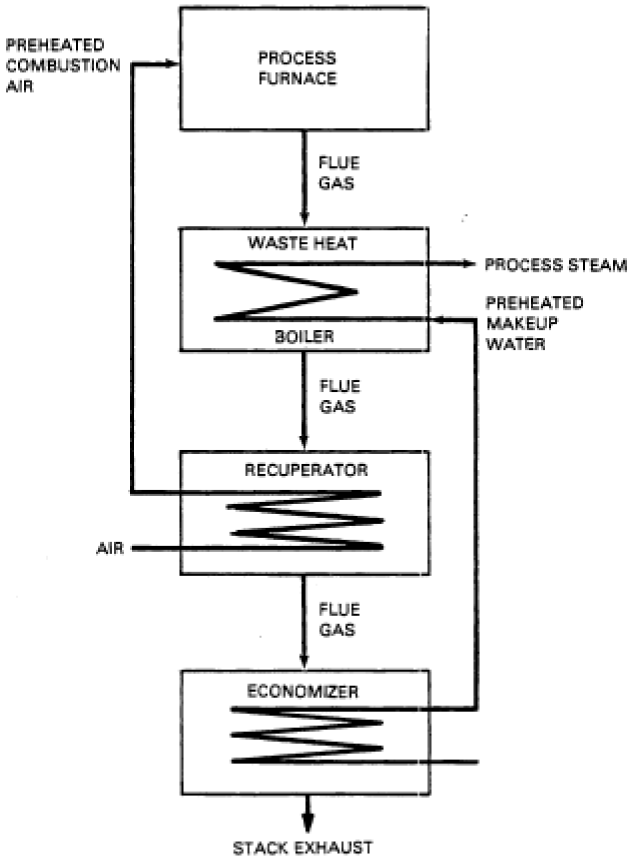


Figure 11.9: Schematic Diagram of Waste Heat Boiler Recuperator and Economizer

Power Generators

Cogeneration where process steam and power are jointly generated is used to reduce heat wastage. Organic Rankine cycle is used where waste heat temperatures are lower compared to conventional steam cycle systems.

Organic Rankine Cycle (ORC)

ORC unit is a power generation plant which on a mini-scale is typically in the range of 10–250 kW. Unlike the traditional power plant where working fluid is water, evaporated gas is steam, and engine is steam turbine, the ORC system uses working fluids which boil at much lower temperatures and pressures than water. Typical organic fluids used include R234fa, R134, pentane, cyclopentane, n-heptace, hexane, and toluene. The ORC systems can even work on low temperature heat sources (90–300˚C) for heat recovery.

The schematic of ORC system is shown in Figure 11.10. The ORC system is based on the principle whereby organic fluid is heated causing it to evaporate, and the resulting gas is used to turn an organic vapour turbine (expander) which is coupled to a generator producing power. The exhaust vapour is subsequently condensed in water or air-cooled condenser and is recycled to the vaporiser by a liquid pump.

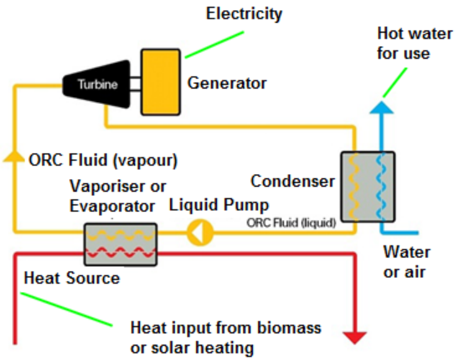


Figure 11.10: Schematic of a Small-Scale Organic Rankine Cycle

11.4.3 Liquid-to-liquid heat exchanger:

Shell-and-tube

The most frequently used industrial heat exchanger is the shell-and-tube heat exchanger. It can be made from any material or combination of materials including metal, graphite and glass. The configuration of this heat exchanger is multiple parallel, small-diameter tubes are mounted inside a single, large-diameter tube wherein one fluid flows on the inside of the tubes, while the other fluid is forced through the shell and over the outside of the tube. To ensure that the shell-side fluid will flow across the tubes, and thus induce higher heat transfer, baffles are placed in the shell as shown in figure 11.11. Depending on the head arrangement at the end of the exchanger, one or more tube passes may be used.

The disadvantage of this exchanger is difficulty in cleaning the outside of the tube bundle because of which tis is normally used for fluids where significant fouling is not expected.

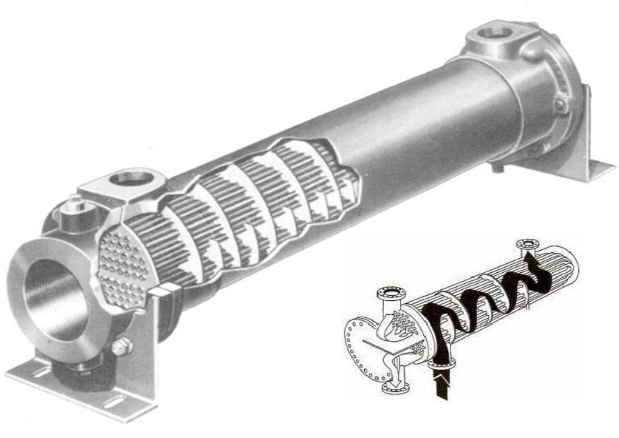


Figure 11.11: Shell-tube heat exchanger with one pass

Plate heat exchanger

Plate heat exchanger also called compact heat exchangers (have surface areas greater than 650 m^2/m^3.), (Figure 11.12) are primarily used in gas-flow systems where the overall heat-transfer coefficient are low and it is desirable to achieve a large surface area in a small volume. They can easily be expanded or contracted to accommodate future system modification. These heat exchangers consists of a large number of thin metal plates (usually stainless steel, titanium, or nickel), which are clamped tightly together and sealed with gaskets. The thin plates are profiled so that 'flow ways' are created between the plates when they are packed together. This leads to formation of large surface area, across which heat transfer can take place. Ports located at the comers of the individual plate separate the 'hot' and 'cold' fluid flows and direct them to alternate passages so that no intermixing of hot and cold fluid occurs. The whole exchanger experiences a counter-flow pattern.

The maximum operating temperature is usually about 130°C if rubber sealing gaskets are fitted, but the operating temperature can be extended to 200°C if compressed asbestos fibre seals are used.

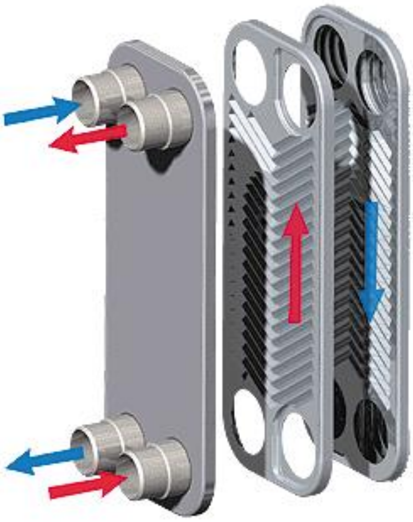
The advantage of these heat exchangers are it is easier to clean, and is only one-fourth the size of the shell-and tube heat exchangers, less prone to fouling and less costly to operate in the long-term than shell-and-tube heat exchangers. For similar applications, plate heat exchangers may be smaller, more efficient, have less internal volume, and cost less than shell-and-tube heat exchangers.

The high-efficiency, low-approach temperatures, counter-flow design, relative ease of fabrication from exotic materials, and clean ability are making the plate heat exchanger attractive for some very difficult liquid-to-liquid applications, such as recovering heat from geothermal brines and manufacturing of chemicals and pharmaceutics.

Although plate heat exchangers are typically meant for liquid to liquid heat exchange, they are now available for even gas to liquid and even for gases laden with tar with provision of cleaning system.

Spiral heat exchanger

Spiral heat exchangers use a double spiral of strip material sandwiched between two plates providing separate spiral flow paths for the fluids as shown in figure 11.13. They can be dismantled easily for cleaning and inspection.



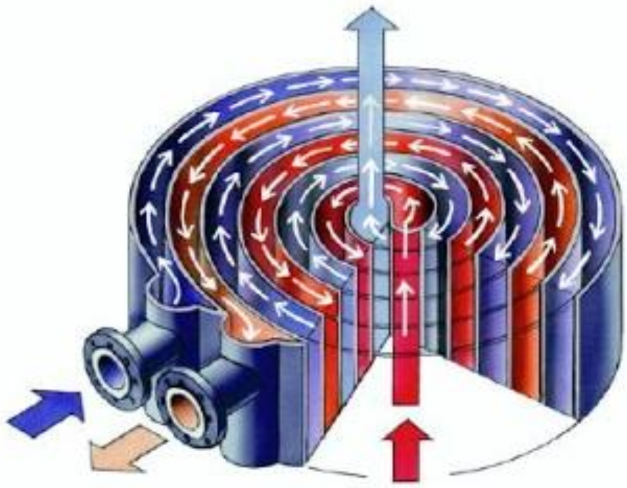


Figure 11.12: Plate Heat Exchanger *Figure 11.13: Spiral Heat Exchanger*

Coil heat exchangers

Coils are often used for cooling small amounts of fluid keeping a critical mechanical equipment cool. Heat is transferred between the fluid in the coil and a fluid bath.

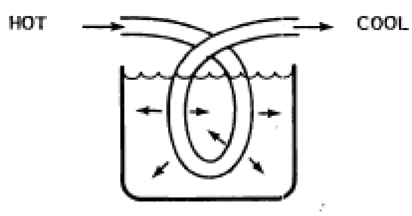


Figure 11.14: Coil Heat Exchanger

Finned-tube heat exchangers

Tube-type heat exchangers often use fins on the heat exchanger tubing. Fins can increase the heat transfer rate by increasing the effective heat transfer area. The fins typically run circumferentially around the outside of the tube, although longitudinal fins and internal fins are also used. The fins may be solid or segmented. (Segmented fins are lighter and increase the heat transfer rate by increasing turbulence.)

Run-around Coils

When two recuperative heat exchangers are linked together by a secondary fluid which transports heat between them, the system is known as a run-around coil. The cooling system in an automobile where the engine is the source of heat and the air is the sink and the heat is transferred using coolant liquid is an example of run-around coil type heat exchanger. Run-around coils are often employed to recover waste heat from exhaust air streams and to preheat incoming supply air. This will thereby help avoid the risk of cross-contamination between the two air streams. Such a system is shown in Figure 11.15.

Run-around coils have the advantage that they can be used in applications where the two fluid streams are physically far apart to use a recuperative heat exchanger. While this feature is usually considered advantageous, it can increase energy consumption since a pump is introduced into the system. It may also result in heat loss from the secondary fluid. This makes it important to insulate the pipe work circuit; otherwise, the overall effectiveness of the system will be reduced. Run-around coils are relatively inexpensive to install since they utilise standard air/water heating coils.

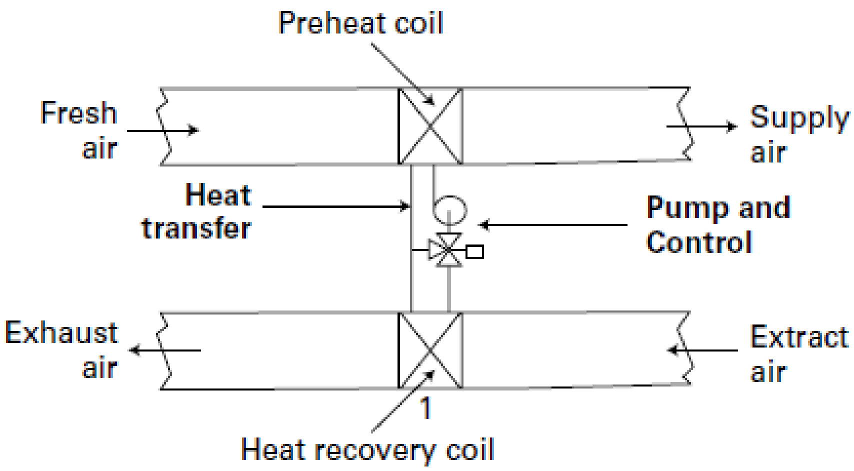


Figure 11.15: Run-around Coil Heat Recovery System

11.4.4 Regenerative Heat Exchangers

In a regenerative heat exchanger a matrix of material is alternately passed from a hot fluid to a cold fluid, so that heat is transferred between the two in a cyclical process. The most commonly type of regenerative heat exchanger is thermal wheel (Figure 11.16) which has a matrix of material mounted on a wheel rotating at about 10 rpm, through hot and cold fluid streams alternatively. The major advantage of the thermal wheel is the large surface area to volume ratio which results in a relatively low cost per unit surface area.

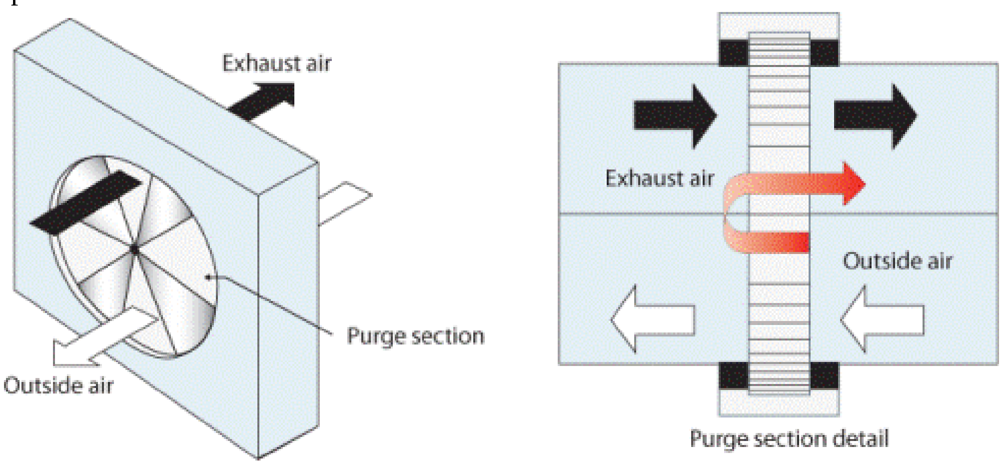


Figure 11.16: Thermal Wheel

The matrix material in the thermal wheel is usually an open structured metal made of knitted stainless steel or aluminium wire, or corrugated sheet aluminium or steel. For use at higher temperatures honeycomb ceramic materials are used. Although thermal wheels are usually used solely to recover sensible heat, it is possible to reclaim the enthalpy of vaporisation of the moisture in the 'hot' stream passing through the thermal wheel. This is achieved by coating a non-metallic matrix with a hygroscopic or desiccant material such as lithium chloride.

The main disadvantage of thermal wheels is that there is the possibility of cross-contamination between the air streams. This can be reduced considerably by ensuring that the cleaner of the two fluids is maintained at the highest pressure and with a use of purging device.

Case 11.1

A rotary heat regenerator was installed on a two colour printing press to recover some of the heat, which had been previously dissipated to the atmosphere, and used for drying stage of the process. The outlet exhaust temperature before heat recovery was often in excess of 100°C. After heat recovery the temperature was 35°C. Percentage heat recovery was 55% and pay back on the investment was estimated to be about 18 months. Cross contamination of the fresh air from the solvent in the exhaust gases was at a very acceptable level.

11.4.5 Low-temperature WHR equipment

9.3.4

9.3.5 Heat Pump

A heat pump is essentially a vapour compression refrigeration machine which takes heat from low temperature source such as air or water and upgrades it to be used at higher temperature. Unlike a conventional refrigeration machine, using heat pump the heat produced at the condenser is used and not wasted to the atmosphere. The Figure 11.17 shows the operating principle of simple vapour compression heat pump.

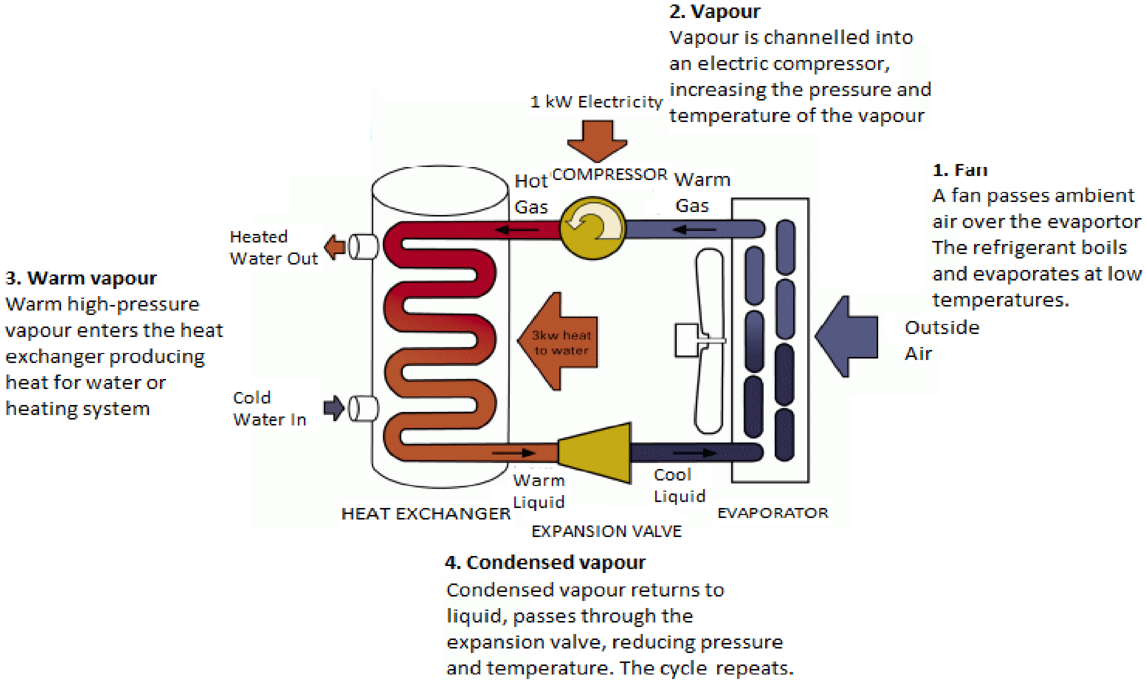


Figure 11.17: Vapor Compression Heat Pump

The performance of the vapour compression refrigeration cycle is quantified by the coefficient of performance (COP), which can be expressed as follows:

For a refrigeration machine: $$\mathrm{COP_{Ref}} = \frac{\text{Useful Refrigeration Output}}{\text{Net Work Input}}$$

For a heat pump: $$\mathrm{COP_{Hp}} = \frac{\text{Useful Heat Rejected Cycle}}{\text{Net Work Input}}$$

Heat pumps are well suited to applications where the evaporating and condensing temperatures are close together such as in the cases when recovering heat from exhaust air in heating and air conditioning applications. As a result, heat pumps are often used in air conditioning applications.

Heat Pipe

Heat pipes are devices which can transfer 1000 times more thermal energy than copper. It can be used in traditionally difficult heat exchange environments such as high particulate gases, dirty liquids, corrosive environments, low temperature gradients.

Heat pipe is basically a metal and metal alloy tube that is sealed on both ends and with an internal wick or mesh along the interior of the pipe. The Heat Pipe comprises of three elements – a sealed container, a capillary wick structure and a working fluid. The capillary wick structure is integrally fabricated into the interior surface of the container tube and sealed under vacuum. Thermal energy applied to the external surface of the heat pipe is in equilibrium with its own vapour as the container tube is sealed under vacuum and causes the working fluid near the surface to evaporate instantaneously. Vapour thus formed absorbs the latent heat of vaporization and this part of the heat pipe becomes an evaporator region. The vapour then travels to the other end the pipe where the thermal energy is removed causing the vapour to condense into liquid again, thereby giving up the latent heat of the condensation. This part of the heat pipe works as the condenser region. The condensed liquid then flows back to the evaporated region. (Figure 11.18) is Heat pipe has a working fluid within a vacuum and typical working fluids used include liquid nitrogen, methanol, water, and sodium. The temperature range along with fluid type and compatible metals tubes are given the table 11.3 below.

Table 11.3: Temperature Ranges for Heat-Transfer Fluids Used in Heat Pipes

Fluid	Temperature range (°C)	Compatible Metals
Nitrogen	-180 to 80	Stainless steel
Ammonia	-70 to 60	Nickel, Aluminium, Stainless steel
Methanol	-45 to 115	Nickel, Copper, Stainless steel
Water	5 to 215	Nickel, Copper
Mercury	190 to 535	Stainless steel
Sodium	510 to 870	Nickel, Stainless steel
Lithium	870 to 1480	Alloy of Niobium and Zirconium
Silver	1480 to 1980	Alloy of Tantalum and Tungsten

The performance (amount of heat that can be transferred) of a heat pipe is a function of its length, diameter, wick structure, and overall shape. The larger the diameter, the more power that can be transported, but longer the length, the less capable is the performance.

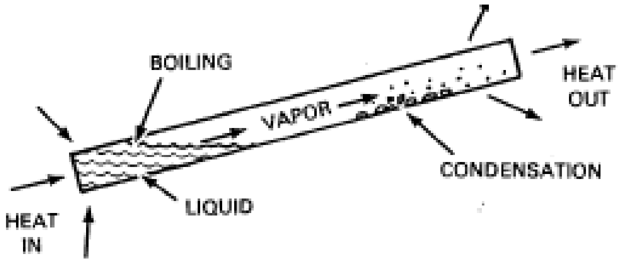


Figure 11.18: Heat Pipe

The heat pipes are used in following industrial applications:

a. Process to Space Heating:

The heat pipe heat exchanger transfers the thermal energy from process exhaust for building heating. The preheated air can be blended if required. The requirement of additional heating equipment to deliver heated make up air is drastically reduced or eliminated.

b. Process to Process:

The heat pipe heat exchangers recover waste thermal energy from the process exhaust and transfer this energy to the incoming process air. The incoming air thus become warm and can be used for the same process/other processes and reduces process energy consumption.

c. HVAC Applications:

Cooling: Heat pipe heat exchangers pre-cools the building make up air in summer and thus reduces the total tons of refrigeration, apart from the operational saving of the cooling system. Thermal energy is supply recovered from the cool exhaust and transferred to the hot supply make up air.

Advantages of heat pipe system

- Heat pipes operates independently so are not vulnerable to a single pipe failure.
- No cross contamination occurs as hot and cold sides are separated by a splitter plate.
- No wear and tear occurs as there are no moving parts inside the heat pipe.
- No additional power is required to run the system

Case 11.2

In a hospital, the HVAC system exhausts 140 m^3/min of air which has a heat recovery potential of 28225kcal/hr. Calculate the savings and payback period of heat recovery system to be installed at a cost of BDT 1,12,000.

Solution:
Savings in Hospital Cooling Systems

	Units	Value
Volume of exhaust	m^3/min	140
Heat recovery potential	kcal/hr	28225
Conversion: 1 kcal/hr	TR	0.00033069
Electricity required	KW/TR	0.8
Plant capacity reduction	TR	9.33
Electricity cost(operation)	BDT/Million kcal (based on 0.8KW/TR)	268
Plant capacity reduction cost (Capital)	BDT/TR	12,000
Capital cost savings	BDT	1,12,000/-
Payback period	hours	16570

9.3.6

11.4.6 Thermo-compressor

In many cases, very low pressure steam are reused as water after condensation for lack of any better option of reuse. In many cases it becomes feasible to compress this low pressure steam by very high pressure steam and reuse it as a medium pressure steam. The major energy in steam, is in its latent heat value and thus thermo compressing would give a large improvement in waste heat recovery.
The thermo-compressor is a simple equipment with a nozzle where HP steam is accelerated into a high velocity fluid. This entrains the LP steam by momentum transfer and then recompresses in a divergent venturi. A figure of thermo-compressor is shown in Figure 11.19.

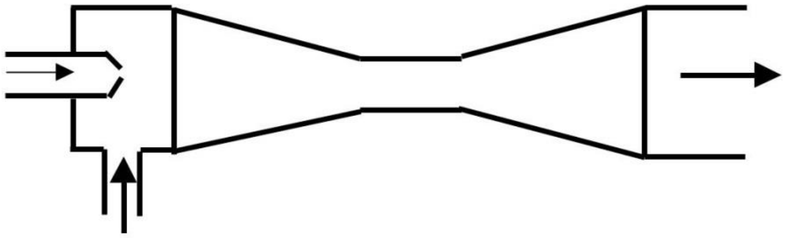


Figure 11.19: Thermo-compressor

It is typically used in evaporators where the boiling steam is recompressed and used as heating steam

Case 11.3

Exhaust steam from evaporator in a fruit juice concentrator plant was condensed in a pre-condenser operation on cooling water upstream of a steam jet vacuum ejector

Equipment Suggested	Alt-1 Thermo compressor Alt-2 shell & tube exchanger
Cost of thermo compressor	BDT 1.5Lakhs
Savings of jacket steam due to recompression of vapour	BDT 5.0 Lakhs per annum
Cost of shell &tube exchanger to pre heat boiler feed water	BDT75,000/-
Savings in fuel cost	BDT 4.5 Lakhs per annum

The recovery technologies for different heat source are given below

Table 11.4: Waste of Heat Recovery Technologies for High range heat sources

High range Heat Source	Temperature range (°C)	Recovery method	Typical uses	Type of heat exchanger (Gas-Gas, Gas-Liquid)	Large temperature differentials permitted	No Cross - contamination
Nickel refining furnace	1370 –1650	RR, CR	1	G-G	x	x
Aluminium refining furnace	650-760	CHW, CR, WHB	1,2,3,5	G-G, G-L	x	x

Zinc refining furnace	760-1100	RR, CR	1	G-G	x	x
Copper refining furnace	760- 815	CHW, CR, WHB	1,2,3,5	G-G, G-L	x	x
Steel heating furnaces	925-1050	RR, CR	1	G-G	x	x
Copper reverberatory furnace	900-1100	RR, CR	1	G-G	x	x
Open hearth furnace	650-700	CHW, CR	1,2,3,5	G-G, G-L	x	x
Cement kiln (Dry process)	620- 730	CHW, CR	1,2,3,5	G-G, G-L	x	x
Glass melting furnace	1000-1550	RR, CR	1	G-G	x	x
Hydrogen plants	650-1000	CHW, CR, WHB	1,2,3,5	G-G, G-L	x	x
Solid waste incinerators	650-1000	CHW, CR, WHB	1,2,3,5	G-G, G-L	x	x
Fume incinerators	650-1450	CHW, CR, WHB	1,2,3,5	G-G, G-L	x	x

RR- Radiation Recuperator; CR - Convection Recuperator; MHW - Metallic Heat Wheel; CHW - Ceramic Heat Wheel; WHB - Waste-heat Boilers

Typical Uses

1.Combustion air preheat 2. Space preheat 3. Boiler makeup water preheat 4. Boiler feed water preheat 5. Domestic hot water 6. Hot water or steam generation. 7. Liquid feed flows requiring heating

(Source: W. Turner Energy Management Handbook, 2007; Waste Heat Recovery: Technology and Opportunities in U.S Industry,2008.)

Table 11.5: Waste Heat Recovery Technologies for medium range heat sources

Heat Source	Temperature range (°C)	Recovery method	Typical uses	Type of heat exchanger (Gas-Gas, Gas-Liquid)	Large temperature differentials permitted	No Cross - contamination
Steam boiler exhausts	230-480	MHW, HHW, PHE	4,6,7	G-G, G-L	-	x
Gas turbine exhausts	370-540	MHW, HHW, PHE	4,6,7	G-G, G-L	-	x
Reciprocating engine exhausts	315-600	CR, HP, WHB, CHW	1	G-G	x	x
Reciprocating engine exhausts (turbo charged)	230- 370	MHW, HHW, PHE	4,6,7	G-G, G-L	-	x
Heat treating furnaces	425 - 650	CR, HP, WHB, CHW	1	G-G	x	x
Drying and baking ovens	230 - 600	CR, HP, WHB, CHW	1	G-G	x	x
Catalytic crackers	425 - 650	CR, HP, WHB, CHW	1	G-G	x	x
Annealing furnace cooling systems	425 - 650	CR, HP, WHB, CHW	1	G-G	x	x

CR - Convection Recuperator; CHW - Ceramic Heat Wheel; PHE – Plate type heat exchanger ; HHW - Hygroscopic Heat Wheel; MHW - Metallic Heat Wheel; FHE- Finned-tube Heat exchanger; ST- shell and tube exchanger; WHB - Waste-heat Boilers; HP - Heat Pipe

Typical Uses

1. Combustion air preheat. 2. Space preheat. 3. Boiler makeup water preheat. 4. Boiler feed water preheat. 5. Domestic hot water 6. Hot water or steam generation. 7. Liquid feed flows requiring heating.

(Source: W. Turner Energy Management Handbook, 2007; Waste Heat Recovery: Technology and Opportunities in U.S Industry,2008.)

Table 11.6: Waste Heat Recovery Technologies for low range heat sources

Heat Source	Temperature range (°C)	Recovery method	Typical uses	Type of heat exchanger (Gas-Gas, Gas-Liquid)	Large temperature differentials permitted	No Cross - contamination
Process steam condensate	55-88	PHE, MHW, HHW	2	G-L	-	x
Cooling water from:						
Furnace doors	32-55	PHE, MHW, HHW	2	G-L	-	x
Bearings, Welding machines, Injection moulding machines.	32-88	PHE, MHW, HHW	2	G-L	-	x
Annealing furnaces	66-230	FHE, WHB, ST	3,6,7	G-G, G-L	x	x
Forming dies, pumps	27-88	PHE, MHW, HHW	2	G-L	-	x
Air compressors	27-50	PHE, MHW, HHW	2	G-L	-	x
Air conditioning and refrigeration condensers	32–43	PHE, MHW, HHW	2	G-L	-	x
Drying, baking and curing ovens	93-230	FHE, WHB, ST	2	G-L		x
Hot processed liquids	32-232	FHE, WHB, ST	3,6,7	G-G, G-L	x	x

MHW - Metallic Heat Wheel; HHW - Hygroscopic Heat Wheel; PHE – Plate type heat exchanger; FHE Finned-tube Heat exchanger; ST- Shell and tube exchanger; WHB - Waste-heat Boilers.

Typical Uses

1. Combustion air preheat. 2. Space preheat. 3. Boiler makeup water preheat. 4. Boiler feed water pre heat. 5. Domestic hot water. 6. Hot water or steam generation. 7. Liquid feed flows requiring heating.

(Source: W. Turner Energy Management Handbook, 2007; Waste Heat Recovery: Technology and Opportunities in U.S. Industry,2008)

CHAPTER 12: INTRODUCTION TO ELECTRIC POWER SUPPLY SYSTEM

12.1 Introduction

An electric power supply system in a country is comprised of generating units that produce electricity; high voltage transmission lines that transport electricity over long distances; distribution lines that deliver the electricity to customers; substations that connect the pieces to each other; and energy control centres to coordinate the operation of the components. Figure1.1shows a simple electric supply system with transmission and distribution network and linkages from electricity sources to end-user.

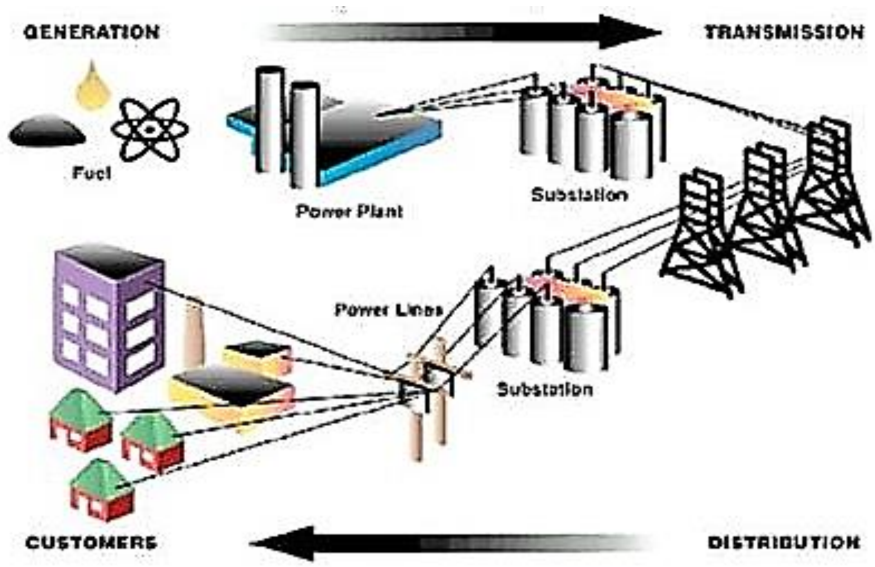


Figure 12.1: Electric supply system

12.2 Power Generation Plant

Fossil fuels such as coal, oil and Natural Gas, nuclear energy, and falling water (hydel) are commonly used energy sources in the power generating plant. A wide and growing variety of unconventional generation technologies and fuels also have been developed, including cogeneration, solar energy, wind generators, and waste material.

The Installed capacity of Power Generation (by plant type) as on May 2022 is 22,348 MW. Including Captive Power & Off Grid Renewable Energy Total Installed Capacity (22,348+2,800+418) =25,556 MW

The maximum power station in Bangladesh run via natural gas, some of them are run by HFO (Heavy fuel oil). Mainly Diesel oil and Furnace oil are used for thermal power plant.

12.3 Transmission and distribution lines

As per Grid Code of Bangladesh, allowable range for frequency variation is 49.0 to 51.0 Hz. Power plants typically produce 50 cycle/second (Hertz) alternating-current (AC)electricity with Terminal voltage of different generators are 11 KV, 11.5 KV and 15.75 KV. The transmission and distribution network include sub-stations, lines and distribution transformers. At the power plant, the 3-phase voltage is stepped up to a higher voltage for transmission on cables strung on cross-country towers. High voltage transmission is used so that smaller, more economical wire sizes can be employed to carry the lower current and to reduce losses. Sub-stations, containing step-down transformers, reduce the voltage for distribution to industrial users. The voltage is further reduced for commercial facilities. Electricity must be generated, as and when it is needed since electricity cannot be stored virtually in the system here is no difference between a transmission line and a distribution line except for the voltage level and power handling capability. Transmission lines are usually capable of transmitting large quantities of electric energy over great distances. They operate at high voltages.

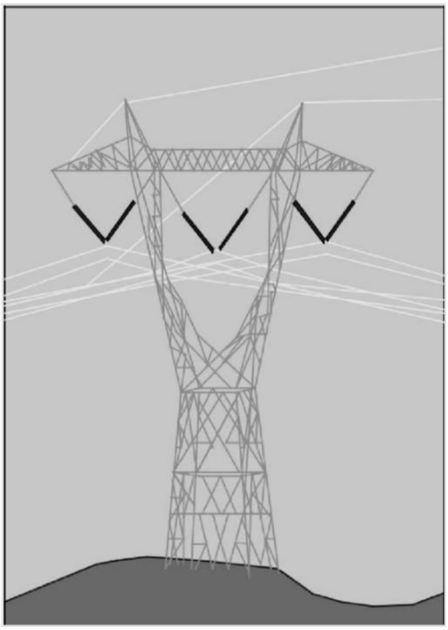


Figure 12.2 Cross Country Tower

Distribution lines carry limited quantities of power over shorter distances. High voltage (HV) and extra high voltage (EHV) transmission is the next stage from power plant to transport A.C. power over long distances at voltages like; 400kV, 230 kV and 132 kV. These are called as the primary grid system. Where transmission is over 1000KM, high voltage direct current transmission (HVDC) is also favoured to minimize the losses.

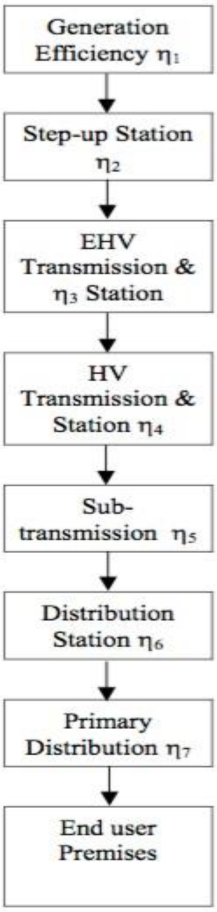
Sub-transmission network at 230 kV, 132kVconstitutes the next link towards the end user.
High voltage transmission network that transmits the power to grid substation transformers to be stepped down at 33 kV, 11 kV and 0.4 kV for delivery to the consumers of various categories.

Distribution at 11kV/6.6kV/3.3kV constitutes the last link to the consumer, who is connected directly or through transformers depending upon the drawl level of service.

Voltage drop in the line is in relation to the resistance and reactance of line, length and the current drawn. For the same quantity of power handled, lower the voltage, higher the current drawn and higher the voltage drop. The current drawn is inversely proportional to the voltage level for the same quantity of power handled.

The power loss in line is proportional to resistance and square of current. (i.e. $P_{Loss}=I^2R$). Higher voltage transmission and distribution thus would help to minimize line voltage drop in the ratio of voltages, and the line power loss in the ratio of square of voltages. For instance, if distribution of power is raised from 11 kV to 33 kV, the voltage drop would be lower by a factor 1/3 and the line loss would be lower by a factor $(1/3)^2$ i.e., 1/9. Lower voltage transmission and distribution also calls for larger quantity of conductor on account of current handling capacity needed.

12.4 Cascade Efficiency



The primary function of transmission and distribution equipment is to transfer power economically and reliably from one location to another. Conductors in the form of wires and cables strung on towers and poles carry the high-voltage, AC electric current. A large number of copper or aluminium conductors are used to form the transmission path. The resistance of the long-distance transmission conductors is to be minimized. Energy loss in transmission lines is wasted in the form of I^2R losses.

Capacitors are used to correct power factor by causing the current to lead the voltage. When the AC currents are kept in phase with the voltage, operating efficiency of the system is maintained at a high level.

Circuit-interrupting devices are switches, relays, circuit breakers, and fuses. Each of these devices is designed to carry and interrupt certain levels of current. Making and breaking the current carrying conductors in the transmission path with a minimum of arcing is one of the most important characteristics of this device. Relays sense abnormal voltages, currents, and frequency and operate to protect the system.

Transformers are placed at strategic locations throughout the system to minimize power losses in the T&D system. They are used to change the voltage level from low-to-high in step-up transformers and from high-to-low in step-down units. Since the power loss of a transmission line is based on I^2R, losses can be reduced to are as on able value by stepping up the source voltage to a high value to proportionally reduce the source current.

The power source to end user energy efficiency link is a key factor which influences the energy input at the source of supply, consider the electricity flow from generation to the user in terms of cascade energy efficiency.

A typical cascade efficiency profile from Generation to 11–33 kV user industry is illustrated below:

Weighted efficiency for various mix of power generation sources viz. (Combined Cycle, Reciprocating Engine, Steam turbine and Gas Turbine) ranges 40-45 % w.r.t. size plant, vintage of plant and capacity utilization.

Step-up to 400 kV to enable EHV transmission. Envisaged maximum losses 1.0 % or efficiency of 99%

EHV transmission and substations at 400 kV / 800 kV. Envisaged maximum losses 1.0 % or efficiency of 99 %

HV transmission & Substations for 132/ 230/ 400 kV. Envisaged maximum losses 2.5 % or efficiency of 97.5%

Sub-transmission at 66/132 kV Envisaged maximum losses 4% or efficiency of 96%. Step-down to a level of 11 / 33kV. Envisaged losses 0.5% or efficiency of 99.5%

Distribution is finally link to end user at 11 / 33 kV. Envisaged losses maximum 5 % of efficiency of 95 %

Cascade efficiency from Generation to end user = $\eta1 \times \eta2 \times \eta3 \times \eta4 \times \eta5 \times \eta6 \times \eta7$

The cascade efficiency in the T&D system from output of the power plant to the end use is 87% (i.e., 0.995 x 0.99 x 0.975 x 0.96 x 0.995 x 0.95 = 87%)

12.5 Industrial End User

At the industrial end user premises again the plant network elements like transformers at receiving sub-station, switch gear, lines and cables, load-break switches, capacitors cause losses which affect the input received energy. A typical plant single line diagram of electrical distribution system is shown in Figure 12.3

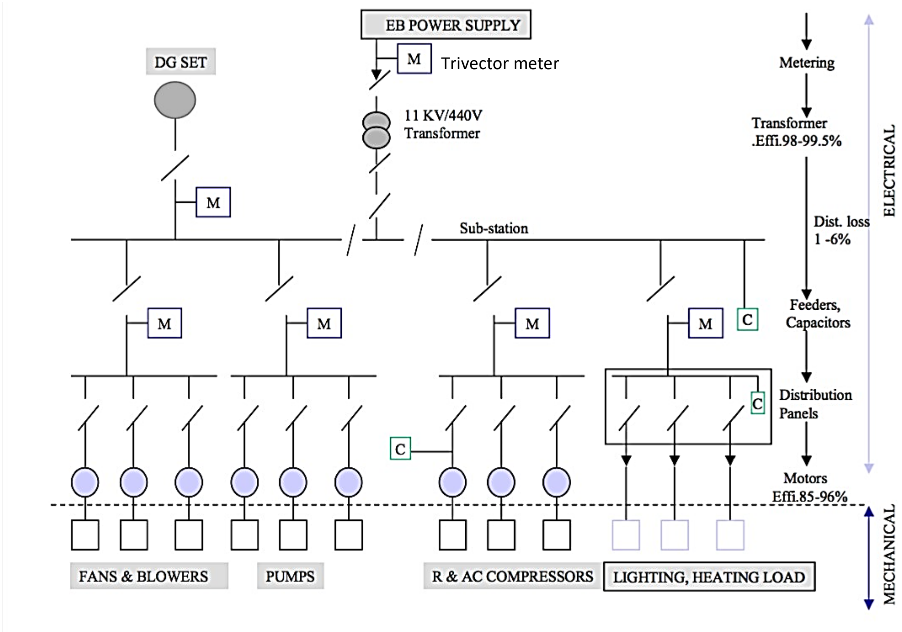


Figure 12.3: Electrical Distribution System – Single Line Diagram

The likely network elements that are encountered at industry up to the motor, i.e., pre-motor system can include:

- Outdoor circuit breakers with typical full load losses of 0.002 – 0.015%
- Receiving transformers with typical operating efficiency of 99 % or above.
- Medium voltage switch gear 5.15kVwhere maximum full load losses can be between 0.005 - 0.02%
- Load break switches where maximum of full load losses can be between 0.003 – 0.025 %.
- Current limiting reactors can have a maximum full load losses ranging from 0.09% to 0.3 %.
- Medium voltage starters can have a maximum full load loss of 0.02% to 0.15%.
- Lines and cables can have a maximum loss ranging for 1% to 6% depending upon lengths, voltage levels, power factor, condition of network in plant
- Motor control centres can have a full load loss range from 0.01% to 0.4 %.
- Low voltage switchgear can have a full load loss ranging from 0.13 % to 0.34 %.

Thus, as per the links available in the in-plant distribution network, the cascade efficiency of pre-motor system can be computed, as a product of efficiencies of the actual links in cascade.

When problems like low voltage at motor terminals are encountered, this pre-motor system needs to be looked into, for improvement opportunities like;

- Relocating transformers close to load centres.
- Increasing cable / line size addition of parallel cable, and minimizing jumpers / loose

connections and optimizing line lengths etc.
- Tap changing as needed at the transformers.
- Capacitor relocation close to load centres or motor terminals, as discussed later.
- Adopting best practices like infrared thermograph of distribution network, for identifying hotspots, which indicate potential of break-down/overloading etc., for attention / maintenance.

ONE Unit saved = TWO Units Generated

After power generation at the plant, it is transmitted and distributed over a wide network. The standard technical losses are around 9.5% in Bangladesh (Efficiency=90.5%). But overall T & D (Transmission and Distribution Loss) losses range from 9 –17%. All these may not constitute technical losses, since un-metered and pilferage are also accounted in this loss.

When the power reaches the industry, it is received by the transformer. The energy efficiency of the transformer is generally very high. Next it goes to the motor through internal plant distribution network. A typical distribution network efficiency including transformer is 95% and motor efficiency is about 90%. Another 30% (Efficiency=70%) is lost in the mechanical system which includes coupling / drive train, a driven equipment such as pump and flow control valves/throttling etc. Thus the overall energy efficiency becomes 50%. (0.90 x 0.95 x 0.9 x 0.70 = 0.54, i.e. 54% efficiency)

Hence one unit saved in the end user is equivalent to two units generated in the power plant. (1 Unit /0.5 Eff =2 Units)

12.6 A Glossary of Basic Electrical system

kWh	Kilowatt-hours are the unit of electrical energy. kWh is obtained by integrating power, expressed in KW with time. For example, a power of 2KW appliance for 15 minutes (1/4 hour) indicates an energy consumption of 2 x 1⁄4 = 0.5 kWh.
Power	$\sqrt{3} \times V \times I \times PF$ for 3 phase systems, where V = Line voltage, I = line current • In delta connected electrical system, V line = V phase, I lines = $\sqrt{3}$ I phase • In star connected electrical system, V line = $\sqrt{3}$ V phase, I lines = I phase and $V \times I$ x PF for single phase systems
KVA	$\sqrt{3} \times V \times I$ for 3 phase systems and V x I for single-phase systems.
Load factor	Load factor is the ratio of the average demand (KVA or KW) to the peak demand for a power system. High load factor leads to better utilization of installed capacity.
Demand Factor	Demand factor is the ratio of maximum demand to the connected load.
Peak Demand or Peak Load	The highest demand on an electric utility system is called Peak Load or Peak Demand. Demand varies with time every day and also from season to season. As electricity cannot be stored easily, utilities have to provide the generating capacity to meet peak demand even it lasts for a short duration.
Connected Load	Connected load is the summation of nameplate ratings (kW or kVA) of the electrical equipment installed in a consumer's premises

CHAPTER 13: TRANSFORMER

13.1 Introduction

A transformer can accept energy at one voltage and deliver it at another voltage. This permits electrical energy to be generated at relatively low voltages and transmitted at high voltages and low currents, thus reducing line losses.

Transformers consist of two or more coils that are electrically insulated, but magnetically linked. The primary coil is connected to the incoming power and the secondary coil connects to the load. The turn's ratio is the ratio between the number of turns on the primary to the turns on the secondary.

The secondary voltage is equal to the primary voltage times the turn's ratio. Ampere- turns are calculated by multiplying the current in the coil times the number of turns. Primary ampere-turns are equal to secondary ampere-turns. Voltage regulation of a transformer is the percent increase in voltage from full load to no load.

13.1 Types of Transformers

Transformers are classified as two categories as given below:

Power transformers: It is used in transmission network of higher voltages, deployed for step-up and step down transformer application. (400 kV, 200 kV, 110kV, 66kV, 33kV)

Distribution transformers: It is used for lower voltage distribution networks as a means to end user connectivity. (11.kV, 6.6kV, 3.3kV, 440V, 230V)

13.2 Rating of transformer

Rating of the transformer is calculated based on the connected load and applying the diversity factor on the connected load, applicable to the particular industry and arrive at the KVA rating of the Transformer. Diversity factor is defined as the ratio of overall maximum demand of the plant to the sum of individual maximum demand of various equipment. Diversity factor varies from industry to industry and depends on various factors such as individual loads, load factor and future expansion needs of the plant. Diversity factor will always be less than one.

13.3 Location of transformer

Location of the transformer is very important as far as distribution loss is concerned. Transformer receives HT voltage from the grid and steps it down to the required voltage. Transformers should be placed close to the load centre, considering other features like optimization needs for centralized control, operational flexibility etc. This will bring down the distribution loss in cables.

13.4 Transformer Losses and Efficiency

The efficiency varies anywhere between 96 to 99 percent. The efficiency of the transformers not only depends on the design but also on the effective operating load.

Transformer losses consist of two parts:

No-load loss (also called core loss) is the power consumed to sustain the magnetic field in the transformer's steel core. Core losses are caused by two factors: hysteresis and eddy current losses. Hysteresis loss is that energy lost by reversing the magnetic field in the core as the magnetizing AC rises and falls and reverses direction. Eddy current loss is a result of induced currents circulating in the core. Core loss occurs whenever the transformer is energized; core loss does not vary with load.

Load loss (also called copper loss) is associated with full-load current flow in the transformer windings. Copper loss is power lost in the primary and secondary windings of a transformer due to the ohmic resistance of the windings. Copper loss varies with the square of the load current.($P=I^2R$).

For a given transformer, the manufacturer can supply values for no-load loss, $P_{NO-LOAD}$, and load loss, P_{LOAD}. The total transformer loss, P_{TOTAL}, at any load level can then be calculated from:

$P_{TOTAL} = P_{NO-LOAD} + (\% \text{ Load}/100)^2 \text{ x } P_{LOAD}$

Where transformer loading is known, the actual transformers loss at given load can be computed as:

$$No\ load\ loss + \left(\frac{KVA\ Load}{Rated\ KVA}\right)^2 full\ load\ loss$$

Table 13.1: Typical Transformer Loss for Distribution Transformers (DT's) above 100kVA

KVA Rating	Voltage Rating (V)	No load loss(W)	Load Loss(W)	Impedance%
160		425	3000	5
200		570	3300	5
250		620	3700	5
315		800	4600	5
500		1100	6500	5
630	11000/433	1200	7500	5
1000		1800	11000	5
1600		2400	15500	5
2000		3000	20000	6
630		1450	7500	5
1000	33000/433	2200	11500	5
1600		3000	16000	6.25
2000		3500	21000	6.25

13.5 Voltage fluctuation control

A control of voltage in a transformer is important due to frequent changes in supply voltage level. Whenever the supply voltage is less than the optimal value, there is a chance of nuisance tripping of voltage sensitive devices. The voltage regulation in transformers is done by altering the voltage transformation ratio with the help of tapping. There are two methods of tap changing facility available.

9.3.7 Off-circuit tap changer

It is a device fitted in the transformer, which is used to vary the voltage transformation ratio. Here the voltage levels can be varied only after isolating the primary voltage of the transformer.

13.5.1 On load tap changer (OLTC)

The voltage levels can be varied without isolating the connected load to the transformer. To minimize the magnetization losses and to reduce the nuisance tripping of the plant, the main transformer (the transformer that receives supply from the grid) should be provided with On Load Tap Changing facility at design stage. The downstream distribution transformers can be provided with off-circuit tap changer.

The On-load gear can be put in auto mode or manually depending on the requirement. OLTC can be arranged for transformers of size 250kVA onwards. However, the necessity of OLTC below 1000 kVA can be considered after calculating the cost economics.

13.6 Parallel operation of transformers

The design of Power Control Centre (PCC) and Motor Control Centre (MCC) of any new plant should have the provision of operating two or more transformers in parallel. Additional switch gears and bus couplers should be provided at design stage.

Whenever two transformers are operating in parallel, both should be technically identical in all aspects and more importantly with same impedance level. This will minimize the circulating current between transformers.

Where the load is fluctuating in nature, it is preferable to have more than one transformer running in parallel, so that the load can be optimized by sharing the load between transformers. The transformers can be operated close to the maximum efficiency range by this operation.

13.7 Energy Efficient Transformers

Most energy loss in dry-type transformers occurs through heat or vibration from the core. The new high-efficiency transformers minimize these losses. The conventional transformer is made up of a silicon alloyed iron (grain oriented) core. The iron loss of any transformer depends on the type of core used in the transformer. The latest technology is to use for the amorphous core. Amorphous material has great advantage in reducing No load loss.

Amorphous core material (AM) offers both reduced hysteresis loss and eddy current loss because this material has a random grain and magnetic domain structure which results in high permeability giving a narrow hysteresis curve compared to conventional core material. Eddy current losses are reduced by the high resistivity of the amorphous material, and the reduced thickness of the film (thickness is approximately 0.03 mm, which is about 1/10 comparing with silicon steel). Amorphous core transformers offer a 70 to 80% reduction in no-load losses compared to transformers using conventional core material.

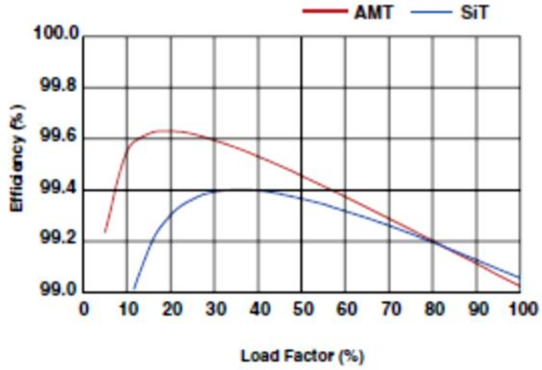


Figure 13.1: Comparison of Conventional and Amorphous Core Transformers

Example 13.4

Transformer loss calculation-

An engineering industry has installed three numbers of 1000KVA transformers for an electrical load of 1500KVA. The No-load loss and the full load loss of the transformers were collected from the transformer certificates as 2.8KW and 11.88KW respectively. Estimate the total loss when 3 transformers in parallel operation and also 2 transformers parallel operation. The transformer losses can also be obtained from manufacturers test certificate which are available in the plant.

a) Total loss when Two transformers in parallel operation:

$$No\ load\ loss\ =\ 2\ \times\ 2.8\ = 5.6$$
$$Load\ Loss\ =\ 2\ \times\ \left(\frac{750}{1000}\right)^2\ \times 11.88$$
$$Total\ Loss\ =\ 5.6\ +\ 13.36\ = 18.96$$

b) Total loss when Three transformers in parallel operation:

No load loss = 3 x 2.8 = 8.4 KW

$$Load\ loss\ =\ 3\ \times\ \left(\frac{500}{1000}\right)^2\ \times 11.88\ =\ 8.91\ kW$$

Total loss = 17.31 kW

Savings by operating 3 transformers in parallel
= 18.96 - 17.31= 1.65 kWh
= 1.65kwh x 24Hrs x 365 days = 14454 kWh /year

CHAPTER 14: ELECTRICAL POWER LOSSES: CAUSES & CONSEQUENCES

14.1 System distribution losses

In an electrical system often the constant no load losses and the variable load losses are to be assessed alongside, over long reference duration, towards energy loss estimation.

Identifying and calculating the sum of the individual contributing loss components is a challenging one, requiring extensive experience and knowledge of all the factors impacting the operating efficiencies of each of these components.

For example the cable losses in any industrial plant will be of the order of 2 to 4 percent. Note that all of these are current dependent, and can be readily mitigated by any technique that reduces facility current load.

In system distribution loss optimization, the various options available include:

- Relocating transformers and sub-stations near to load centres
- Re-routing and re-conducting such feeders and lines where the losses/voltage drops are higher.
- Power factor improvement by incorporating capacitors at load end.
- Optimum loading of transformers in the system.
- Opting for lower resistance All Aluminium Alloy Conductors (AAAC) in place of conventional Aluminium Cored Steel Reinforced (ACSR) lines
- Minimizing losses due to weak links in distribution network such as jumpers, loose contacts, old brittle conductors.
- Distribution loss assessment and optimization studies today are feasible on account of accurate metering developments on the one hand and availability of powerful computer-based load flow analysis packages on the other.
- Using full infrared thermography system, each electrical panel can be scanned to identify points of high system heat. Called "hotspots", these high heat points result from connections become looser corroded overtime. The resulting increase in resistance at that spot in the system can add wattage losses to the electrical energy consumption. These hot spots also create safety risks and risks to abrupt system failure. Fixing them is often as simple as de-energizing that point in the system, and then using a wrench to tighten a bolt.

As far as electricity distribution utilities are concerned, involving large network and complex connectivity features, there exist well proven computer-based application packages which can be used for network load flow analysis. The analysis outputs can help a utility engineer to assess the extent of transmission and distribution losses, to identify sections for improvement where voltage drops are high, to identify avenues for loss reduction such as ideal location of sub-stations, feeder augmentation, etc.

14.2 Analysis of Electrical Power Systems

System Problem	Common Causes	Possible Effects	Solutions
Voltage imbalances among the three phases	Improper transformer taps settings, single-phase loads not balanced among phases, poor connections, bad conductors,	Motor vibration, premature motor failure A 5% imbalance causes a 40% increase in motor losses.	Balance loads among phases.

	transformer grounds or faults.		
Voltage deviations from rated voltages (Too low or high)	Improper transformer settings, Incorrect selection of motors.	Over-voltages in motors reduce efficiency, power factor and equipment life	Correct transformer settings, motor ratings and motor input voltages
Poor connections in distribution or at connected loads.	Loose bus bar connections, loose cable connections, corroded connections, poor crimps, lose or worn contactors	Produces heat, causes failure at connection site, leads to voltage drops and voltage imbalances	Use Infra-Red camera to locate hot-spots and correct.
Undersized conductors.	Facilities expanding beyond original designs, poor power factors	Voltage drop and energy waste.	Reduce the load by conservation load scheduling.
Insulation leakage	Degradation over time due to extreme temperatures, abrasion, moisture, chemicals	May leak to ground or to another phase.	Insulation leakage
Low Power Factor	Inductive loads such as motors, transformers, and lighting ballasts Non-linear loads, such as most electronic loads.	Reduces current-carrying capacity of wiring, voltage regulation effectiveness, and equipment life.	Add capacitors to counteract reactive loads.
Harmonics (non-sinusoidal voltage and/or current wave forms)	Office-electronics, UPSs, variable frequency drives, high intensity discharge lighting and electronic and core-coil ballasts.	Over-heating of neutral conductors, motors, transformers, switch gear. Voltage drop, low power factors, reduced capacity.	Take care with equipment election and isolate sensitive electronics from noisy circuits.

An analysis of an electrical power system may uncover energy waste, fire hazards, and equipment failure. Facility / Energy managers increasingly find that reliability-centered maintenance can save money, energy, and downtime.

14.3 Power factor improvement and benefits

The ratio of kW to kVA is called the power factor which is always less than or equal to unity. Theoretically, when electric utilities supply power, if all loads have unity power factor, maximum power can be transferred for the same distribution system capacity. However, as the loads are inductive in nature with the power factor ranging from 0.2 to 0.9, the electrical distribution network is stressed for capacity at low power factors.

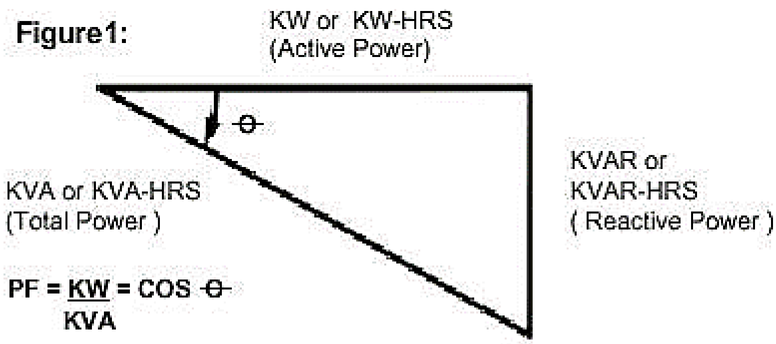


Figure 14.1: Power factor

14.3.1 Improving Power Factor

The solution to improve the power factor is to add power factor correction capacitors to the plant power distribution system. They act as reactive power generators, and provide the needed reactive power to accomplish KW of work. This reduces the amount of reactive power and thus total power generated by the Utilities (Distribution companies)

Example 14.1

A chemical industry had installed a 1500 KVA transformer. The initial demand of the plant was 1160 KVA with power factor of 0.70. The % loading of transformer was about 78% (1160/1500=77.3%). To improve the power factor and thereby avoiding the penalty, the unit had added about 410 KVAR in motor load end. This improved the power factor to 89%, and reduced the required KVA to 913, which is the vector sum of KW and KVAR.
After improvement the plant had avoided penalty and the 1500 KVA transformer now loaded only to 60% of capacity. This will allow the addition of more loads in the future to be supplied by the transformer.

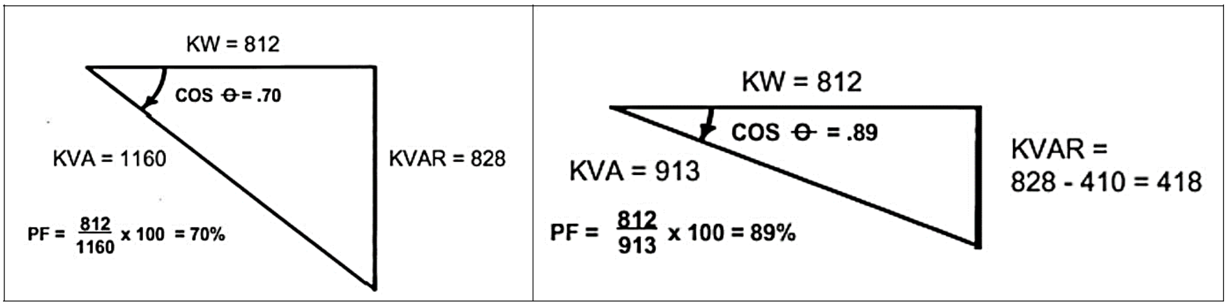


Figure 14.2 a: Power factor before and after Improvement

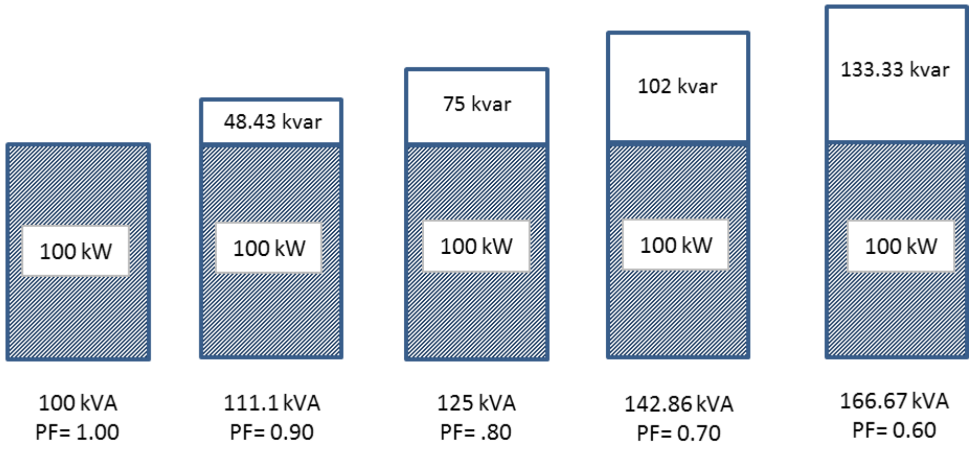


Figure 14.2b: Increase in the apparent and reactive powers as a function of the load power factor, holding the real power of the load constant

The advantages of improvement by capacitor addition

a) Reactive component of the network is reduced and also the total current in the system from the source end.
b) I^2R power losses are reduced in the system because of reduction in current.
c) Voltage level at the load end is increased.
d) KVA loading on the source generators as also on the transformers and lines up to the capacitors reduces giving capacity relief. A high-power factor can help in utilizing the full capacity of the electrical system.

Cost benefits of PF improvement

While costs of PF improvement are in terms of investment needs for capacitor addition the benefits to be quantified for feasibility analysis are:

a) Reduced KVA (Maximum demand) charges in utility bill
b) Reduced distribution losses (KWH) within the plant network
c) Better voltage at motor terminals and improved performance of motors
d) A high-power factor eliminates penalty charges imposed when operating with a low power factor
e) Investment on system facilities such as transformers, cables, switchgears etc. for delivering load is reduced

Selection, Location and Sizing of Capacitor

The figures given in table 14.1 are the multiplication factors which are to be multiplied with the input power (kW) to give the KVAR of capacitance required to improve present power factor to a new desired power factor.

Table 14.1: Multiplication factors for selection of capacitors

Original P.F.	Desired P.F.				
	1.0	0.95	0.90	0.85	0.80
0.55	1.518	1.189	1.034	0.899	0.763

0.60	1.333	1.004	0.849	0.714	0.583
0.65	1.169	0.840	0.685	0.549	0.419
0.70	1.020	0.691	0.536	0.400	0.270
0.75	0.882	0.553	0.398	0.262	0.132
0.80	0.750	0.421	0.266	0.130	
0.85	0.484	0.291	0.136		
0.90	0.328	0.155			
0.95	**0.620**				

Having known the existing power factor, the multiplication factor may be calculated for raising the power factor from the present value to the desired value.

Example 14.2

If power factor of 30 kW load is to be improved from 0.80 to 0.95, then

Size of the capacitor = kW ×multiplication factor = 30 × 0.421 = 12.63 (or) 13 KVAR

In case of induction motors of different ratings and speeds, in order to improve their power factor to 0.95 and above, the rating of the capacitor (in KVAR) for direct connection to induction motor can be referred to in the chapter on electric motors.

Location of Capacitors

Location of capacitors is an important factor to be considered. For the benefit of electricity boards, connection of capacitors on H.T. side is good enough. Although the cost of H.T. capacitor per KVAR is low, the cost of the associated switchgear is quite high.

Alternatively, the capacitors can be connected on L.T. side of the main substation. The capacitors may be placed at load centres viz., directly with motors or group of motors at motor control centres. Correction of PF at the motors has number of advantages, as the induction motors are the main source of reactive currents in every industrial plant. The advantages include the absence of additional switchgear; no separate control of capacitor is required in switching on and off operations and reduced effect of motor inrush currents.

From energy efficiency point of view, capacitor location at receiving substation only helps the utility in loss reduction. Locating capacitors at user end motors will help to reduce loss within the plant's distribution network as well and directly benefit the user by reduced demand cost.

Reduction in the distribution loss in KWH when tail end power factor is raised from PF_1 to a new power factor PF_2, will be proportional to $[1 - (PF_1 / PF_2)^2]$

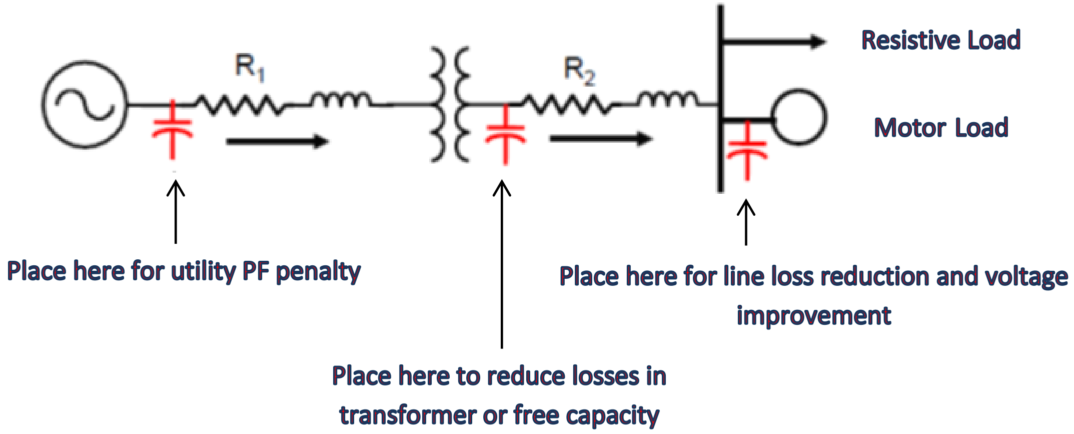


Figure 14.3: Effect of Location

CHAPTER 15: HARMONICS AND ITS EFFECTS

15.1 Introduction

In any alternating current network, flow of current depends upon the voltage applied and the impedance (resistance to AC) provided by elements like resistances, reactance of inductive and capacitive nature. As the value of impedance in above devices is constant, they are called linear whereby the voltage and current relation is of linear nature.

Linear loads occur when the impedance is constant; then the current is proportional to the voltage (A straight line graph, as shown in Figure–15.1). Simple loads, composed of one of the elements shown in Figure–15.2, do not produce harmonics.

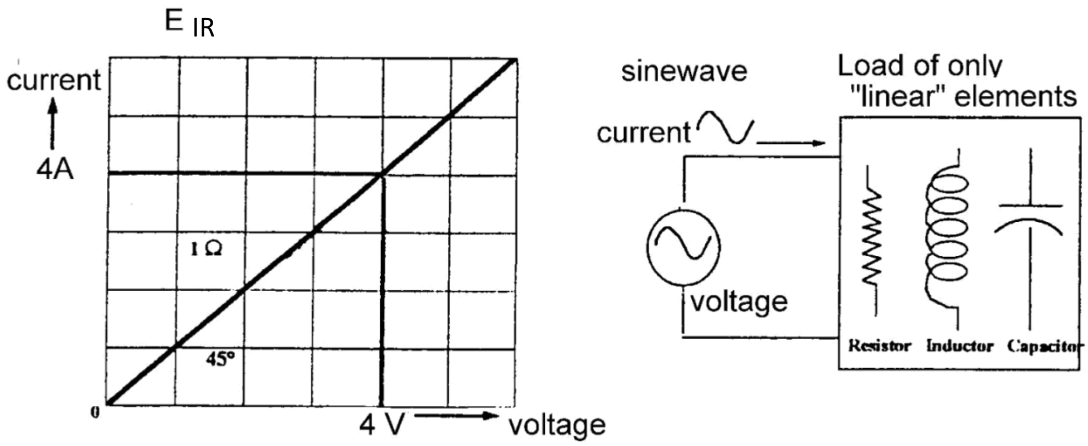


Figure 15.1: Linear loads

However, in real life situation, various devices liked diodes, silicon-controlled rectifiers, thyristors, voltage & current controllers, induction & arc furnaces are also deployed for various requirements and due to their varying impedance characteristic, these Non-Linear devices cause distortion in voltage and current waveforms which is of increasing concern in recent times.

Example for Non-Linear loads

Non-linear loads occur when the impedance is not constant; then the current is not proportional to the voltage (as shown in Figure 15.11. Combinations of the components shown in Figure 15.2 normally create non-linear loads and harmonics.

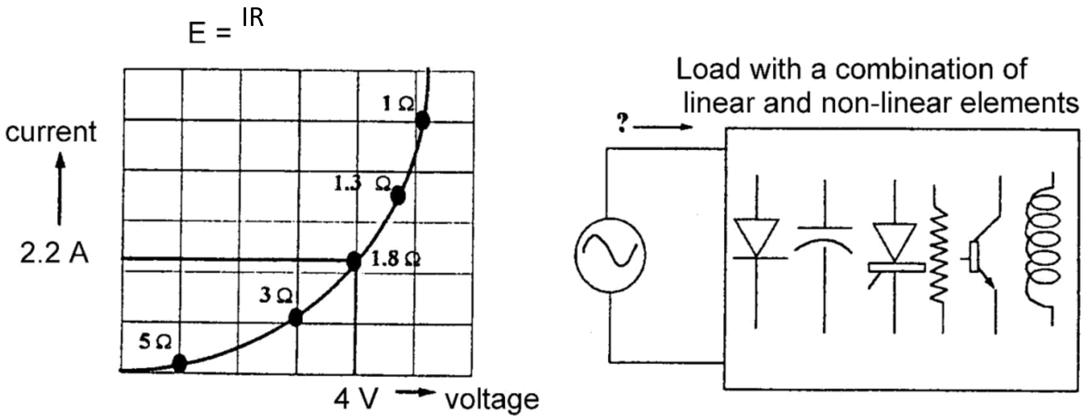


Figure 15.2: Non-Linear loads

Harmonics occurs as spikes at intervals which are multiples of the mains (supply) frequency and these distort the pure sine wave form of the supply voltage &current. Thus harmonics are multiples of the fundamental frequency of an electrical power system. If for example, the fundamental frequency is 50Hz, then the 5^{th} harmonic is five times that frequency, or 250 Hz. Likewise, the 7^{th} harmonic is seven times the fundamental or 350Hz, and so on for higher order harmonics.
The magnitude and order of harmonics is governed by the nature of the device being used and the impact is expressed as Total Harmonic Distortion (THD). Harmonics can be expressed in terms of current or voltage.

In terms of voltage, it is expressed as a percentage of fundamental voltage by the expression:

$$\%THD = \sqrt{\sum_{n=2}^{n=n} \frac{V_n^{\ 2}}{V_1}} * 100$$

where V_1 is the fundamental frequency voltage and V_n is n^{th} harmonic voltage component.

In terms of current, it is expressed as below:

A 5th harmonic current is simply a current flow at 250Hz on a 50Hz system. The 5th harmonic current flowing through the system impedance creates a 5^{th} harmonic voltage. The following is the formula for calculating the THD for current:

$$= \sqrt{\frac{(I_5^2 + I_7^2)}{I_1}}$$

I_1 = current at 50 Hz = 250 Amps, I_5 = current at 250 Hz = 50 Amps I_7 = current at 350 Hz = 35 Amps
If I_1 = 250 Amps, I_5 = 50 Amps and I_7 = 35Amps

Then...

$$I_{THD} = \sqrt{\frac{(50^2 + 35^2)}{250}} \quad x \ 100 = 24\%$$

When harmonic currents flow in a power system, they are known as poor "power quality". Other causes of poor power quality include transients such as voltages pikes, surges, sags, and ringing. Because they repeat every cycle, harmonics are regarded as a steady-state cause of poor power quality.

The harmonic assessment can be carried out at site by using a load analyzer. The wave form is sampled and analysed through various harmonic frequencies, i.e. multiples of the mains frequency for assessing THD. Load analysers are available in market, which can measure THD up to 63^{rd} harmonic.

15.2 Causes and Effects of Harmonics in electrical systems

15.2.1 Causes of Harmonics

Devices that draw non-sinusoidal currents when a sinusoidal voltage is applied create harmonics. Frequently these are devices that convert AC to DC. Listed below are some of these devices.

1. Electronic Switching Power Converters

   - Computers, Uninterruptible power supplies (UPS), Solid-state rectifiers
   - Electronic process control equipment, PLC's, etc.
   - Electronic lighting ballasts, including light dimmer
   - Reduced voltage motor controllers

2. Arcing Devices

   - Discharge lighting, e.g. Fluorescent, Sodium and Mercury vapor
   - Arc furnaces, Welding equipment, Electrical traction system

3. Ferromagnetic Devices

   - Transformers operating near saturation level
   - Magnetic ballasts (Saturated Iron core)
   - Induction heating equipment, Chokes, Motors

4. Appliances

- TV sets, air conditioners, washing machines, microwave ovens
- Fax machines, photocopiers, printers

These devices use power electronics liked diodes and thyristors which are a growing percentage of the load in industrial power systems. Normally each load would manifest a specific harmonic spectrum. Many problems can arise from harmonic currents in a power system. Some problems are easy to detect. Higher RMS current and voltage in the system are caused by harmonic currents, which can result in any of the problems listed below.

15.2.2 Effects of Harmonics on Network

The effects of harmonics on distribution network include:

- Metering errors in electromagnetic type meters.
- Overloading and overheating of motors due to increased iron losses & overheating of conductors.
- Overloading of neutral conductor especially in low voltage distribution network and High neutral currents
- Malfunctioning of control equipment and protection relays due to false signals.
- Blown Fuses (no apparent fault)
- Misfiring of AC and DC Drives
- Tripped Circuit Breakers Voltage distortion
- High neutral to ground voltages Increased system losses (heat)
- Rotating and electronic equipment failures
- Capacitor bank over-load and failures
- Reduced power factor

15.3 Harmonic Filters

Harmonic filters consist of a capacitor bank and reactor in series are designed and adopted for suppressing harmonics, by providing low impedance path for harmonic component. The Harmonic filters connected suitably near the equipment generating harmonics help to reduce THD to acceptable limits. In present context where no Electro Magnetic Compatibility regulations exist, an application of

Harmonic filters is very relevant for industries having diesel power generation sets and co-generation units. Energy managers / auditors can address the issue of harmonics from the point of view of energy efficiency and power quality assurance.

The Harmonic Mitigation solutions currently in use in the industry broadly fall into the following categories:

1. Passive Harmonic Filter (PHF)
2. Advance Active Filters (AAF)
3. Active Front End based VFDs (AFE)

15.3.1 Passive Harmonic Filter (PHF)

It is the most common method for the cancellation of harmonic current in the distributed system. These filters are basically designed on principle either single tuned/double tuned or band pass filter technology. Passive filters offer very low impedance in the network at the tuned frequency to divert all the harmonic current at the tuned frequency.

15.3.2 Advance Active Filters (AAF)

It is connected parallel with the distribution system. Distribution system consists of a wide percentage of harmonics produced by non- linear loads. Active filters compensate current harmonics by injecting equal magnitude but opposite phase harmonic compensating current.

15.3.3 Active Front End based VFDs (AFE)

It is used in VFDs because it:

- has the major advantage of mitigation of harmonics without using external filter,
- maintains unity power factor at the point of common coupling,
- supports Bidirectional power flow which makes recovery of energy to the mains by saving it,
- provides clean power to the grid which in turn does not affect the other loads connected to it,
- maintains the DC voltage irrespective of the supply variations.

15.4 Harmonics Limits:

The permissible harmonic limit for different current (Isc / I_L) as per IEEE standard is given in Table 15.1 and for different bus voltage are given in Table 15.5 Current Distortion Limits for General Distribution System's end-User limits (120 Volts To 69,000 Volts)

Table 15.1 Maximum Harmonic Current Distortion in % of I_L

Individual Harmonic Order (Odd Harmonics)						
Isc/I_L	h<11	$11 \leq h < 17$	$17 \leq h < 23$	$23 \leq h < 35$	$35 \leq h$	TDD
< 20*	4.0	2.0	1.5	0.6	0.3	5.0
20 < 50	7.0	3.5	2.5	1.0	0.5	8.0
50 < 100	10.0	4.5	4.0	1.5	0.7	12.0

100 < 1000	12.0	5.5	5.0	2.0	1.0	15.0
> 1000	15.0	7.0	6.0	2.5	1.4	20.0
Even harmonics are limited to 25% of the odd current harmonic limits above.						
Current distortions that result in a direct current offset, e.g. half wave converters are not allowed.						
*All power generation equipment is limited to these values of current distortion, regardless of actual Isc/IL.						
Where, Isc = Maximum short circuit current at PCC (Point of Common Coupling). And I_L = Maximum Demand Load Current (fundamental frequency component) at PCC. TDD = Total Demand Distortion, harmonic current distortion in % of maximum demand load current (15 or 30 min demand).						

Table 15.5: Total Harmonic Distribution for Different Voltage Levels in %

Bus Voltage at PCC	Individual Voltage Distortion (%)	Total Voltage Distortion THD (%)
69 kV and below	3.0	5.0
69.001 kV Thru 161 kV	1.5	2.5
161 kV and above	1.0	1.5

Note: High voltage systems can have up to 2.0% THD where the cause is an HVDC terminal that will attenuate by the time it is tapped for a user.

Two very important points must be made in reference to the above.

1. The customer is responsible for maintaining current distortion to within acceptable levels, while the utility is responsible for limiting voltage distortion.
2. The limits are only applicable at the point of common coupling (PCC) between the utility and the customer. The PCC, while not explicitly defined, is usually regarded as the point at which the utility equipment ownership meets the customer’s or the metering point.

Therefore, the above limits cannot be meaningfully applied to distribution panels or individual equipment within a plant. The entire plant must be considered complying with these limits.

CHAPTER 16: ELECTRIC MOTOR EFFICIENCY AND LOSS REDUCTION

16.1 Introduction

Electric motors convert electrical power into mechanical power by the interaction between the magnetic fields set up in the stator and rotor windings within a motor. In industrial applications, electric motor driven systems are used for various applications such as pumping, compressed air, fans, conveyors etc.

All industrial electric motors can be broadly classified as Induction Motors, Direct Current Motors or Synchronous Motors. All motor types have the same four operating components: Stator (stationary windings), Rotor (rotating windings), Bearings, and Frame (enclosure). All motors convert electrical energy in to mechanical energy by the interaction between the magnetic fields set up in the stator and rotor windings.

16.2 Motor Types

9.3.8

16.2.1 Induction Motors

Induction motors are the most commonly used in industrial applications. The induction motor is the most popular type of AC motor because of its simplicity and ease of operation. In fact, an induction motor is basically a rotating transformer.
There are two types of induction motor rotors

- Cage rotors and
- Wound rotors.

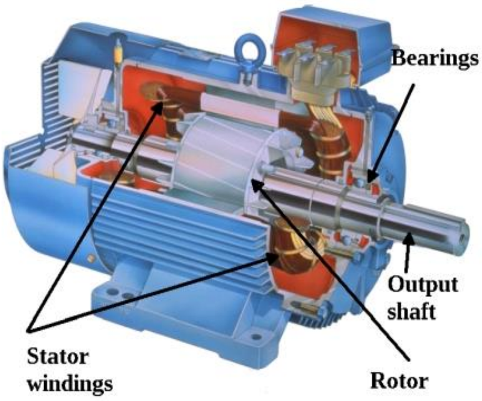


Figure 16.1: Induction Motor

Cage rotors consist of a series of parallel bars all around the rotor, shorted together at each end. Wound rotors are complete three-phase rotor windings, with the phases brought out of the rotor through slip rings and brushes. Wound rotors are more expensive and require more maintenance than cage rotors,

Slip-ring motor

The slip-ring motor or wound-rotor motor is a variation of the squirrel cage induction motor.

This motor type is ideal for very high inertia loads, where it is required to generate the pull-out torque at almost zero speed and accelerate to full speed in the minimum time with minimum current draw.

16.2.2 Direct-Current (DC) Motors

Direct-Current motors, as the name implies, use direct, i.e. unidirectional, current. Used in special applications, they only represent small percentage of motors used in industry, *e.g.* where high torque starting or where smooth acceleration over a broad speed range is required. Before the widespread use of power electronic rectifier-inverters, dc motors were unexcelled in speed control applications.

The working of DC motor is based on the principle that when a current-carrying conductor is placed in a magnetic field, it experiences a mechanical force. The direction of mechanical force is given by Fleming's Left-hand Rule. There is no basic difference in the construction of a DC generator and a DC motor. In fact, the same D.C machine can be used interchangeably as a generator or as a motor.

There are five major types of dc motors in general use:

1. The separately excited dc motor
2. The shunt dc motor
3. The permanent-magnet dc motor
4. The series dc motor
5. The compounded dc motors

16.2.3 Synchronous Motors

In synchronous machines, rotor-winding currents are supplied directly from the stationary frame through a rotating contact. AC power is fed to the stator of the synchronous motor. The rotor is fed by dc from a separate source. The rotor magnetic field locks onto the stator rotating magnetic field and rotates at the same speed. The speed of the rotor is a function of the supply frequency and the number of magnetic poles in the stator. While induction motors with a slip, i.e., rpm is less than the synchronous speed, the synchronous motor rotate with no slip, i.e., the rpm is same as the synchronous speed governed by supply frequency and number of poles. The basic principle of synchronous motor operation is that the rotor "chases" the rotating stator magnetic field around in a circle, never quite catching up with it. The slip energy is provided for by the D.C. excitation power.

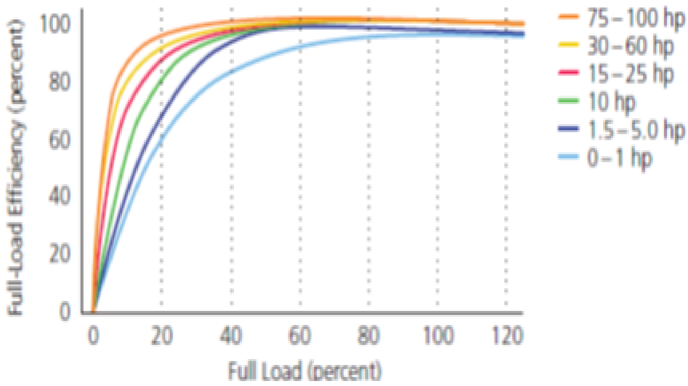
16.3 Motor Characteristics

16.3.1 Motor Speed

The speed of a motor is the number of revolutions in a given time frame, typically revolutions per minute (RPM). The speed of an AC motor depends on the frequency of the input power and the number of poles for which the motor is wound. The synchronous speed in RPM is given by the following equation, where the frequency is in hertz or cycles per second:

$$\text{Synchronous Speed (RPM)} = \frac{120 * Frequency}{No.of\ Poles}$$

The actual speed with which the motor operates, will be less than the synchronous speed. The difference between synchronous and full load speed is called slip and is measured in percent. It is



calculated using this equation:

$$\text{Slip (\%)} = \frac{\textit{Synchronous Speed} - \textit{Full Load Speed}}{\textit{Synchronous Speed}} * 100$$

As per relation stated above, the speed of an AC motor is determined by the number of motor poles and by the input frequency. It can also be seen that theoretically speed of an AC motor can be varied infinitely by changing the frequency.

16.3.2 Volts/Hz Relationship

It has been seen that by changing the frequency, one can change the speed of the motor. However, frequency is not the only parameter that must be changed. Notice in the motor model below that the impedance of a motor will change with frequency since the impedance of an inductor equals to $2\pi fl$. At low frequencies, this impedance approaches zero making the circuit appear to be a short circuit.

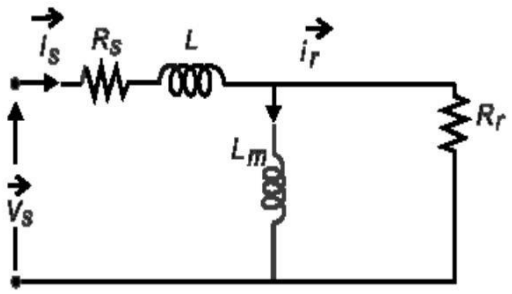


Figure 16.2: Volts/Hz Relationship

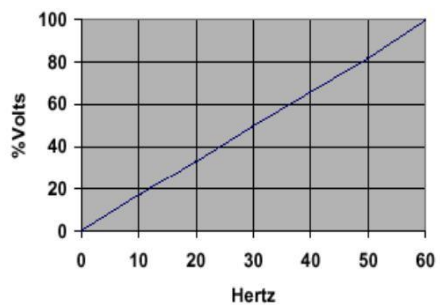


Figure 16.3: Efficiency at different load

To maintain a constant flux in the motor, the voltage to the motor must also be changed. This ratio is constant over most of the entire speed range. By keeping the ratio constant, a fixed speed induction motor can be made to run at variable speed and provide constant torque as required by driven machine. At low speeds, due to the motor having inherent resistance in the windings, the ratio must be altered to provide enough magnetizing flux to spin the motor. The VFD allows this relationship to be altered by changing the voltage boost parameter.

9.3.9

16.3.3 Power Factor

The power factor of the motor is given as: Power Factor = Cos φ = kW/kVA

As the load on the motor comes down, the magnitude of the **active current** reduces. However, there is no corresponding reduction in the **magnetizing curren**t, with the result that the motor power factor reduces, with a reduction in applied load. Induction motors, especially those operating below their rated capacity, are the main reason for low power factor in electric systems.

16.3.4 Motor Efficiency Parameters

Two important attributes relating to efficiency of electricity use by Induction motors are efficiency (η= mechanical energy output/ electrical energy input), and power factor (PF). Motors are characterized by power factors less than one. As a result, the total current draw by motor is higher than a device with higher PF for same power output.

An important effect of operating with a PF less than one is that resistance losses in wiring upstream of the motor will be higher, since these are proportional to the square of the current. Thus, both a high value for η and a PF close to unity are desired for efficient overall operation in a plant.
Squirrel cage motors are normally more efficient than slip-ring motors, and higher-speed motors are normally more efficient than lower-speed motors.

Efficiency is also a function of motor temperature. Totally-enclosed, fan-cooled (TEFC) motors are more efficient than screen- protected drip- proof (SPDP) motors. Also, as with most equipment, motor efficiency increases with the rated capacity.

The efficiency of a motor is determined by intrinsic losses that can be reduced only by changes in motor design. Intrinsic losses are of two types–

- Fixed Loss, i.e., independent of motor load

Fixed losses consist of magnetic core losses and friction and windage losses. Magnetic core losses (sometimes called iron losses) consist of eddy current and hysteresis losses in the stator. Friction and windage losses are caused by friction in the bearings of the motor and aerodynamic losses associated with the ventilation fan and other rotating parts.

- Variable Loss, i.e., dependent on load.

Variable losses consist of resistance losses in the stator and in the rotor and miscellaneous stray losses. Resistance to current flow in the stator and rotor result in heat generation that is proportional to the resistance of the material and the square of the current (I^2R). Stray losses arise from a variety of sources and are difficult to either measure directly or to calculate, but are generally proportional to the square of the rotor current.

Part-load performance characteristics of a motor also depend on its design. For operating loads in the range of 50 – 100 percent of rated load, the reductions in η decreases significantly, and PF continues to fall. Both η and PF fall to very low levels at low loads.

16.4 Field Tests for Determining Efficiency

16.4.1 No Load Test:

The motor is run at rated voltage and frequency without any shaft load. Input power, current frequency and voltage are noted. The no load P.F. is quite low and hence low PF wattmeter is required.
From the input power, stator I^2R losses under no load are subtracted to give the sum of friction, wind age and core losses. To separate core and F&W losses, test is repeated at variable voltages. It is worthwhile plotting no-load input kW versus Voltage; the intercept is F& W kW loss component.

16.4.2 Stator and Rotor I^2R Losses:

The stator winding resistance is directly measured by a bridge or volt amp method. The resistance must be corrected to the operating temperature. For modern motors, the operating temperature is likely to be in the range of 100^0C to 120^0C and necessary correction should be made. Correction to 75^0C may be inaccurate. The correction factor is given as follows:

$$\frac{R_2}{R_1} = \frac{235 - t_2}{235 + t_1} +$$

The rotor resistance can be determined from locked rotor test at reduced frequency, but rotor I^2R losses are measured from measurement of rotor slip.

Rotor I^2R losses = Slip × (Stator Input – Stator I^2R Losses – Core Loss)

Accurate measurement of slip is possible by stroboscope or non- contact type taco meter. Slip also must be corrected to operating temperature.

16.4.3 Stray Load Losses:

These losses are difficult to measure with any accuracy. IEEE Standard 112 gives a complicated method, which is rarely used on shop floor. IS and IEC standards take a fixed value as 0.5 % of output. It must be remarked that actual value of stray losses is likely to be more. IEEE – 112 specifies values from 0.9 % to 1.8%.

Motor Rating	Stray Losses
1 – 125HP	1.8 %
125 – 500HP	1.5 %
501 – 2499HP	1.2 %
2500 and above	0.9 %

16.4.4 Points for Users

It must be clear that accurate determination of efficiency is very difficult. The same motor tested by different methods and by same methods by different manufacturers can give a difference of 2%. In view of this, for selecting high efficiency motors, the following can be done:

- When purchasing large number of small motors or a large motor, ask for a detailed test certificate. If possible, try to remain present during the tests.
- See that efficiency values are specified without any tolerance
- Check the actual input current and kW, if replacement is done
- For new motors, keep a record of no load input current and power

- Use values of efficiency for comparison and for confirming; rely on measured inputs for all calculations.

16.5 Estimation of efficiency in the field

- Measure stator resistance and correct to operating temperature. From rated current value, I^2R losses are calculated.
- From rated speed and output, rotor I^2R losses are calculated
- From no load test, core and F & W losses are determined.

The method is illustrated by the following example:

Example 16.1

Motor Specifications

Rated power	=	34 kW/45 HP
Voltage	=	415 Volt
Current	=	57 Amps
Speed	=	1475 rpm
Insulation class	=	F
Frame	=	LD 200L
Connection	=	Delta
No load test Data		
Voltage, V	=	415 Volts
Current, I_{NL}	=	16.1 Amps
Frequency, F	=	50 Hz
Stator phase resistance at 30^0C	=	0.264 Ohms
No load power, P_{nl}	=	1063.74 Watts

a) Calculate iron plus friction and windage losses
b) Calculate stator resistance at 120^0C

$$R_2 = R_1 * \frac{235 + t_2}{235 + t_1}$$

c) Calculate stator copper losses at operating temperature of resistance at 120^0C
d) Calculate full load slip (s) and rotor input assuming rotor losses are slip times rotor input.
e) Determine the motor input assuming that stray losses are 0.5% of the motor rated power
f) Calculate motor full load efficiency and full load power factor

Solution

a) Iron plus friction and windage loss, $P_i + P_{fw} + P_{st} = P_{nl}$ = 1063.74 Watts

Stator Copper loss,

$$P_{st}\ (30°\text{C}) = 3\left(\frac{i}{\sqrt{3}}\right)^2 R = 3 \times \left(\frac{16.1}{\sqrt{3}}\right)^2 \times 0.264 = 68.43\ Watts$$

So, $P_i + P_{fw} = P_{nl} - P_{st}$ = 1063.74 – 68.43 = 995.3

b) Stator Resistance at 120^0C,

R(120^0C) = 0.264 × (120 + 235)/ (30+235) = 0.354 ohms

c) Stator copper losses at full load,

P_{st} (120^0C) $=3\times(57/\sqrt{3})^2 \times 0.354 = 1150.1$Watts

d) Full load slip

S = (1500 – 1475) / 1500 = 0.0167

Rotor input, $P_r = P_{output} / (1\text{-}S) = 34000 / (1\text{-}0.0167) = 34577.4$ Watts

e) Motor full load input power

$P_{input} = P_r + P_{st(120^{\circ}C)} + P_i + P_{fw} + P_{stray} = 34577.4 + 1150.1 + 995.3 + (0.005 \times 34000) = 36892.8$ Watts

f) Motor efficiency at full load Efficiency = $P_{out}/P_{input} \times 100 = 34000/36892.8 \times 100 = 92.2\%$
Full Load PF = $P_{input} / (\sqrt{3} \times V \times I) = 36892.8 / (\sqrt{3} \times 415 \times 57) = 0.9$

Comments:

a) The measurement of stray load losses is very difficult and not practical even on test beds.
b) The actual value of stray loss of motors up to 200HP is likely to be1%to3% compared to 0.5 % assumed by standards.
c) The value of full load slip taken from the name plate data is not accurate. Actual measurement under full load conditions will give better results.
d) The friction and windage losses really are part of the shaft output; however, in the above calculation, it is not added to the rated shaft output, before calculating the rotor input power. The error however is minor.
e) When a motor is rewound, there is a fair chance that the resistance per phase would increase due to winding material quality and the losses would be higher. It would be interesting to assess the effect of a nominal 10 % increase in resistance per phase.

16.6 Energy-Efficient Motors

Energy-efficient motors are the ones in which, design improvements are incorporated specifically to increase operating efficiency over motors of standard design. Design improvements focus on reducing intrinsic motor losses. Improvements include the use of lower-loss steel a longer core (to increase active material), thicker wires (to reduce resistance), thinner laminations, smaller air gap between stator and rotor, copper instead of aluminium bars in the rotor, superior bearings and a smaller fan, etc. energy-efficient motors now available operate with efficiencies that are typically 3 to 4 percentage points higher than standard motors. As per the standard IEC 60034-30-1, energy-efficient motors are designed to operate without loss in efficiency at loads between 75 % and 100 % of rated capacity. This may result in major benefits in varying load applications. The power factor is about the same or may be higher than for standard motors. Furthermore, energy- efficient motors have lower operating temperatures and noise levels, greater ability to accelerate higher-inertia loads, and are less affected by supply voltage fluctuations.

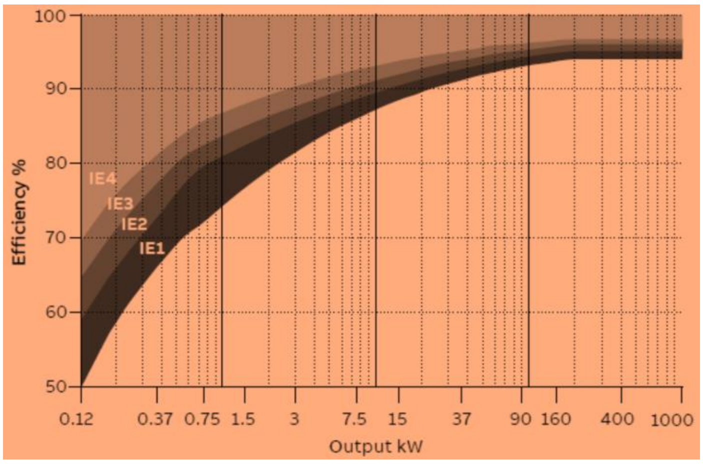


Figure 16.4: IE efficiency classes for 4 pole motors at 50 Hz

16.7 Measures adopted for energy efficiency improvement

16.7.1 Stator and Rotor I2 R Losses

9.3.10

These losses are major losses and typically account for 55% to 60% of the total losses. I^2R losses are heating losses resulting from current passing through stator and rotor conductors. I^2R losses are the function of a conductor resistance, the square of current. Resistance of conductor is a function of conductor material, length and cross-sectional area. The suitable selection of copper conductor size will reduce the resistance. Reducing the motor current is most readily accomplished by decreasing the magnetizing component of current. This involves lowering the operating flux density and possible shortening of air gap. Rotor I^2R losses are a function of the rotor conductors (usually Aluminium) and the rotor slip. Utilization of copper conductors will reduce the winding resistance. Motor operation closer to synchronous speed will also reduce rotor I^2R losses.

16.7.2 Core Loses

Core losses are those found in the stator-rotor magnetic steel and are due to hysteresis effect and eddy current effect during 50 Hz magnetization of the core material. These losses are independent of load and account for 20 – 25 % of the total losses.

The hysteresis losses which are a function of flux density, are be reduced by utilizing low-loss grade of silicon steel laminations. The reduction of flux density is achieved by suitable increase in the core length of stator and rotor. Eddy current losses are generated by circulating current within the core steel laminations. These are reduced by using thinner laminations.

16.7.3 Friction and Windage Losses

Friction and Wind age losses results from bearing friction, windage and circulating air through the motor and account for 8–12% of total losses. These losses are independent of load. The reduction in heat generated by stator and rotor losses permits the use of smaller fan. The windage losses also reduce with the diameter of fan leading to reduction in wind age losses.

16.7.4 Stray Load-Losses

These losses vary according to square of the load current and are caused by leakage flux induced by load currents in the laminations and account for 4 to 5% of total losses. These losses are reduced by careful selection of slot numbers, tooth/slot geometry and air gap.

As a result of the modifications to improve performance, the costs of energy-efficient motors are higher than those of standard motors. The higher cost will often be paid back rapidly in saved operating costs, particularly in new applications or end-of-life motor replacements. In cases where existing motors have not reached the end of their useful life, the economics will be less clearly positive.

Energy efficient motors cover a wide range of ratings and the full load efficiencies are higher by 3 to 7 %. The mounting dimensions are also maintained as per BDS 1196:1988 to enable easy replacement.

Because the favourable economics of energy-efficient motors are based on savings in operating costs, there may be certain cases which are generally economically ill-suited to energy-efficient motors. These include highly intermittent duty or special torque applications such as hoists and cranes, traction drives, punch presses, machine tools, and centrifuges. In addition, energy efficient designs of multi-speed motors are generally not available. Furthermore, most energy-efficient motors produced today are designed only for continuous duty cycle operation.

Given the tendency of over sizing on the one hand and ground realities like; voltage, frequency variations, efficacy of rewinding in case of a burnout, on the other hand, benefits of EEM's can be achieved only by careful selection, implementation, operation and maintenance efforts of energy managers.

Energy Efficient Motors		
SL.	Power Loss Area	Efficiency Improvement
1	Iron	Use of thinner gauge, lower loss core steel reduces eddy current losses. Longer core adds more steel to the design, which reduces losses due to lower operating flux densities.
2	Stator I^2R	Use of more copper and larger conductors increases cross sectional area of stator windings. This lowers resistance (R) of the windings and reduces losses due to current flow (I).
3	Rotor I^2R	Use of larger rotor conductor bars increases size of cross section, lowering conductor resistance (R) and losses due to current flow (I).
4	Friction & Windage	Use of low loss fan design reduces losses due to air movement.
5	Iron	Use of optimized design and strict quality control procedures minimizes stray load losses.

16.8 Factors Affecting Energy Efficiency & Minimizing Motor Losses in operation

16.8.1 Power Supply Quality

Motor performance is affected considerably by the quality of input power that is the actual volts and frequency available at motor terminals vis-à-vis rated values as well as voltage and frequency variations and voltage unbalance across the three phases. Motors in Bangladesh must comply with standards set by the Bangladesh Standards and Testing Institution (BSTI) for tolerance to variations in input power quality. The BSTI standards specify that a motor should be capable of delivering its rated output with a voltage variation and frequency variation. Voltage fluctuations can have detrimental impacts on motor performance. The general effects of voltage and frequency variation on motor performance are presented in following figure 16.5:

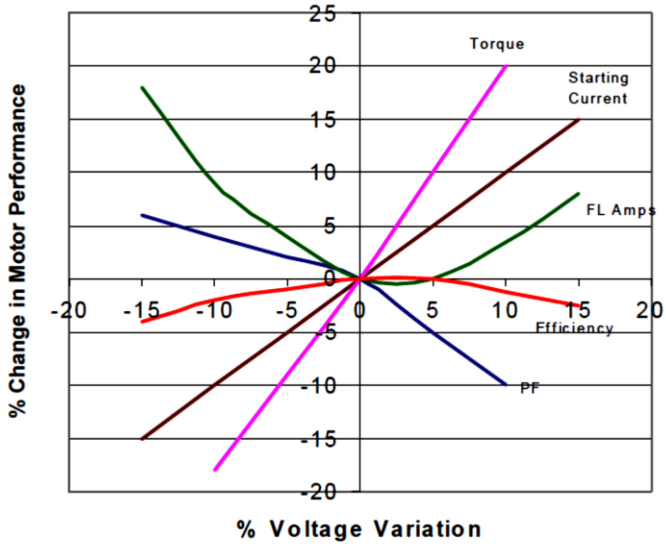


Figure 16.5: Effect of Voltage Variation on Induction Motors

Effect of Frequency Variation

Motors built in accordance to NEMA standards are designed to operate successfully at rated load and at rated voltage with a variation in the frequency of up to 5% above or below the rated frequency. The information in the following table is based on voltage being held constant.

Freq.	Starting and Max. Torque	Synchronous Speed	% Slip	Full Load Speed	Full Load Eff	Full Load PF	Full Load Current	Locked Rotor Current	Temp. Rise @ Full Load	Max. Overload Capacity	Magnetic Noise (No load)
105%	Decrease 10%	Increase 11%	Practically No Change	Increase 5%	Slight Increase	Slight Increase	Decrease Slightly	Decrease 5-6%	Decrease Slightly	Decrease Slightly	Decrease Slightly
95%	Increase 11%	Decrease 10%	Practically No Change	Decrease 5%	Slight Decrease	Slight Decrease	Increase Slightly	Increase 5-6%	Increase Slightly	Increase Slightly	Increase Slightly

Effect of Voltage Variation

Induction motors are normally designed to give satisfactory performance on a line voltage of up to 10% above or 10% below the rated value per NEMA standards

Voltage	Starting and Max. Torque	Synchro-nous Speed	% Slip	Full Load Speed	Full Load Eff	Full Load PF	Full Load Current	Locked Rotor Current	Temp. Rise @ Full Load	Max. Overload Capacity	Magnetic Noise (No load)
110%	Increase 21%	No change	Decrease 17%	Increase 1%	Increase 0-1 point	Decrease 2-8 points	Decrease 0-7%	Increase 10-14%	Decrease 4-6OC	Increase 21%	Increase slightly
90%	Decrease 21%	No change	Increase 23%	Decrease 1%	Decrease 1-3 points	Increase 1-3 points	Increase 10-12%	Decrease 10-12%	Increase 4-8OC	Decrease 19%	Decrease slightly

The options available for an energy manager to ensure near to rated voltage at motor terminals include:

a) Load end power factor improvement by providing matching PF capacitors.
b) Minimizing line / cable voltage drops from sub-station to motor terminals.
c) Transformers tap changing as required in case of consistent and continuous low voltage situations.

Voltage unbalance, the condition where the voltages in the three phases are not equal, can be still more detrimental to motor performance and motor life. Unbalance typically occurs as a result of supplying single-phase loads disproportionately from one of the phases. It can also result from the use of different sizes of cables in the distribution system.

Table 16.1: Example of the Effect of Voltage Unbalance on Motor Performance

	Percent unbalance in voltage*		
	0.30	2.30	5.40
Unbalance in current (%)	0.4	17.7	40.0
Increased temperature rise(^{0}C)	0	30	40

Percent unbalance in voltage is defined as $\frac{(V_{max} - V_{avg})}{V_{avg}} \times 100$, Where V_{max} and V_{avg} are the largest and the average of the three phase voltages, respectively.

The NEMA (National Electrical Manufacturers Association of USA) standard definition of voltage unbalance is given by the following equation:

Voltage unbalance = Maximum deviation from mean of V_{ab}, V_{bc}, V_{ca}

For example, if the line voltages are V_{ab} = 410, V_{bc} = 417, and V_{ca} = 408

% Voltage unbalance = (417 – 411.7/ 411.667) x 100 = 1.29 %

Where,
Mean = (410 + 417 + 408)/3 = 411.7
Hence the voltage unbalance is 1.29%.

Common Causes of Voltage Unbalance

It is recommended that the voltage unbalance at the motor terminals not exceed 1%, anything above this will lead to de rating of the motor. The common causes of voltage unbalance are
Some of the more common causes of unbalanced voltages are:

- Unbalanced incoming utility supply
- Unequal transformer tap settings
- Large single phase distribution transformer on the system
- Open phase on the primary of a 3-phase transformer on the distribution system
- Faults or grounds in the power transformer
- Open delta connected transformer banks
- A blown fuse on a 3-phase bank of power factor improvement capacitors
- Unequal impedance in conductors of power supply wiring

- Unbalanced distribution of single-phase loads such as lighting
- Heavy reactive single-phase loads such as welders

Voltage unbalance is probably the leading power factor problem that results in motor overheating and premature motor failure.

Voltage unbalance causes extremely high current imbalance. The magnitude of current imbalance may be 6 to 10 times as large as the voltage imbalance. A motor will run hotter when operating on a power supply with voltage unbalance. The additional temperature rise is estimated with the following equation

$$\text{Additional temperature rise} = 2 \times (\%\ \text{Voltage unbalance})^2$$

For example, if the voltage unbalance is 2% for a motor operating at 100°C, the additional temperature rise will be 8°C. The winding insulation life is reduced by one half for each 10 °C increase in operating temperature.

The options that an Energy Manager can exercise to minimize voltage unbalance include:

- Balancing any single-phase loads equally among all the three phases
- Segregating any single-phase loads which disturb the load balance and feed them from a separate line / transformer.

16.8.2 Motor Loading

9.3.11

Measuring Load

Knowing the load on the motor over its typical operating cycle is critical to understanding the potential for improving motor use efficiency. Under-loading and variable loading can produce inefficient motor operation. However, it is normally quite difficult to ascertain the load on the motor, as it requires measuring input power, current, voltage, frequency and motor speed under both load and no-load conditions. Measurement of the stator resistance is also required. It is generally inadequate to measure only the current drawn under load, as this can give misleading results. The no-load measurements provide the basis for estimating fixed losses, which, together with the measurements under load, permit motor efficiency to be estimated (IEEE, 1984). Proper instrumentation is critical to making accurate measurements.

Reducing Under-loading

Probably the most pervasive practice contributing to sub- optimal motor efficiency is that of under-loading. Under-loading results in lower efficiency and power factor, and higher than necessary first cost for the motor and related control equipment. Under-loading is common for several reasons. Original equipment manufacturers tend to use a large safety factor in motors they select. Under-loading of the motor may also occur from under- utilization of the equipment. For example, machine tool equipment manufacturers provide for a motor rated for the full capacity load of the equipment. The user may need this full capacity rarely, resulting in under- loaded operation most of the time. Another common reason for under-loading is selection of a larger motor to enable the output to be maintained at the desired level even when input voltages are abnormally low. Finally, under- loading also results from selecting a large motor for an application requiring high starting torque where a special motor, designed for high torque, would have been suitable.

A careful evaluation of the load would determine the capacity of the motor that should be selected. Another aspect to consider is the incremental gain in efficiency achievable by changing the motor. Larger motors have inherently higher rated efficiencies than smaller motors. Therefore, there placement of motors operating at 60–70% of capacity or higher is generally not recommended. However, there are no rigid rules governing motor selection; the savings potential needs to be evaluated on a case-to-case basis. When downsizing, it may be preferable to select an energy-efficient motor, the efficiency of which may be higher than that of a standard motor of higher capacity.

For motors which consistently operate at loads below 50% of rated capacity, an inexpensive and effective measure might be to operate in star mode. A change from the standard delta operation to star operation involves re-configuring the wiring of the three phases of power input at the terminal box.

Operating in the star mode leads to a voltage reduction by a factor of '√3'. Motor output falls to one-third of the value in the delta mode, but performance characteristics as a function of load remain unchanged. Thus, full-load operation in star mode gives higher efficiency and power factor than partial load operation in the delta mode. However, motor operation in the star mode is possible only for applications where the torque-to-speed requirement is lower at reduced load.

For applications with high initial torque and low running torque needs, Delta-Star starters are also available in market, which help in load following de-rating of electric motors after initial start-up.

Sizing to Variable Load

Industrial motors frequently operate under varying load conditions due to process requirements. A common practice in cases where such variable-loads are found is to select a motor based on the highest anticipated load. In many instances, an alternative approach is typically less costly, more efficient, and provides equally satisfactory operation. With this approach, the optimum rating for the motor is selected on the basis of the load duration curve for the particular application. Thus, rather than selecting a motor of high rating that would operate at full capacity for only a short period, a motor would be selected with a rating slightly lower than the peak anticipated load and would operate at overload for a short period of time. Since operating within the thermal capacity of the motor insulation is of greatest concern in a motor operating at higher than its rated load, the motor rating is selected as that which would result in the same temperature rise under continuous full-load operation as the weighted average temperature rise over the actual operating cycle. Under extreme load changes, e.g. frequent starts / stops, or high inertia loads, this method of calculating the motor rating is unsuitable since it would underestimate the heating that would occur.

Where loads vary substantially with time, in addition to proper motorizing, the control strategy employed can have a significant impact on motor electricity use. Traditionally, mechanical means (e.g. throttle valves in piping systems) have been used when lower output is required. More efficient speed control mechanisms include multi-speed motors, eddy- current couplings, fluid couplings, and solid-state electronic variable speed drives.

16.8.3 Power Factor Correction

9.3.12

As noted earlier, induction motors are characterized by power factors less than unity, leading to lower overall efficiency (and higher overall operating cost) associated with a plant's electrical system. Capacitors connected in parallel (shunted) with the motor are typically used to improve the power factor. The impacts of PF correction include reduced kVA demand (and hence reduced utility demand charges), reduced I^2R losses in cables up stream of the capacitor (and hence reduced energy charges), reduced voltage drop in the cables (leading to improved voltage regulation), and an increase in the overall efficiency of the plant electrical system.

The size of capacitor required for a particular motor depends upon the no-load reactive kVA (KVAR) drawn by the motor, which can be determined only from no-load testing of the motor. In general, the capacitor is then selected to not exceed 90% of the no-load KVAR of the motor. (Higher capacities could result in over-voltages and motor burn-outs).Alternatively, typical power factors of standard motors can provide the basis for conservative estimates of capacitor ratings to use for different size motors.

Table 16.2: Capacitor ratings for power factor correction by direct connection to induction motors

Motor Rating (HP)	Capacitor rating (KVAR) for Motor Speed					
	3000	1500	1000	750	600	500
5	2	2	2	3	3	3
7.5	2	2	3	3	4	4
10	3	3	4	5	5	6
15	3	4	5	7	7	7
20	5	6	7	8	9	10
25	6	7	8	9	9	12
30	7	8	9	10	10	15
40	9	10	12	15	16	20
50	10	12	15	18	20	22
60	12	14	15	20	22	25
75	15	16	20	22	25	30
100	20	22	25	26	32	35
125	25	26	30	32	35	40
150	30	32	35	40	45	50
200	40	45	45	50	55	60
250	45	50	50	60	65	70

Since a reduction in line current, and associated energy efficiency gains, are reflected backwards from the point of application of the capacitor, the maximum improvement in overall system efficiency is achieved when the capacitor is connected across the motor terminals, as compared to somewhere further upstream in the plant's electrical system. However, economies of scale associated with the cost of capacitors and the labour required to install them will place an economic limit on the lowest desirable capacitor size.

Energy managers can, by a motor load survey, arrive at capacitor ratings, locations and cost benefits. One factor to be considered "operating hours" of motor.

16.8.4 Maintenance

Inadequate maintenance of motors can significantly increase losses and lead to unreliable operation. For example, improper lubrication can cause increased friction in both the motor and associated drive transmission equipment. Resistance losses in the motor, which rise with temperature, would increase. Providing adequate ventilation and keeping motor cooling ducts clean can help dissipate heat to reduce excessive losses. The life of the insulation in the motor would also be longer: for every 10^0C increase in motor operating temperature over the recommended peak, the time before rewinding would be needed is estimated to be halved.

A check list of good maintenance practices to help ensure proper motor operation would include:

- Inspecting motors regularly for wear in bearings and housings (to reduce frictional losses) and for dirt/dust in motor ventilating ducts (to ensure proper heat dissipation).
- Checking load conditions to ensure that the motor is not over or under loaded. A change in motor load from the last test indicates a change in the driven load, the cause of which should be understood.
- Lubricating appropriately. Manufacturers generally give recommendations for how and when to lubricate their motors. Inadequate lubrication can cause problems, as noted above. Over-lubrication can also create problems, e.g., excess oil or grease from the motor bearings can enter

the motor and saturate the motor insulation, causing premature failure or creating a fire risk.

- Checking periodically for proper alignment of the motor and the driven equipment. Improper alignment can cause shafts and bearings to wear quickly, resulting in damage to both the motor and the driven equipment.
- Ensuring that supply wiring and terminal box are properly sized and installed. Inspect regularly the connections at the motor and starter to be sure that they are clean and tight.

16.8.5 Age

Most motor cores are manufactured from silicon steel or de-carbonized cold-rolled steel, the electrical properties of which do not change measurably with age. However, poor maintenance (inadequate lubrication of bearings, insufficient cleaning of air cooling passages, etc.) can cause a deterioration in motor efficiency overtime. Ambient conditions can also have a detrimental effect on motor performance. For example, excessively high temperatures, high dust loading, corrosive atmosphere, and humidity can impair insulation properties; mechanical stresses due to load cycling can lead to mis-alignment. However, with adequate care, motor performance can be maintained.

16.8.6 Rewinding Effects on Energy Efficiency

It is common practice in industry to rewind burnt-out motors. The population of rewound motors in some industries exceeds 50% of the total population. Careful rewinding can sometimes maintain motor efficiency at previous levels, but in most cases, losses in efficiency result. Rewinding can affect a number of factors that contribute to determining motor efficiency: winding and slot design, winding material, insulation performance, and operating temperature. For example, a common problem occurs when heat is applied to strip old windings: the insulation between laminations can be damaged, thereby increasing eddy current losses. A change in the air gap may affect power factor and output torque.

However, if proper measures are taken, motor efficiency can be maintained, and in some cases increased, after rewinding. Efficiency can be improved by changing the winding design, though the power factor could be affected in the process. Using wires of greater cross section, slot size permitting, would reduce stat or losses thereby increasing efficiency. However, it is generally recommended that the original design of the motor be preserved during the rewind, unless there are specific, load-related reasons for redesign.

The Impact of rewinding on motor efficiency and power factor can be easily assessed if the no-load losses of a motor are known before and after rewinding. Maintaining documentation of no-load losses and no-load speed from the time of purchase of each motor can facilitate assessing this impact.

Table 16.3 Monitoring Format for Rewound Motors

Section	Equipment Code	Motor Code	Motor Type		No Load Current				Starter Resistance/phase		No load loss	
			Sq.Cage	Slip Ring	New Motor		After Rewinding		New	Rewound	New	Rewound
					A	V	A	V			Watts	Watts

16.8.7 Speed Control of AC Induction Motors

Electro-Mechanical Speed Control Systems

Electro-mechanical speed control mechanisms include purely mechanical systems, multi- speed motors, eddy-current drives, and fluid couplings. The characteristics of these are summarized in the table below.

Table 16.4: Electro Mechanical Speed Control alternatives for AC Induction Motors

VSD Type (Power, Speed Range)	Advantages	Disadvantages
ELECTRO-MECHANICAL CONTROL METHODS		
Gears, Pulleys, etc.		
Variable Pulley Sheaves	Low Cost	Low power savings; high maintenance costs
Gears	Low Cost	Low power savings; high maintenance costs
Chains	Low Cost	Low power savings; high maintenance costs
Friction Drives	Low Cost	Low power savings; high maintenance costs
Multispeed Motors	Operational at 2 or 4FixedSpeeds	Stepped speed control;
Eddy-current Drives >0kW, 10:1	Simple; relatively low cost; step less speed control	lower efficiency than single-speed motors
Fluid Coupling Drives>0 kW, 5: 1	Simple; relatively low cost; stepless speed control	Needs low efficiency at below 50% rated speed

16.8.8 Transmission Efficiency

Power transmission equipment linking motors to driven machines including shafts, belts, chains, and gears should be properly selected, installed and maintained. When possible, use flat belts in place of V-belts. Helical gears are more efficient than worm gears; use worm gears only with motors under 10hp. As far as possible it is better to have a direct drive thus avoiding losses in motor power transmission to the driven machine.

Power transmission Efficiency margin from V belt drive to flat belt drive 5 to 6 % and from Worm gearbox to Helical Gearbox 8 to 10 %

16.8.9 Soft Starters

A soft starter is another form of reduced voltage starter for AC induction motors which facilitates gradual acceleration of motor and consequent elimination of shocks during starting (soft start). The starting current with a soft starter is only 1.5 to 2 times the full load current as against 5–7 times in the case of other conventional starters. Because of this cable sizes, contactors and motors can be sized lower during the initial selection. The soft starter employs solid state devices to control the current flow and therefore the voltage applied to the motor.

Advantages:

- Nanosecond response on account of micro-electronics involved.
- Reduced power consumption and hence reduced energy bills, at part loads.

- Power factor improvement on a continuous basis
- Reduction in maximum demand
- Reduced peak motor current during starting
- Reduced motor temperature, increased motor life and decreased maintenance needs
- When using a generator, the power generated can be used to operate more equipment, since the starting and running currents of motors are lower, when motors are fitted with energy-saver-soft-starters.

Typical Applications

Plastic injection moulding machines, Machine tools / motor generator welding sets, chemical process equipment, unloading type air compressors, punch presses, centre less grinding and polishing machines, blowers, wherever the motor load is varying continuously.

16.9 CASE STUDY

Refrigeration plant study in a chemical complex indicated part load operation of reciprocating compressor drives with unloader mechanism, as illustrated below:

Item Reference	Brine Unit	Chilled Water Unit
Motor input kW	53	74.1
Rpm	750	780
Op. hours / day	14.5	9.0
% ON time	58	38
Power consumption/day (kWh)	768.5	666.9

The Compressor speed can be increased or decreased with a change in the drive pulley or the driven pulley or in some cases, both pulleys. By pulley diameter modification, the machines were de-rated to match required capacity. A higher sized reciprocating compressor operating with higher unloading percentage was downsized by reducing the motor (drive) pulley size from 12” to 7.5” in case of Brine unit and 12” to 6” in case of Chilled water unit .

Despite increased use hours due to derating effects, the specific power consumption reduced as the evaporator and condenser became oversized for the de-rated condition, and the energy consumption reduced as well as follows:

Item Reference	Brine Unit	Chilled Water Unit
Motor input kW	32.3	35.6
Speed Rpm	480	409.5
Op. hours / day	18.0	14.0
Average energy consumption/day (kWh)	581.4	498.4

The energy savings of 355.6kWh/day by the simple modifications, are a significant 25%. The interesting part of the exercise was that the investment is nominated, and the pay back is in order of days. Most cases, where load-unload cycling of reciprocating machines takes place for capacity control, pulley diameter modification offers a simple, cheap solution to derate the machine capacity with energy savings potential of significant order.

CHAPTER 17: VARIABLE FREQUENCY DRIVE

Although there are many methods of varying the speeds of the driven equipment such as hydraulic coupling, gear box, variable pulley etc., the most possible method is one of varying the motor speed itself by varying the frequency and voltage by a variable frequency drive.

17.1 Concept of Variable Frequency Drive

The speed of an induction motor is proportional to the frequency of the AC voltage applied to it, as well as the number of poles in the motor stator. This is expressed by the equation:

$$RPM = \frac{120f}{p} \cdots\cdots\cdots (17.1)$$

Where f is the frequency in Hz, and p is the number of poles in any multiple of 2.

Therefore, if the frequency applied to the motor is changed, the motor speed changes in direct proportion to the frequency change. The control of frequency applied to the motor is the job given to the VFD.

The VFD's basic principle of operation is to convert the electrical system frequency and voltage to the frequency and voltage required to drive a motor at a speed other than its rated speed. The two most basic functions of a VFD are to provide power conversion from one frequency to another, and to enable control of the output frequency.

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Figure: 17.1 Components of a Variable Frequency Drive

Principles of VFD’s

The VFD is a system made up of active/passive power electronics devices (IGBT, MOSFET, etc.), a high-speed central controlling unit and optional sensing devices, depending upon the application requirement. A typical modern-age intelligent VFD for the three-phase induction motor is shown in Figure 17.1.

The basic function of the VFD is to act as a variable frequency generator in order to vary speed of the motor as per the user setting. The rectifier and the filter convert the AC input to DC with negligible ripple. The inverter, under the control of the microcontroller, synthesizes the DC into three-phase variable voltage, variable frequency AC.

A single VFD has the capability to control multiple motors. The VFD is adaptable to almost any operating condition.

17.1 VFD Selection

The size of the VFD depends mainly on driven load type and characteristics. This will determine the drive capacity in terms of full load current (FLC) and power delivered (kW).

17.2 Variable Frequency Drives: Precautions

- Ensure that the power voltage supplied to VFDs is stable within plus or minus 10% to prevent tripping faults.
- Motors operating at low speeds can suffer from reduced cooling. For maximum protection on motors to be run at low speeds, install thermal sensors that interlock with the VFD control circuit. Standard motor protection responds only to over-current.
- Speed control wiring, which is often 4 mA to 20 mA or 0 VDC to 5 VDC, should be separated from other wiring to avoid erratic behaviour. Parallel runs of 115V and 24V control wiring may cause problems.
- Precautions for specifying, installing and operating VFDs are numerous. Improper installation and start-up accounts for 50 % of VFD failures
- Use the VFD start-up sheet to guide the initialization check prior to energizing the VFD for the first time.
- Corrosive environments, humidity above 95%, ambient air temperatures exceeding 40^0C (104^0F), and conditions where condensation occurs may damage VFDs.
- If a VFD is started when the load is already spinning, the VFD will try to pull the motor down to a low, soft-start frequency. This can result in high current and a trip unless special VFDs are used.
- Switching from grid power to emergency power while the VFD is running is not possible with most types of VFDs. If power switching is anticipated, include this capacity in the specification.
- If electrical disconnects are located between the VFD and motor, interlock the run- permissive circuit to the disconnect.
- If a motor always operates at rated load, a VFD will increase power use, due to electrical losses in the VFD.

17.2.1 Harmonics in VFD

A key concern with VFD operation is the generation of harmonics-multiples of the fundamental frequency (50Hz) which result in a non-sinusoidal high for inverters with only a few pulses per second as compared to more complex ones that produce a 12-step (or higher) voltage waveform or that employ pulse width modulation.

Harmonics increase motor losses, and can adversely affect the operation of sensitive auxiliary equipment. Then on-sinusoidal supply results in harmonic currents in the stator which increases the total current draw. In addition, the rotor resistance (or more precisely impedance) increases significantly at harmonic frequencies, leading to less efficient operation. Also, stray load losses can increase significantly at harmonic frequencies. Overall motor losses increase by about 20% with a six-step voltage wave form compared to operation with a sinusoidal supply. In some cases, the motor may have to be derated as a result of the losses. Alternatively, additional circuitry and switching devices can be employed to minimize losses.

Motor instability, characterized by hunting of the rotor (a phenomenon where the rotor accelerates or decelerates about a stable speed), may occur for certain critical frequency ranges and loading conditions. Motors are inherently unstable at low frequencies. Instability can also occur due to the interaction between the motor and the converter. This is especially true of motors of low rating, which have low inertia. Instabilities can be reduced by changing the machine parameters (e.g., motor impedance) or by employing closed loop feedback systems. The VFD supplier should be consulted to ascertain the impact of inverters on motor performance.

Harmonics can also contribute to low power factor. Shunt capacitors that might be used to compensate for low power factor also generate harmonics. If parallel resonance occurs between the shunt capacitor and VFD (at frequency determined by the capacitance and system inductance), the voltage waveform may undergo significant distortion causing motor overheating, capacitor failure or mis-operation of the control. To avoid resonance, reactive filters can be designed for the VFD. Filters are designed to eliminate resonance at the fifth and seventh frequency harmonics which are the most harmful. Low level distortions may still be present, but these do not pose a serious problem.

17.2.2 Other operating concerns

Steep voltage transients, e.g., caused by switching of shunt capacitors or transient system faults, can affect VFD operation. Isolation transformers or special VFD inverter designs can be used to prevent such transients from tripping or otherwise affecting VFD operation. A power supply with unstable voltage and frequency also hampers regenerative braking, thus eroding efficiency.

When a totally-enclosed fan-cooled motor is controlled to operate at very low speed, some derating may be required if the cooling is inadequate.

In cases where some of the operating time is at close to rated load, system efficiency might be increased by using a bypass arrangement to avoid the losses in the VFD. The VFD would be engaged at lower loads, when the VFD-related reductions in power would more than off-set in efficiencies of the VFD. Such a bypass arrangement would also provide for greater reliability in case of a VSD failure.

17.3 CASE STUDY

Based on study of humidification plants in a Rayon industry, it was established that the air flow demand in supply air and return air varies as per season and the supply and return fans rated 16 kW, 12 kW respectively were running at constant load. Towards energy efficiency improvement, the drives were converted variable frequency drives. The part load effects one summarized as follows:

Supply Frequency C/S	Supply Air Fan		Return Air Fan	
	KW Drawn	% Drop in	KW Drawn	% Drop in
50	16.4	Capacity Ref.	12	Capacity Ref.
45	12.0	10.0	8.7	10.0
40	8.4	20.0	6.1	20.0
35	5.6	30.0	4.1	30.0
30	3.5	40.0	2.6	40.0

As the flow requirements vary, the following schedule was adopted with power savings indicated alongside.

Months	***Recommended Frequency***	***Average %kW Savings***
October, Nov, Dec, Jan	35	51
Feb, March, Sept.	40	35
April, August, July	45	18
May, June	50	-

Covering all 10fans, with 142kW consumption among five sets of supply air & return air fans, the savings achieved were 377223kWh worth BDT.13.16lakhs/yea against an investment of BDT 12.5lakhs

@ BDT 1.25lakh/ drive yielding a simple payback period of less than one year

CHAPTER 18: PUMPS AND PUMPING SYSTEM

18.1 Pump Types

Pumps come in a variety of sizes for a wide range of applications. They can be classified according to their basic operating principle as dynamic or displacement pumps. Dynamic pumps can be sub-classified as centrifugal and special effect pumps. Displacement pumps can be sub-classified as rotary or reciprocating pumps.

In principle, any liquid can be handled by any of the pump designs. Where different pump designs could be used, the centrifugal pump is generally the most economical followed by rotary and reciprocating pumps. Although, positive displacement pumps are generally more efficient than centrifugal pumps, the benefit of higher efficiency tends to be offset by increased maintenance costs.

Since, worldwide, centrifugal pumps account for the majority of electricity used by pumps, the focus of this chapter is on centrifugal pump

18.2 Centrifugal Pumps

A centrifugal pump (Figure 18.1) is of a very simple design. The two main parts of the pump are the impeller and the diffuser. Impeller, which is the only moving part, is attached to a shaft and driven by a motor. Impellers are generally made of bronze, polycarbonate, cast iron, stainless steel as well as other materials. The diffuser (also called as volute) houses the impeller and captures and directs the water off the impeller.

Water enters the centre (eye) of the impeller and exits the impeller with the help of centrifugal force. As water leaves the eye of the impeller a low-pressure area is created, causing more water to flow into the eye. Atmospheric pressure and centrifugal force cause this to happen. Velocity is developed as the water flows through the impeller spinning at high speed. The water velocity is collected by the diffuser and converted to pressure by specially designed passageways that direct the flow to the discharge of the pump, or to the next impeller should the pump have a multi-stage configuration.

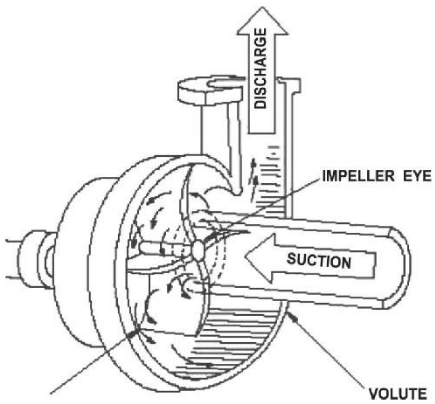


Figure 18.1 Centrifugal Pump

The pressure (head) that a pump will develop is in direct relationship to the impeller diameter, the number of impellers, the size of impeller eye, and shaft speed. Capacity is determined by the exit width of the impeller. The head and capacity are the main factors, which affect the horsepower size of the motor to be used. The more the quantity of water to be pumped, the more energy is required.

A centrifugal pump is not positive acting, it will not pump the same volume always. The greater the depth of the water, the lesser is the flow from the pump. Also, when it pumps against increasing pressure, the less it will pump. For these reasons it is important to select a centrifugal pump that is designed to do a particular job.

Since the pump is a dynamic device, it is convenient to consider the pressure in terms of head i.e. meters of liquid column. The pump generates the same head of liquid whatever the density of the liquid being pumped. The actual contours of the hydraulic passages of the impeller and the casing are extremely important, in order to attain the highest efficiency possible. The standard convention for centrifugal pump is to draw the pump performance curves showing Flow on the horizontal axis and Head generated on the vertical axis. Efficiency, Power & NPSH Required (described later), are also all conventionally shown on the vertical axis, plotted against Flow, as illustrated in Figure 18.2.

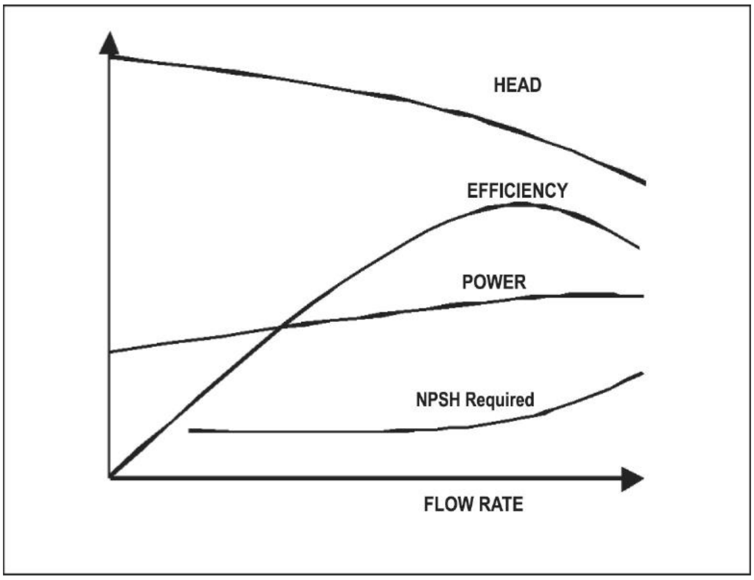


Figure 18.2 Pump Performance

Given the significant amount of electricity attributed to pumping systems, even small improvements in pumping efficiency could yield very significant savings of electricity. The pump is among the most inefficient of the components that comprise a pumping system, including the motor, transmission drive, piping and valves.

18.3 Hydraulic Power, Pump Shaft Power and Motor Input Power

Hydraulic Power $P_h(kW) = \frac{Q\left(\frac{m^3}{s}\right)\times(h_d - h_s)\times p\left(\frac{kg}{m^3}\right)\times g\left(\frac{m}{s^2}\right)}{1000} \cdots\cdots\cdots (18.1)$

Where h_d -discharge head, h_s-suction head, ρ-density of the liquid, g- acceleration due to gravity

Pump Shaft Power $P_s = \frac{P_h}{\eta_{Pump}} \cdots\cdots\cdots (18.2)$

Motor Input Power, $P_E = \frac{P_s}{\eta_{Motor}} \cdots\cdots\cdots (18.3)$

18.4 Performance Terms and Definitions

Pump Capacity, Q = Volume of liquid delivered by pump per unit time, m^3/hr or m^3/sec
Q is proportional to N, where N is the rotational speed of the pump (RPM)

Static Suction Head is the vertical distance in meters from the centreline of the pump to the free level of the liquid to be pumped. Suction Head exists when the source of supply is above the centreline of the pump.

Static Discharge Head is the vertical distance in feet metres between the pump centreline and the point of free discharge or the surface of the liquid in the discharge tank.

Total Static Head is the vertical distance in metres between the free level of the source of supply and the point of free discharge or the free surface of the discharge liquid.

Friction Head is the head required to overcome the resistance to flow in the pipes, valves and fittings. It is dependent upon the size and type of pipe flow rate, and nature of the liquid and varies as a function (roughly as the square) of the capacity flow through the system.

Velocity Head is the energy of a liquid as a result of its motion at some velocity V. It is the equivalent head in metres through which the water would have to fall to acquire the same velocity, or in other words, the head necessary to accelerate the water. The velocity head is usually insignificant and can be ignored in most high head systems. However, it can be a large factor and must be considered in low head systems.

Total Head or Total Dynamic head, H **is** the difference of discharge and suction pressure.
It represents the net work done on unit weights of a liquid in passing from inlet of the pump to the discharge of the pump.

System resistance is the head that is required to move liquid through a piping system at various flow rates. It is the sum of frictional head & total static head

System resistance: The sum of frictional head in resistance & total static head.

System Curve is a graphical representation of the pump head that is required to move fluid through a piping system at various flow rates. The system curve helps quantify the resistance in a system due to friction and elevation change over the range of flows. When there are no control features in the system, such as flow control valves, then the pump and system curves will intersect at the operating flow rate.

Pump Efficiency: Fluid power and useful work done by the pump divided by the power input in the pump shaft.

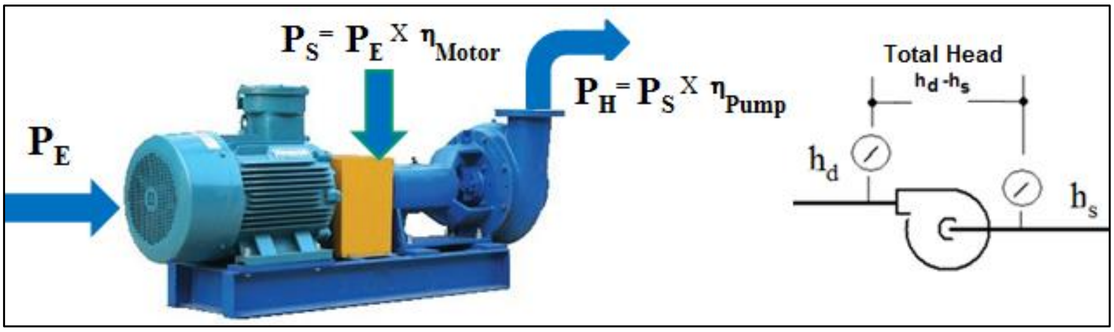


Figure 18.4: Parameters relate to Pump Efficiency

18.5 System Characteristics

In a pumping system, the objective, in most cases, is either to transfer a liquid from a source to a required destination, e. g. filling a high-level reservoir or to circulate liquid around a system e. g. as a means of heat transfer in heat exchanger.

A pressure is needed to make the liquid flow at the required rate and this must overcome head 'losses' in the system. Losses are of two types: static and friction head.

Static head is simply the difference in height of the supply and destination reservoirs, as in Figure 18.5. In this illustration, flow velocity in the pipe is assumed to be very small. Another example of a system with only static head is pumping into a pressurized vessel with short pipe runs. Static head is independent of flow and graphically would be shown as in Figure 18.6.

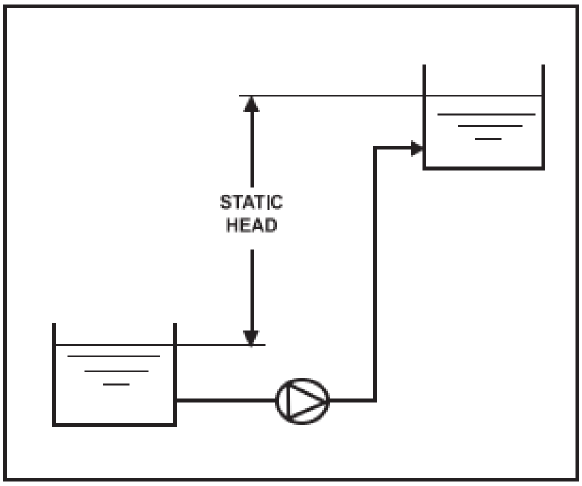


Figure 18.5 Static Head

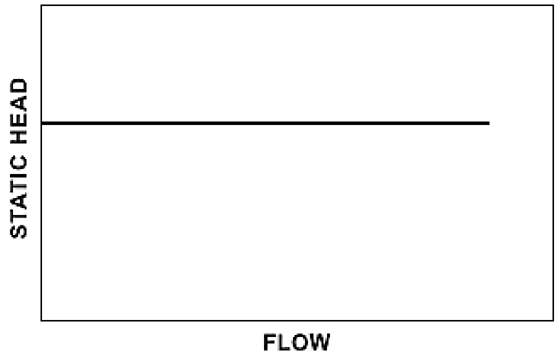


Figure 18.6 Static Head vs. Flow

Friction head (sometimes called dynamic head loss) is the friction loss, on the liquid being moved, in pipes, valves and equipment in the system. Friction tables are universally available for various pipe fittings and valves. These tables show friction loss per 100 feet (or meters) of a specific pipe size at various flow rates. In case of fittings, friction is stated as an equivalent length of pipe of the same size. The friction losses are proportional to the square of the flow rate. A closed loop circulating system without a surface open to atmospheric pressure, would exhibit only friction losses and would have a system friction head loss vs. flow curve as Figure

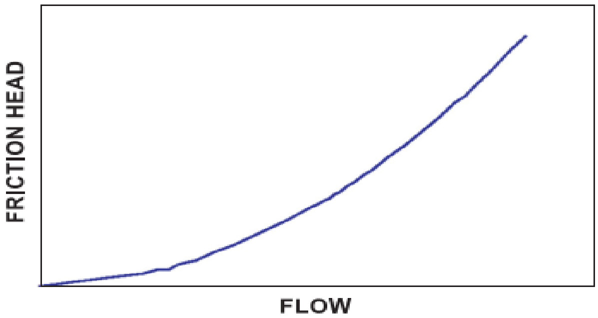
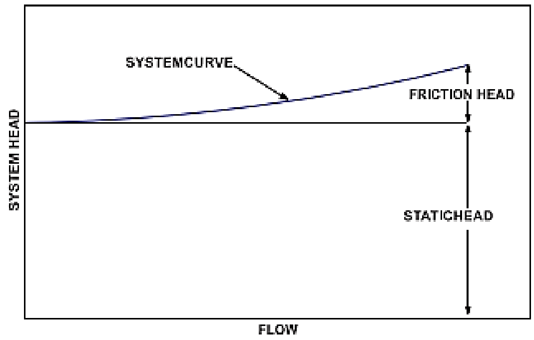


Figure 18.7 Friction Head vs. Flow

Most systems have a combination of static and friction head and the system curves for two cases are shown in Figures 18.8 and 18.9. The ratio of static to friction head over the operating range influences the benefits achievable from variable speed drives which shall be discussed later



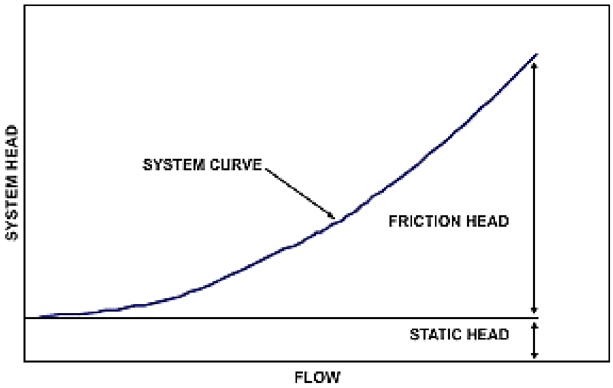


Figure 18.8 System with High Static Head *Figure 18.9 System with Low Static Head*

Static head is a characteristic of the specific installation and reducing this head where this is possible generally helps both the cost of the installation and the cost of pumping the liquid. Friction head losses must be minimized to reduce pumping cost, but after eliminating unnecessary pipe fittings and length, further reduction in friction head will require larger diameter pipe, which adds to capital cost.

18.6 Pump Curves

The performance of a pump can be expressed graphically as head against flow rate. The centrifugal pump has a curve where the head falls gradually with increasing flow. This is called the pump characteristic curve (Head — Flow curve). See Figure 18.10.

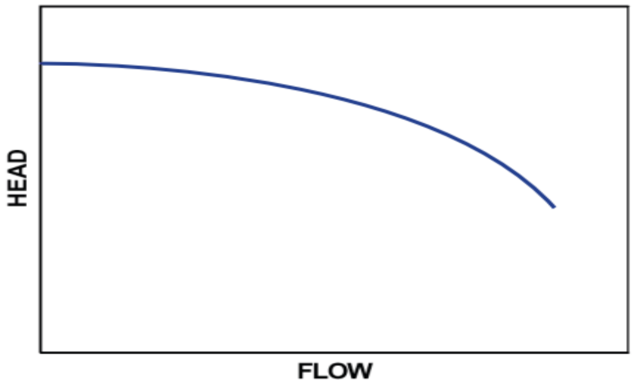


Figure 18.10 Head-Flow Curve

Pump operating point

When a pump is installed in a system the effect can be illustrated graphically by superimposing pump and system curves. The operating point will always be where the two curves intersect. Figure: 18.11.

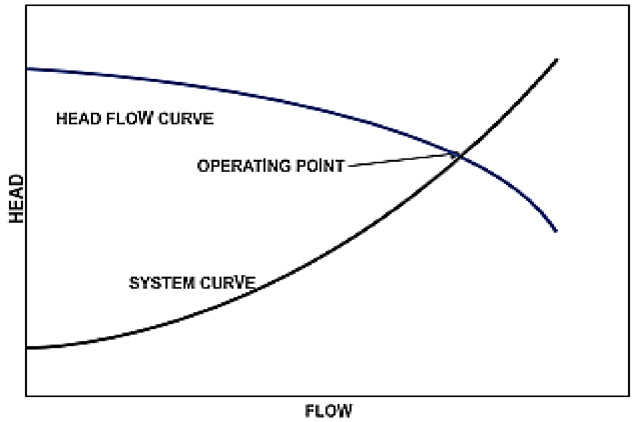


Figure 18.11 Pump Operating Point

If the actual system curve is different in reality to that calculated, the pump will operate at a flow and head different to that expected. For a centrifugal pump, an increasing system resistance will reduce the flow, eventually to zero, but the maximum head is limited as shown. Even so, this condition is only acceptable for a short period without causing problems. An error in the system curve calculation is also likely to lead to a centrifugal pump selection, which is less than optimal for the actual system head losses. Adding safety margins to the calculated system curve to ensure that a sufficiently large pump is selected will generally result in installing an oversized pump, which will operate at an excessive flow rate or in a throttled condition, which increases energy usage and reduces pump life.

18.7 Factors Affecting Pump Performance

18.7.1 Matching Pump and System Head-flow Characteristics

Centrifugal pumps are characterized by the relationship between the flow rate (Q) they produce and the pressure (H) at which the flow is delivered. Pump efficiency varies with flow and pressure, and it is highest at one particular flow rate.

The Figure 18.12 below shows a typical vendor-supplied head-flow curve for a centrifugal pump. Pump head-flow curves are typically given for clear water. The choice of pump for a given application depends largely on how the pump head-flow characteristics match the requirement of the system downstream of the pump.

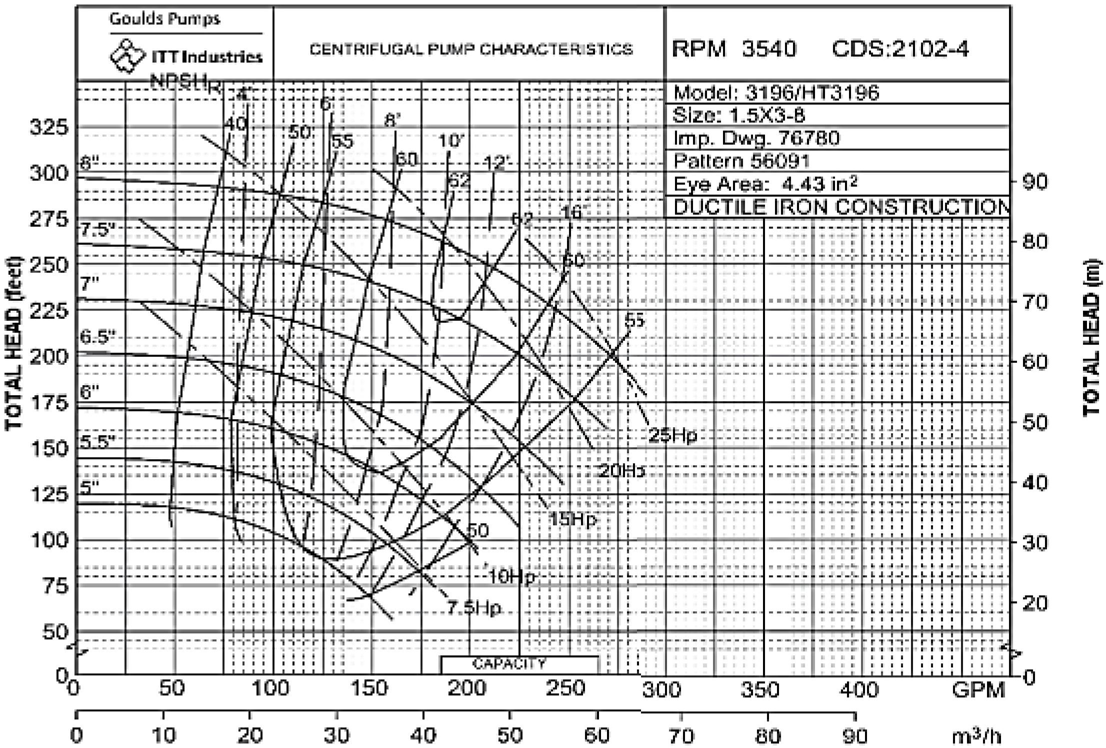


Figure 18.12 Typical Centrifugal Pump Performance Curve

18.7.2 Effect of over sizing the pump

As mentioned earlier, pressure losses to be overcome by the pumps are functions of flow -the system characteristics are also quantified in the form of head-flow curves. The system curve is basically a plot of system resistance i.e., head to be overcome by the pump versus various flow rates. The system curves change with the physical configuration of the system; for example, the system curves depend upon height or elevation, diameter and length of piping, number and type of fittings and pressure drops across various equipment - say a heat exchanger.

A pump is selected based on how well the pump curve and system head-flow curves match. The pump operating point is identified as the point, where the system curve crosses the pump curve when they are superimposed on each other. The Figure 6.11 shows the effect on system curve with throttling.

In the system under consideration, water has to be first lifted to a height-this represents the static head.

Then, we make a system curve, considering the friction and pressure drops in the system-this is shown as the green curve.

Suppose, we have estimated our operating conditions as 500 m^3/hr flow and 50 m head, we will choose a pump curve which intersects the system curve (Point A) at the pump's best efficiency point (BEP).

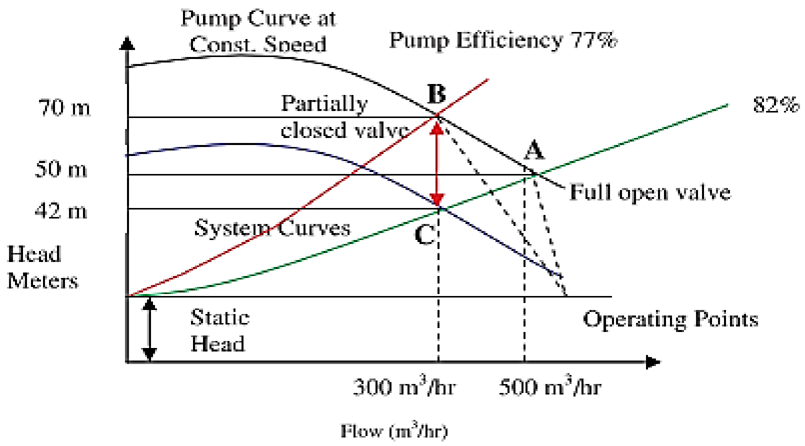


Figure 18.13: Effect on System Curve with Throttling

But, in actual operation, we find that 300 m^3/hr is sufficient. The reduction in flow rate has to be affected by a throttle valve. In other words, we are introducing an artificial resistance in the system.

Due to this additional resistance, the frictional part of the system curve increases and thus the new system curve will shift to the left - this is shown as the curve crossing point B.

So the pump has to overcome additional pressure in order to deliver the reduced flow. Now, the new system curve will intersect the pump curve at point B. The revised parameters are 300 m^3/hr at 70 m head. The red double arrow line shows the additional pressure drop due to throttling.

It may be noted that the best efficiency point has shifted from 82% to 77% efficiency. So it is actually needed to operate at point C, which is 300 m^3/hr on the original system curve. The head required at this point is only 42 meters.

Hence a new pump is needed, which will operate with its best efficiency point at C. But there are other simpler options rather than replacing the pump. The speed of the pump can be reduced or the existing impeller can be trimmed (or new lower size impeller). The blue pump curve represents either of these options.

18.8 Efficient Pumping System Operation

To understand a pumping system, one must realize that all of its components are interdependent. When examining or designing a pump system, the process demands must first be established and most energy efficiency solution introduced. For example, does the flow rate have to be regulated continuously or in steps? Can on—off batch pumping be used? What is the flow rates needed and how are they distributed in time?

The first step to achieve energy efficiency in pumping system is to target the end-use. A plant water balance would establish usage pattern and highlight areas where water consumption can be reduced or optimized. Good water conservation measures, alone, may eliminate the need for some pumps.

Once flow requirements are optimized, then the pumping system can be analysed for energy conservation opportunities. Basically, this means matching the pump to requirements by adopting proper flow control strategies. Common symptoms that indicate opportunities for energy efficiency in pumps are given in the Table 18.1.

Table 18.1 Symptoms that indicate potential opportunity		
Symptom	Likely Reason	Best Solutions

Throttle valve-controlled systems	Oversized pump	Trim impeller, smaller impeller, variable speed drive, two speed drive, lower RPM
Bypass line (partially or completely) open	Oversized pump	Trim impeller, smaller impeller, open variable speed drive, two speed drive, lower RPM
Multiple parallel pump system with the same number of pumps always operating	Pump use not monitored or controlled	Install controls
Constant pump operation in batch environment	Wrong system design	On-off controls
High maintenance cost (seals, bearings)	Pump operated far away from BEP	Match pump capacity with system requirement

Effect of speed variation

As stated above, a centrifugal pump is a dynamic device with the head generated from a rotating impeller. There is therefore a relationship between impeller peripheral velocity and generated head. Peripheral velocity is directly related to shaft rotational speed, for a fixed impeller diameter and so varying the rotational speed has a direct effect on the performance of the pump. All the parameters shown in figure 6.2 will change if the speed is varied and it is important to have an appreciation of how these parameters vary in order to safely control a pump at different speeds. The equations relating rotodynamic pump performance parameters of flow, head and power absorbed, to speed are known as the Affinity Laws:

$$Q \propto N$$

$$H \propto N^2$$

$$P \propto N^3$$

Where,
Q = Flow rate
H = Head
P = Power absorbed
N = Rotating speed

Efficiency is essentially independent of speed

Flow: Flow is proportional to the speed
$Q_1 / Q_2 = N_1 / N_2$
Example: 100/ Q_2 = 3000/1500
Q_2 = 50 m^3/hr

Head: Head is proportional to the square of speed
$H_1/H_2 = N_1^2 / N_2^2$

Example: 100/ H_2 = 3000^2 / 1500^2

H_2 = 25 m

Power (kW): Power is proportional to the cube of speed

$kW_1 / kW_2 = N_1^3 / N_2^3$

18.8.1.1 Example 6.1

$40/KW_2 = 3000^3 / 1500^3$

$KW_2 = 5$ kW

As can be seen from the above laws, reduction in speed will result in considerable reduction in power consumption. This forms the basis for energy conservation in centrifugal pumps with varying flow requirements. The implication of this can be better understood as shown in an example of a centrifugal pump in Figure 6.13 below.

Points of equal efficiency on the curves for three different speeds are joined to make the iso-efficiency lines, showing that efficiency remains constant over small changes of speed providing the pump continues to operate at the same position related to its best efficiency point (BEP).

The affinity laws give a good approximation of how pump performance curves change with speed but in order to obtain the actual performance of the pump in a system, the system curve also has to be taken into account.

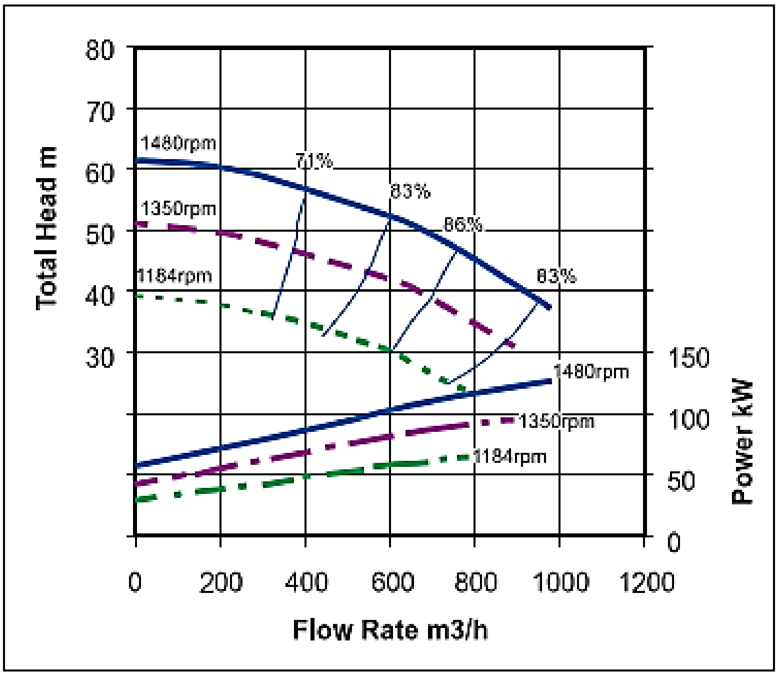


Figure 18.14 Example of Speed Variation Effecting Centrifugal Pump Performance

Effects of impeller diameter change

Changing the impeller diameter gives a proportional change in peripheral velocity, so it follows that there are equations, similar to the affinity laws, for the variation of performance with impeller diameter D:

$$Q \propto D$$

$$H \propto D^2$$

$$P \propto D^3$$

Efficiency varies when the diameter is changed within a particular casing. Note the difference in iso-efficiency lines in Figure 6.14 compared with Figure 6.13. The relationships shown here apply to the case for changing only the diameter of an impeller within a fixed casing geometry, which is a common practice for making small permanent adjustments to the performance of a centrifugal pump. Diameter changes are generally limited to reducing the diameter to about 75% of the maximum, i.e., a head reduction to about 50%. Beyond this, efficiency and NPSH are badly affected. However, speed change can be used over a wider range without seriously reducing efficiency. For example, reducing the speed by 50% typically results in a reduction of efficiency by l or 2 percentage points. The reason for the small loss of efficiency with the lower speed is that mechanical losses in seals and bearings, which generally represent <5% of total power, are proportional to speed, rather than speed cubed. It should be noted that if the change in diameter is more than about 5%, the accuracy of the squared and cubic relationships can fall off and for precise calculations, the pump manufacturer's performance curves should be referred to.

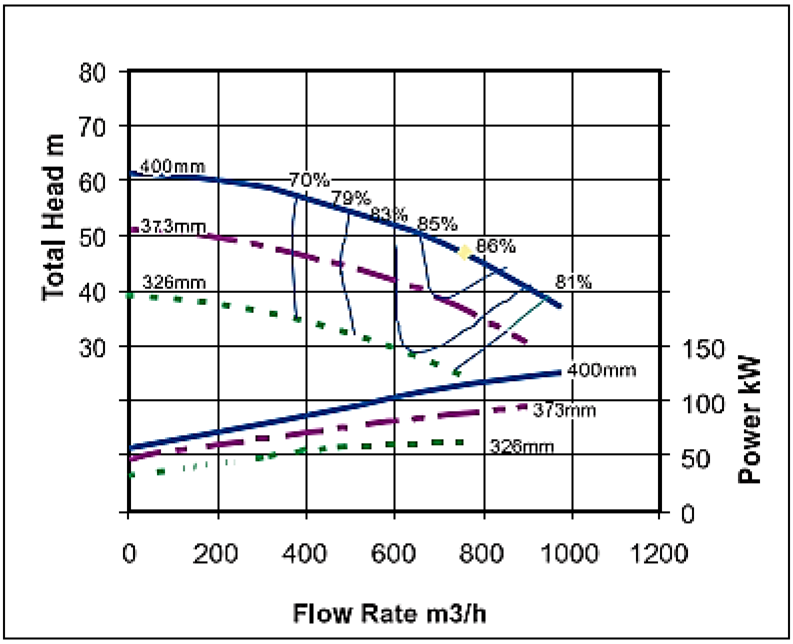


Figure 18.15 Example: Impeller Diameter Reduction on Centrifugal Pump Performance

The illustrated curves are typical of most centrifugal pump types. Certain high flow, low head pumps have performance curve shapes somewhat different and have a reduced operating region of flows. This requires additional care in matching the pump to the system when changing speed and diameter.

Pump suction performance

Liquid entering the impeller eye turns and is split into separate streams by the leading edges of the impeller vanes, an action which locally drops the pressure below that in the inlet pipe to the pump. If the incoming liquid is at a pressure with insufficient margin above its vapour pressure then vapour cavities or bubbles appear along the impeller vanes just behind the inlet edges. This phenomenon is known as cavitation and has three undesirable effects:

1. The collapsing cavitation bubbles can erode the vane surface, especially when pumping water-based liquids.
2. Noise and vibration are increased, with possible shortened seal and bearing life.
3. The cavity areas will initially partially choke the impeller passages and reduce the pump performance. In extreme cases, total loss of pump developed head occurs.

The value, by which the liquid pressure at the eye of pump exceeds the liquid vapour pressure, is expressed as a head of liquid and referred to as Net Positive Suction Head Available - (NPSHA). This is a characteristic of the system design. The value of NPSH needed at the pump suction to prevent the pump from cavitation is known as NPSH Required - (NPSHR). This is a characteristic of the pump design.

The three undesirable effects of cavitation described above begin at different values of NPSHA and generally there will be cavitation erosion before there is a noticeable loss of pump head. However, for a consistent approach, manufacturers and industry standards, usually define the onset of cavitation as the value of NPSHR when there is a head drop of 3% compared with the head with cavitation free performance. At this point cavitation is present and prolonged operation at this point will usually lead to damage. It is usual therefore to apply a margin by which NPSHA should exceed NPSHR.

As would be expected, the NPSHR increases as the flow through the pump increases, see fig 6.2. In addition, as flow increases in the suction pipework, friction losses also increase, giving a lower NPSHA at the pump suction, both of which give a greater chance that cavitation will occur. NPSHR also varies approximately with the square of speed in the same way as pump head and conversion of NPSHR from one speed to another can be made using the following equations

$$\mathbf{Q} \propto \mathbf{N}$$

$$\mathbf{NPSHR} \propto \mathbf{N}^2$$

It should be noted however that at very low speeds there is a minimum NPSHR plateau, NPSHR does not tend to zero at zero speed. It is therefore essential to carefully consider NPSH in variable speed pumping.

18.9 Flow Control Strategies

Pump control by varying speed

To understand how the speed variation changes the duty point, the pump and system curves are over-laid. Two systems are considered, one with only friction loss and another where static head is high in relation to friction head. It will be seen that the benefits are different.

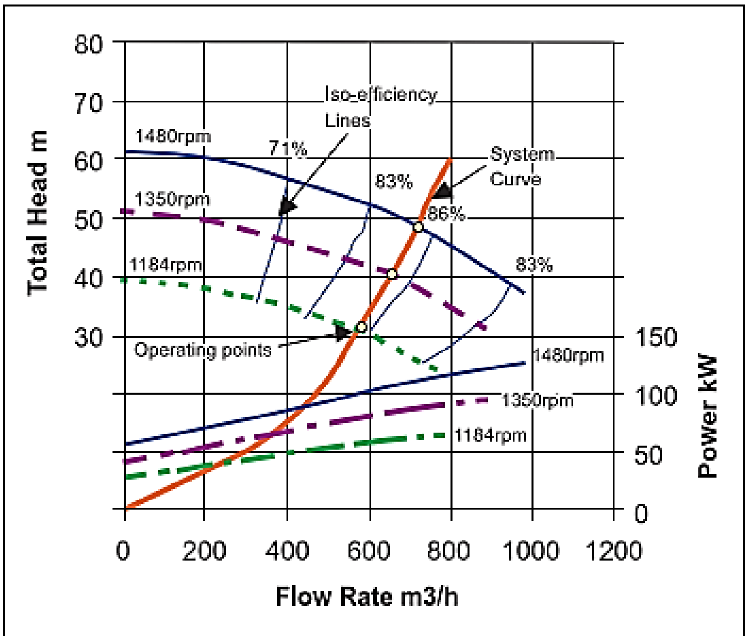


Figure 18.16: Example of the Effect of Pump Speed Change in a System with Only Friction Loss

In Figure 18.16, reducing speed in the friction loss system moves the intersection point on the system curve along a line of constant efficiency. The operating point of the pump, relative to its best efficiency point, remains constant and the pump continues to operate in its ideal region. The affinity laws are obeyed which means that there is a substantial reduction in power absorbed accompanying the reduction in flow and head, making variable speed the ideal control method for systems with friction loss.

In a system where static head is high, as illustrated in Figure 18.17, the operating point for the pump moves relative to the lines of constant pump efficiency when the speed is changed. The reduction in flow is no longer proportional to speed. A small turn down in speed could give a big reduction in flow rate and pump efficiency, which could result in the pump operating in a region where it could be damaged if it ran for an extended period of time even at the lower speed. At the lowest speed illustrated, (1184 rpm), the pump does not generate sufficient head to pump any liquid into the system, i.e., pump efficiency and flow rate are zero and with energy still being input to the liquid, the pump becomes a water heater and damaging temperatures can quickly be reached.

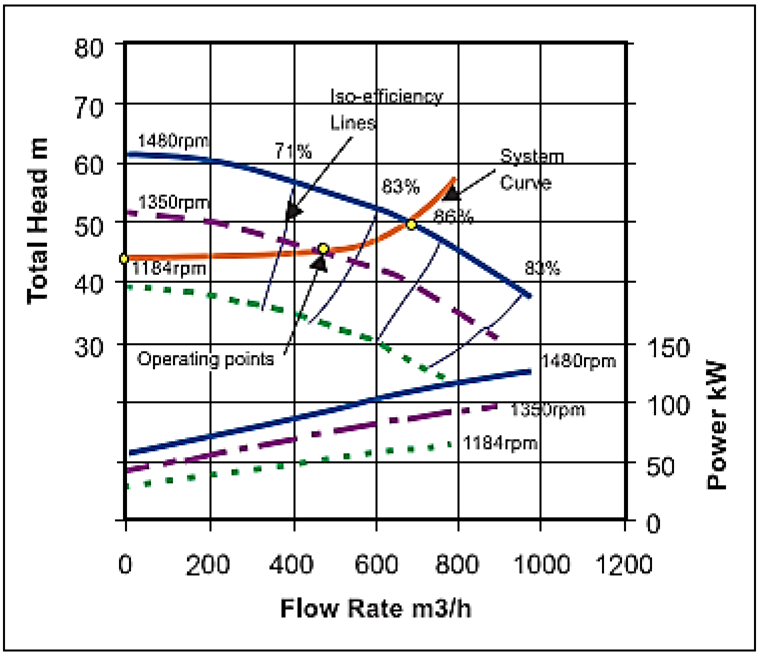


Figure 18.17: Example for the Effect of Pump Speed Change with a System with High Static Head

The drop in pump efficiency during speed reduction in a system with static head, reduces the economic benefits of variable speed control. There may still be overall benefits but economics should be examined on a case-by-case basis. Usually, it is advantageous to select the pump such that the system curve intersects the full speed pump curve to the right of best efficiency, in order that the efficiency will first increase as the speed is reduced and then decrease. This can extend the useful range of variable speed operation in a system with static head. The pump manufacturer should be consulted on the safe operating range of the pump.

It is relevant to note that flow control by speed regulation is always more efficient than by control valve. In addition to energy savings there could be other benefits of lower speed. The hydraulic forces on the impeller, created by the pressure profile inside the pump casing, reduce approximately with the square of speed. These forces are carried by the pump bearings and so reducing speed increases bearing life. It can be shown that for a centrifugal pump, bearing life is inversely proportional to the 7th power of speed. In addition, vibration and noise are reduced and seal life is increased providing the duty point remains within the allowable operating range.

The corollary to this is that small increases in the speed of a pump significantly increase power absorbed, shaft stress and bearing loads. It should be remembered that the pump and motor must be sized for the maximum speed at which the pump set will operate. At higher speed the noise and vibration from both pump and motor will increase, although for small increases the change will be small. If the liquid contains abrasive particles, increasing speed will give a corresponding increase in surface wear in the pump and pipework.

The effect on the mechanical seal of the change in seal chamber pressure should be reviewed with the pump or seal manufacturer, if the speed increase is large. Conventional mechanical seals operate satisfactorily at very low speeds and generally there is no requirement for a minimum speed to be specified, however due to their method of operation, gas seals require a minimum peripheral speed of 5 m/s

Pumps in parallel switched to meet demand

Another energy efficient method of flow control, particularly for systems where static head is a high proportion of the total, is to install two or more pumps to operate in parallel. Variation of flow rate is achieved by switching on and off additional pumps to meet demand. The combined pump curve is obtained by adding the flow rates at a specific head. The head/flow rate curves for two and three pumps are shown in Figure 18.18.

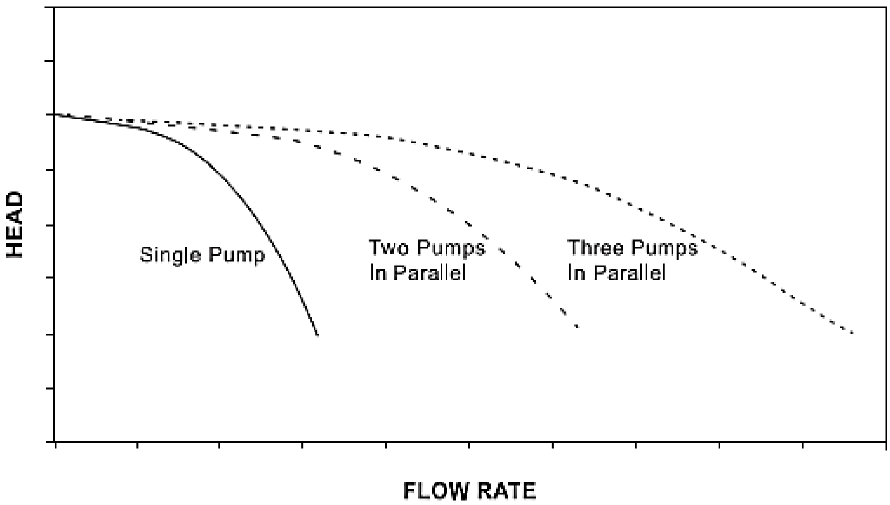


Figure 18.18: Typical Head-Flow Curves for Pumps in Parallel

The system curve is usually not affected by the number of pumps that are running. For a system with a combination of static and friction head loss, it can be seen, in Figure 6.18, that the operating point of the pumps on their performance curves moves to a higher head and hence lower flow rate per pump, as more pumps are started. It is also apparent that the flow rate with two pumps running is not double that of a single pump. If the system head were only static, then flow rate would be proportional to the number of pumps operating.

It is possible to run pumps of different sizes in parallel provided their closed valve heads are similar. By arranging different combinations of pumps running together, a larger number of different flow rates can be provided into the system.

Care must be taken when running pumps in parallel to ensure that the operating point of the pump is controlled within the region deemed as acceptable by the manufacturer. It can be seen from Figure 18.19 that if 1 or 2 pumps were stopped then the remaining pump(s) would operate well out along the curve where NPSH is higher and vibration level increased, giving an increased risk of operating problems.

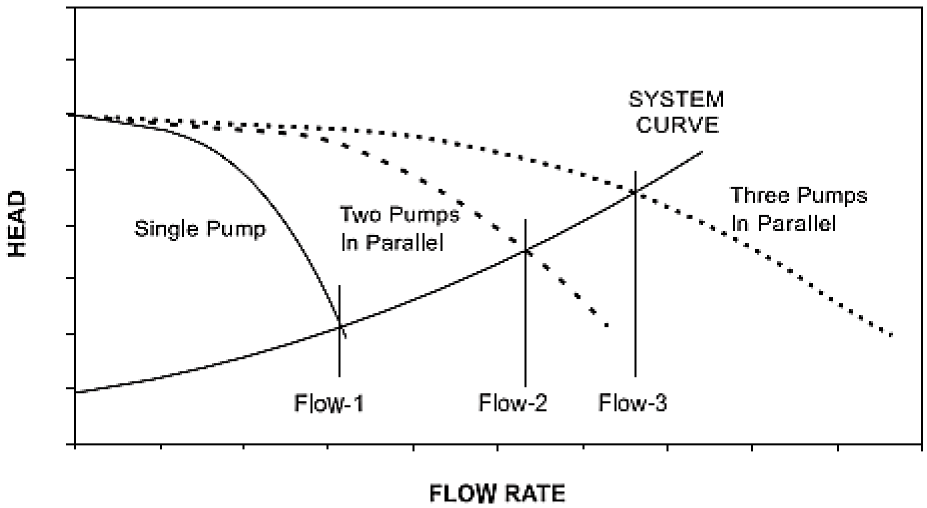


Figure 18.19: Typical Head-Flow Curves for Pumps in Parallel, With System Curve Illustrated

18.9.1 Stop/start control

In this control method, the flow is controlled by switching pumps on or off. It is necessary to have a storage capacity in the system e.g., a reservoir, a wet well, an elevated tank or an accumulator type pressure vessel. The storage can provide a steady flow to the system with an intermittent operating pump. When the pump runs, it does so at the chosen (presumably optimum) duty point and when it is off, there is no energy consumption. If intermittent flow, stop/start operation and the storage facility are acceptable, this is an effective approach to minimize energy consumption.

The stop/start operation causes additional loads on the power transmission components and increased heating in the motor. The frequency of the stop/start cycle should be within the motor design criteria and checked with the pump manufacturer.

It may also be used to benefit from “off pea” energy tariffs by arranging the run times during the low tariff periods.

To minimize energy consumption with stop/start control, it is better to pump at as low flow rate as the process permits. This minimizes friction losses in the pipe and an appropriately small pump can be installed. For example, pumping at half the flow rate for twice as long can reduce energy consumption to a quarter. It means it is beneficial to run one pump at full capacity continuously rather than running two pumps at a time with a stop/start control.
Flow control valve

With this control method, the pump runs continuously and a valve in the pump discharge line is opened or closed to adjust the flow to the required value.

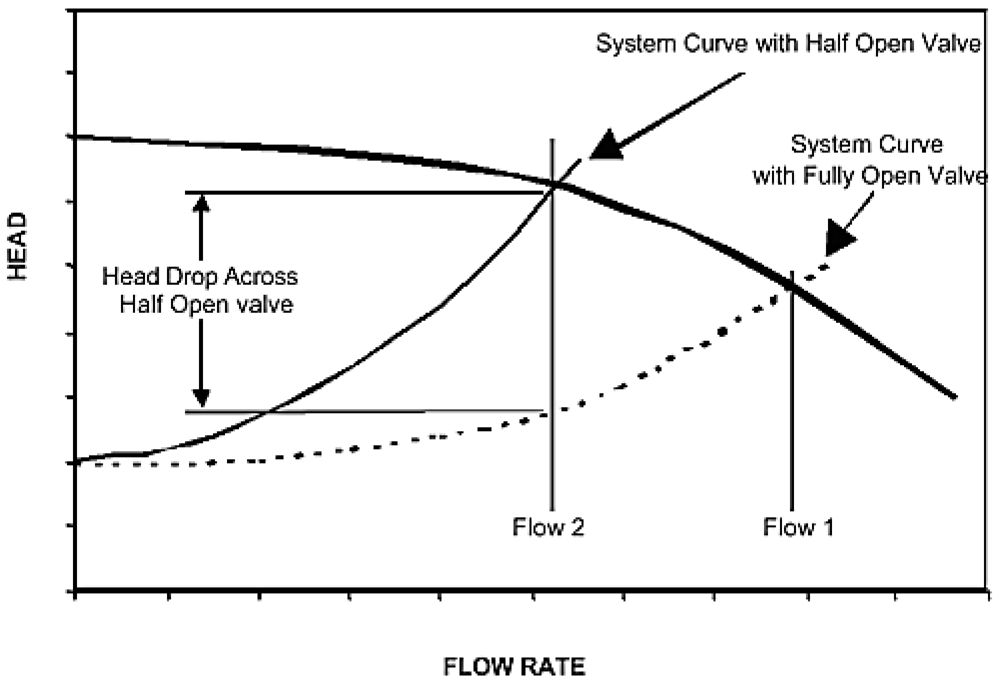


Figure 18.20: Control of Pump Flow by Changing System Resistance Using 3 Valve.

To understand how the flow rate is controlled, see Figure 6.19. With the valve fully open, the pump operates at “Flow 1”. When the valve is partially closed, it introduces an additional friction loss in the system which is proportional to flow squared. The new system curve cuts the pump curve at “Flow 2” which is the new operating point. The head difference between the two curves is the pressure drop across the valve.

It is usual practice with valve control to have the valve 10% shut even at maximum flow. Energy is therefore wasted overcoming the resistance through the valve at all flow conditions. There is some reduction in pump power absorbed at the lower flow rate (see Figure 6.19), but the flow multiplied by the head drop across the valve, is wasted energy. It should also be noted that while the pump will accommodate changes in its operating point as far as it is able within its performance range, it can be forced to operate high on the curve where its efficiency is low and its reliability is affected.

Maintenance cost of control valves can be high, particularly on corrosive and solids-containing liquids. Therefore, the lifetime cost could be unnecessarily high.

By-pass control

With this control approach, the pump runs continuously at the maximum process demand duty with a permanent by-pass line attached to the outlet. When a lower flow is required the surplus liquid is bypassed and returned to the supply source.

An alternative configuration may have a tank supplying a varying process demand, which is kept full by a fixed duty pump running at the peak flow rate. Most of the time, the tank overflows and recycles back to the pump suction. This is even less energy efficient than a control valve because there is no reduction in power consumption with reduced process demand.

The small by-pass line sometimes installed to prevent a pump running at zero flow is not a means of flow control, but required for the safe operation of the pump.

Fixed Flow reduction

18.9.2 Impeller trimming

Impeller trimming refers to the process of machining the diameter of an impeller to reduce the energy added to the system liquid.

Impeller trimming offers a useful correction to pumps that, through overly conservative design practices or changes in system loads are oversized for their application.

Trimming an impeller provides a level of correction below buying a smaller impeller from the pump manufacturer. But in many cases, the next smaller size impeller is too small for the pump load. Also, smaller impellers may not be available for the pump size in question and impeller trimming is the only practical alternative short of replacing the entire pump/motor assembly. (See Figures 18.21 & 18.22 for before and after impeller trimming).

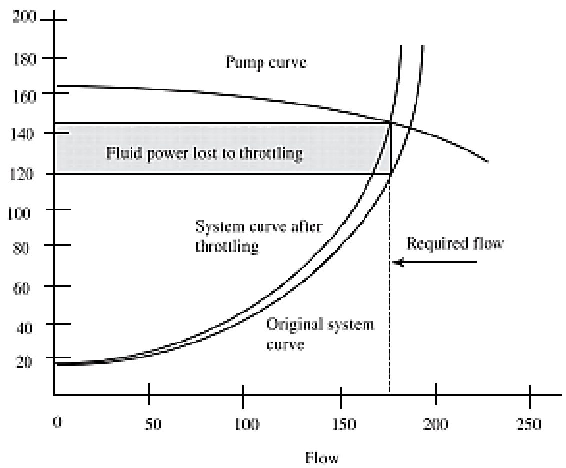


Figure 18.21 Before Impeller Trimming

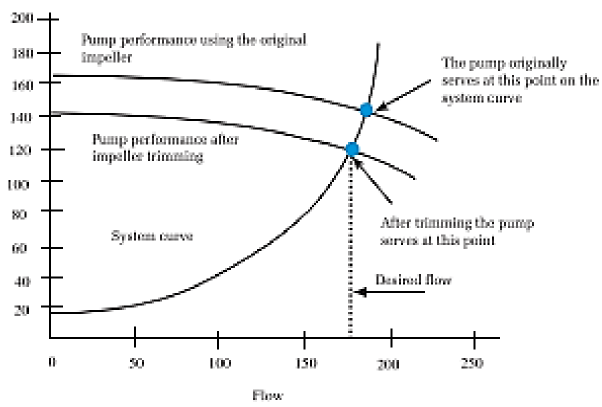


Figure 18.22 After Impeller Trimming

Impeller trimming reduces tip speed which in turn directly lowers the amount of energy imparted to the system liquid and lowers both the flow and pressure generated by the pump.

The Affinity Laws, which describe centrifugal pump performance, provide a theoretical relationship between impeller size and pump output (assuming constant pump speed):

$$Q_2 = \frac{D_2}{D_1} \times Q_1$$

$$H_2 = \left[\frac{D_2}{D_1}\right]^2 \times H_1$$

$$P_2 = \left[\frac{D_2}{D_1}\right]^3 \times P_1$$

Where:
Q = flow

H = head
P = power
D = diameter of impeller

Subscript l = original pump,
Subscript 2 = pump after impeller trimming

Trimming an impeller changes its operating efficiency and the non-linearities of the Affinity Laws with respect to impeller machining complicate the prediction of pump performance. Consequently, impeller diameters are rarely reduced below 75 percent of their original size.

Variable Speed Drives (VSDs)

In contrast, pump speed adjustments provide the most efficient means of controlling pump flow. By reducing pump speed, less energy is imparted to the fluid and less energy needs to be throttled or bypassed. There are two primary methods of reducing pump speed: multiple-speed pump motors and variable speed drives (VSDs).

Although both directly control pump output, multiple-speed motors and VSDs serve entirely separate applications. Multiple-speed motors contain a different set of windings for each motor speed consequently they are more expensive and less efficient than single speed' motors. Multiple speed motors also lack subtle speed changing capabilities within discrete speeds.

VSDs allow pump speed adjustments over a continuous range, avoiding the need to jump from speed to speed as with multiple-speed pumps. VSDs control pump speeds using several different types of mechanical and electrical systems. Mechanical VSDs include hydraulic clutches, fluid couplings and adjustable belts and pulleys. Electrical VSDs include eddy current clutches, wound-rotor motor controllers and variable frequency drives 01FDs). VFDs adjust the electrical frequency of the power supplied to a motor to change the motor's rotational speed. VFDs are by far the most popular type of VSD.

However, pump speed adjustment is not appropriate for all systems. In applications with high static head, slowing a pump risks inducing vibrations and creating performance problems that are similar to those found when a pump operates against its shutoff head. For systems in which the static head represents a large portion of the total head, caution should be used in deciding whether to use VFDs. Operators should review the performance of VFDs in similar applications and consult VFD manufacturers to avoid the damage that can result when a pump operates too slowly against high static head.

For many systems, VFDs offer a means to improve pump operating efficiency despite changes in operating conditions. The effect of slowing pump speed on pump operation is illustrated by the three curves in Figure 18.23. When a VFD slows a pump, its head/flow and power curves drop down and to the left and its efficiency curve shifts to the left. This efficiency response provides an essential cost advantage by keeping the operating efficiency as high as possible across variations in the system's flow demand, the energy and maintenance costs of the pump can be significantly reduced.

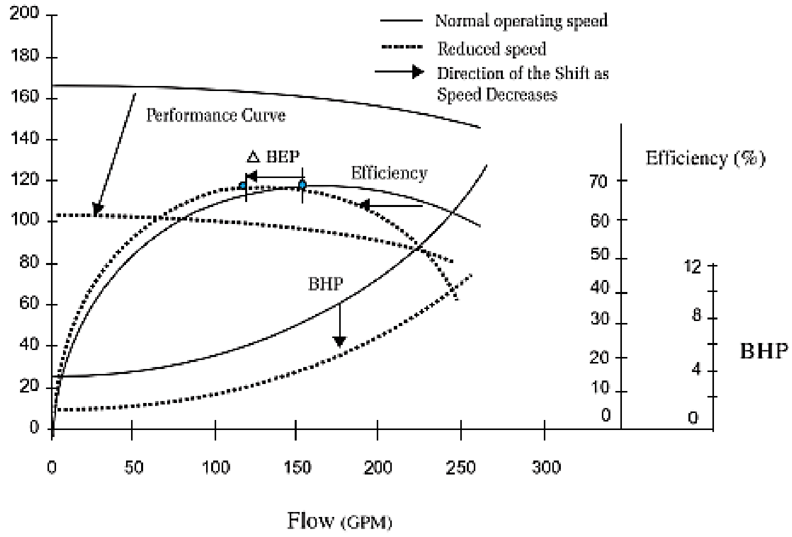


Figure 18.23: Effect of VFD

VFDs may offer operating cost reductions by allowing higher pump operating efficiency but the principal savings derive from the reduction in frictional or bypass flow losses. Using a system perspective to identify areas in which fluid energy is dissipated in non-useful work often reveals opportunities for operating cost reductions.

For example, in many systems, increasing flow through bypass lines does not noticeably impact the backpressure on a pump. Consequently, in these applications pump efficiency does not necessarily decline during periods of low flow demand. By analysing the entire system, however, the energy lost in pushing liquid through bypass lines and across throttle valves can be identified.

Another system benefit of VFDs is a soft start capability. During start up, most motors experience in-rush currents that are 5 to 6 times higher than normal operating currents. This high current fade when the motor spins up to normal speed. VFDs allow the motor to be started with a lower start up current (usually only about 1.5 times the normal operating current). This reduces wear on the motor and its controller. VFDs will consume 4 to 6% power as a running cost apart from its initial cost.

18.10 Boiler Feed Water Pumps (BFP)

The feed water pumps are normally multi stage centrifugal pumps, sized based on boiler design pressure. The operation of a multistage pump is similar to the operation of several single stage pumps, of identical capacity, in series. Since most boilers operate below design pressure, the feed water pump head is often higher than required. This excessive pump head is dropped across pressure reducing valves and manual valves. Installing a VFD on the feed water pump in such cases can decrease pump power consumption and improve control performance. Trimming the impeller, reducing number of stages or changing the feed water pumps may also be feasible depending on variation in operating load of the boiler.

Boiler Feed Pump Control with VFD

There are several ways of controlling the pump

- **One pump, one boiler, no feed water regulating valve:** In this the pump speed is varied according to the level of water in the boiler. The level control system used for the feed water admission valve transmits its signal directly to the pump VFD controller. With this system it is possible to eliminate not only the feed pump constant discharge but also the boiler feed water regulating control valve and, thereby, cut initial capital investment. The inherent efficiency loss due to throttling is eliminated.

- **Constant discharge pressure control:** The feed pump is controlled to a predetermined pressure setting irrespective of plant load. The advantage of this system is that the pump will not be required to operate near shut off pressures, due to the shifting of the operating point on the curve.
- **Constant differential pressure control:** Feed pump pressure is controlled to produce a predetermined pressure drop across the feed water regulating valve, usually approximately 3.5 to 5.5 kg/cm^2, thus allowing the boiler feed pump to follow plant demand.

Optimizing Boiler Feed Water Pump Capacity – Case study.

A waste heat boiler has two feed water pumps, each of 6 stages and having a capacity of 35 m3/hr. The pumps are designed to generate a head of 276 m, normally one pump is operated.

The actual steam demand is 28 TPH at 15 kg/cm^2. The capacity of the feed water pumps is far in excess of the requirement. This results in throttling of pump discharge leading to energy loss. To save energy in the BFW pumps, it was suggested to remove two impeller stages of the pump to effectively regulate the pressure developed in the pumps.

The impact of this measure on power consumption was then evaluated and the results are given in Table below:

Operation of pumps	
With 6 stages (impellers)	53
With 4 stages (impellers)	35
Actual power savings achieved	18

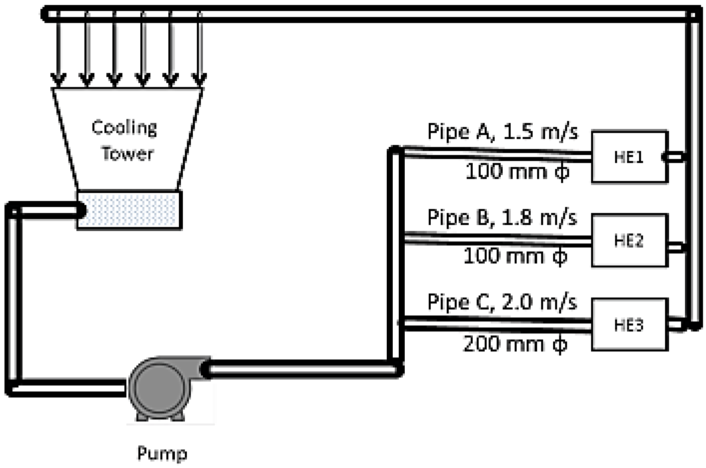
18.11 Energy Conservation Opportunities in Pumping Systems

- Ensure adequate NPSH at site of installation.
- Ensure availability of basic instruments at pumps like pressure gauges, flow meters.
- Operate pumps near Best Efficiency Point.
- Modify pumping system and pumps losses to minimize throttling.
- Adapt to wide load variation with variable speed drives or sequenced control of multiple units.
- Stop running multiple pumps - add an auto-start for an on-line spare or add a booster pump in the problem area.
- Use booster pumps for small loads requiring higher pressures.
- Increase liquid temperature differentials to reduce pumping rates in case of heat exchangers.
- Decrease outlet cold water temperature of cooling tower in order to reduce the pumping flow rates in case of mixing.
- Separate High Pressure and Low-Pressure systems
- Repair seals and packing to minimize water loss by dripping.
- Balance the system to minimize flows and reduce pump power requirements.
- Avoid pumping head with a free-fall return (gravity); Use siphon effect to advantage:
- Conduct water balance to minimize water consumption.
- Avoid cooling water re-circulation in DG sets, air compressors, refrigeration systems, cooling towers feed water pumps, condenser pumps and process pumps.
- In multiple pump operations, carefully combine the operation of pumps to avoid throttling.
- Provide booster pump for few areas of higher head.
- Replace old pumps by energy efficient pumps.
- In the case of over designed pump, provide variable speed drive, or downsize / replace impeller or replace with correct sized pump for efficient operation.
- Optimize number of stages in multi-stage pump in case of head margins.

- Reduce system resistance by pressure drop assessment and pipe size optimization.

Example 18.1

The cooling water circuit of a process industry is depicted in the figure below. Cooling water is pumped to three heat exchangers via pipes A, B and C where flow is throttled depending upon the requirement. The diameter of pipes and measured velocities with non-contact ultrasonic flow meter in each pipe are indicated in the figure.



The following are the other data:

Measured motor power : 50.7 kW
Motor efficiency at operating load : 90%
Pump discharge pressure : 3.4 kg/cm2
Suction head : 2 meters

Determine the efficiency of the pump.

Solution:

Flow in pipe A	22/7 x $(0.1)^2$/4 x 1.5
	0.011786 m^3/s
Flow in pipe B	22/7 x $(0.1)^2$/4 x 1.8
	0.014143 m^3/s
Flow in pipe C	22/7 x $(0.2)^2$/4 x 2.0
	0.062857 m^3/s
Total flow	0.088786 m^3/s
Total head	34 m – 2 m = 32 m
Pump hydraulic power	0.088786 x 32 x 9.81
	27.9 kW
	27.9 x 100/50.7 x 0.9
Pump efficiency	61 %

Example 18.2

A centrifugal water pump operates at 30 m^3/hr and at 1440 RPM. The pump operating efficiency is 65%

and motor efficiency is 89%. The discharge pressure gauge shows 3.4 kg/cm^2. The suction is 3 m below the pump centreline. If the speed of the pump is reduced by 25 %, estimate the following:

- pump flow,
- pump head and
- motor power.

Solution:

Flow = 30 m^3/hr

Head developed by the pump = 34 – (-3) = 37 m

Power drawn by the pump = (30/3600) x 37 x 1000 x 9.81/(1000 x 0.65)
= 4.65 kW

Flow at 75 % speed = 30 / Q2 = 1440/1080
= 22.5 m^3/hr

Head at 75 % speed = 37 / H2 = (1440/1080)^2
= 20.81 m

Shaft Power at 75 % speed = 4.65/kW2 = (1440)^3 / (1080)^3
= 1.96 kW

Power drawn by motor = 1.96 / 0.89
= 2.2 kW

CHAPTER 19: COMPRESSED AIR SYSTEM

19.1 Introduction

Air compressors account for a significant amount electricity used in industrial sector. Air compressors are used in a variety of industries to supply process requirements, operate pneumatic tools and equipment, and for instrumentation. The generation efficiency is only about 10% as shown in the figure 3.1 and balance 90% of energy of the power of the prime mover being converted to unusable heat energy and to a lesser extent lost in form of friction, misuse and noise. Further considering the distribution efficiency, the overall efficiency can be as low as 6.5% when pressure drops, leaks, and part-load control losses are considered.

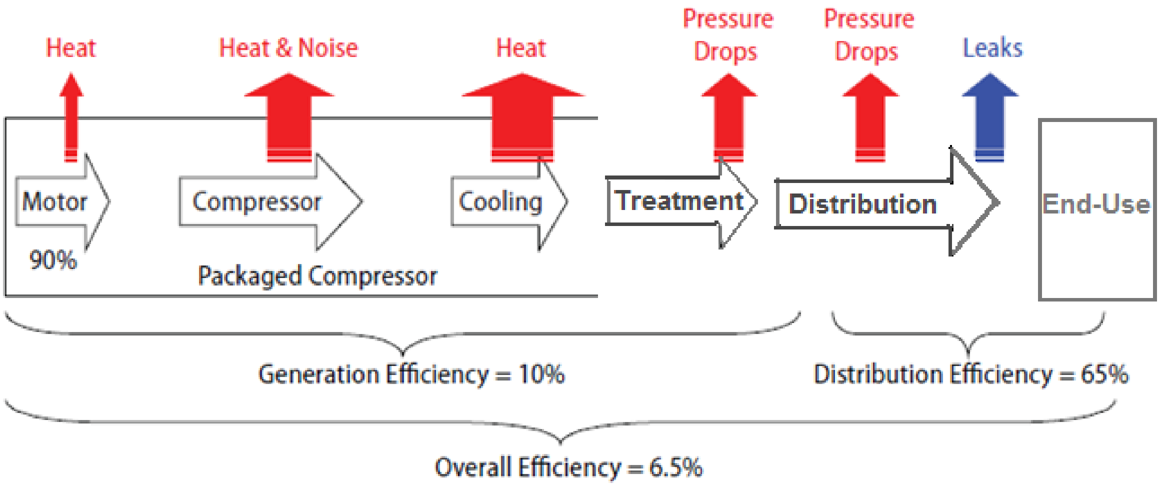


Figure 19.1: Efficiency of Compressed Air System

19.2 Compressor Types

Compressors are broadly classified as dynamic and positive displacement types.

Dynamic compressors are centrifugal compressors and are further classified as radial and axial flow types. Positive displacement compressors are further classified as reciprocating and rotary compressors, under which there are further sub-classifications.

Dynamic compressors increase the fluid's velocity, which is then converted to increased pressure at the outlet. Positive displacement compressors increase the pressure of the gas by reducing the volume. The flow and pressure requirements of a given application determine the suitability of a particulars type of compressor.

Table 19.1: General Selection Criteria for Compressors

Type of Compressor	Capacity (m^3/h)		Pressure(bar)	
	From	To	From	To
Roots power compressor single stage	100	30000	0.1	1
Reciprocating				
- Single / Two stage	100	12000	0.8	12

- Multi stage	100	12000	12.0	700
Screw				
- Single stage	100	2400	0.8	13
- Two stage	100	2200	0.8	24
Centrifugal	600	300000	0.1	450

19.3 Comparison of Different Compressors

The power consumption of various compressors depends on the operating pressure, free air delivery and efficiency etc. The variations in power consumption during unloading/part load operation are more significant and depend on the type of compressor and method of capacity control. The relative efficiencies and part load power consumption of different compressors are given in Table 19.2

Table 19.2 Comparison of Different Compressors

Item	Reciprocating	Rotary vane	Rotary Screw	Centrifugal
Efficiency at full load	High	Medium-high	High	High
Efficiency at part load	High due to staging	Poor: below 60% of full load	Poor: below 60% of full load	Poor: below 60% of full load
Efficiency at no load (power as % of full load)	High (10-25%)	Medium (30-40%)	High-poor (25-60%	High-medium (20-30%)

In case of reciprocating machines, the unload power consumption is in the order of 25% of full load power. While in screw compressors, the unload power consumption is marginally higher compared to reciprocating machines.

It is preferable to use screw compressors for constant air requirement. If screw compressors have to be installed for fluctuating loads, it is desirable to have screw compressor with variable speed drive to further optimize unload power consumption.

Some of the plants have adopted the strategy of operating screw compressor at full load for meeting the base-load requirement and reciprocating compressor for fluctuating load to optimize on unload power consumption.

19.4 System Components

Compressed air systems, depending on the requirement, consist of a number of components compressors filters, air dryers, inter-coolers, after coolers, oil separators, valves, nozzles, and piping.

- **Intake Air Filters:** Prevent dust and atmospheric impurities from entering compressor. Dust causes sticking valves, scored cylinders, excessive wear etc.
- **Inter-stage Coolers:** Reduce the temperature of the air(gas) before it enters the next stage to reduce the work of compression and increase efficiency. They can be water-or air-cooled.
- **After Coolers:** Reduce the temperature of the discharge air, and thereby reduce the moisture carrying capacity of air.
- **Air-dryers:** Air dryers are used to remove moisture, as air for instrument and pneumatic equipment needs to be relatively free of any moisture. The moisture is removed by suing ads or bents or refrigerant dryers, or state of the art heat less dryers.

- **Moisture Traps:** Air traps are used for removal of moisture in the compressed air distribution lines. They resemble steam traps in which the air is trapped and moisture is removed.
- **Receivers:** Depending on the system requirements, one or more air receivers are generally provided to reduce output pulsations and pressure variations.

19.5 Compressor Performance

19.5.1 Capacity of a Compressor: Free Air Delivery (FAD)

Free air, as defined by CAGI (Compressed Air & Gas Institute) is air at ATMOSPHERIC conditions at any specific location. Because the barometer and temperature may vary at different localities and at different times, it follows that this term does not mean air under standard conditions.
Measured in CFM (Cubic feet per minute) this is the amount of compressed air converted back to the actual inlet (free air) conditions before it was compressed. In other words, the volume of air, which is drawn in from the atmosphere by the compressor, then compressed and delivered at a specific pressure.

19.5.2 Compressor Efficiency Definitions

Compressor efficiency is often expressed as either an adiabatic or isothermal or mechanical efficiency. These are computed as the isothermal and adiabatic power respectively, divided by the actual power consumption. The calculation of isothermal power excludes that needed to overcome friction and generally gives an efficiency that is lower than adiabatic efficiency. This is an important consideration when selecting compressors based on reported values of efficiency. Manufacturers generally provide the adiabatic (theoretical) horsepower required for compression. The actual power intake would be slightly higher because of mechanical losses.

For practical purposes, the most effective guide in comparing compressor efficiencies is the specific power consumption for different compressors that would provide identical duty.

19.5.3 Isothermal Efficiency

The iso-thermal efficiency of a multi-stage air compressor can be calculated as a ratio of the theoretical kW required for a duty condition and the actual kW input measured. This efficiency would reflect the combined efficiency of the compressor and the drive motor and the method can be adopted to assess the performance for identifying margins with respect to rated values, merit rating of compressors, maintenance planning, etc.

$$Theoretical\ kW = \left(\frac{NK}{K-1}\right)\left(Q\,\frac{P_s}{0.612}\right)\left[\left(\frac{P_d}{P_s}\right)^{\frac{K-1}{NK}} - 1\right]$$

N = No. of stages
K = Ratio of specific heats (1.35 for air)
P_s = suction pressure in kg/cm^2
P_d = Discharge pressure in kg/cm^2
Q = Actual air flow (m^3/min.) Actual kW = $\sqrt{3}$ V I × PF as measured

Efficiency of compressor and motor combination = $\dfrac{100 \times \text{Theoretical kW}}{Actual\ kW}$

It is also a done thing, to compute and add-up stage wise work of compression (theoretical kW) in case the performance of intercoolers is not optimal.

19.5.4 Volumetric Efficiency

$$Volumetric\ efficiency = \frac{Free\ air\ delivered\ (m^3/\min)}{Compressor\ displacement\ (m^3/\min)}\ x100$$

Compressor Displacement $= \frac{\pi}{4} D^2 L S \chi\, n$

D	=	Cylinder bore, meter
L	=	Cylinder stroke, meter
S	=	Compressor speed rpm
χ	=	1 for single acting and
		2 for double acting cylinders
n	=	No. of cylinders

19.5.5 Efficient Compressor Operation

9.3.13 Reciprocating Compressors

The capacity of reciprocating compressors can be controlled by throttling suction or discharge pressure, by using the cylinder expansion (clearance) volume, bypassing gas externally, using cylinder run-loaders, or by speed control. External bypass involves feeding some of the output back to the suction (the gas may have to be cooled before being fed back to the compressor). Though this method can provide 0 – 100 % capacity control, it does not result in any significant power reduction at reduced flow. However, at very low capacities, gas bypass is generally the only solutions inciter methods may result in unstable operation. Throttling is another alternative, but saves relatively little energy. The most common and more efficient method is to employ automatic or manual cylinder un-loaders or to use clearance pockets in the cylinder. Reduction in power consumption is proportional to capacity control. The most efficient method of controlling capacity, however, is to vary the speed of the prime movers since capacity is directly proportional to the speed.

The performance of reciprocating compressors varies based on the altitude, inlet air (gas) temperature, discharge pressure, the effectiveness of inter stage cooling and operational speed. Increase in altitude, with the resultant reduction in pressure, increases the compression ratio leading to higher discharge temperature and reduced efficiency. However, for a given compressors ratio, the specific power requirement, which varies directly with the suction pressure, decreases with an increase in altitude. The effect of altitude on multi- staged compressors is slight.

The discharge pressure should be kept at the minimum required for the process or for operation of pneumatic equipment for a number of reasons, including minimizing power consumption. Also, compressor capacity varies inversely with discharge pressure. Another disadvantage of higher discharge pressures is the increased loading on compressor piston rods and their subsequent failure. Lower pressure also results in lower leakage losses. In general, when compressing gas starting at ambient temperature and pressure through a pressure ratio exceeding 4, multistage compression with inter cooling should be considered to maintain the temperature of the compressed gas.

Multi-stage compressors are usually provided with inter coolers to reduce the temperature of the air (gas) discharged between stages. Ideally, the intake temperature at each stage should be the same as that at the first stage (referred to a perfect cooling) so that the volume of air to be compressed does not increase. The provision of well- designed inter cooling systems reduces power consumption. However, use of very cold water can result in condensation which may result in water entering the cylinder, thereby reducing valve life, accelerating wear and scoring of pistons, piston rings and cylinder. Condensation can also occur when the relative humidity of inlet air is high and the compressor cylinder temperature is lower than inlet air temperature (for example, as a result of higher than required flow of cooling water). The condensed water may also wash away the oil film on the cylinder and cause rust which will result in an abrasion during compressor operation and significantly reduce efficiency. At the other extreme, if cooling is insufficient, the discharge temperature increases. High temperature operation reduces oil viscosity and the oil film thickness can be reduced.

The location of the compressor should be considered during the selection process. Locations with high moisture or high temperature can cause operational trouble and increase power consumption. Cooling should be adequate in such cases. When locating the suction inside buildings, care should be taken to ensure adequate clearance between the suction and the walls to reduce pulsation and vibrations.

9.3.14 Centrifugal Compressors

Manufacturers specify discharge pressure and power requirement as a function of the inlet volumetric flow rate. These performance curves are valid at only the given inlet conditions. Therefore, to optimize process efficiency and to predict performance at different process and inlet conditions, performance curves which provide the polytropic head and polytropic efficiency is a function of the inlet volume flow is useful for such analysis. The manufacturer should be consulted in such cases.

The major limitation of a centrifugal compressor is that is operates at peak efficiency at design point only and any deviation from the operating point is detrimental to its performance. When selecting centrifugal compressors, close attention should be paid during system design to ensure that at high pressure, with the consequent reduction in flow, the surge point is not reached. Surge point is the point on the performance curve where a further decrease inflow (typically in the region of 50 - 70 % of rated capacity) causes instability, resulting in a pulsating flow, which may lead to overheating, failure of bearings due to thrust reversals, or excessive vibration. Bypass valves advents are commonly used to prevent surging.

Using variable inlet-guide vanes, throttling of suction pressure or throttling of discharge pressure can control the output of centrifugal compressors. However, since centrifugal compressors follow the same affinity laws as centrifugal pumps another efficient way to match compressor output to meet varying load requirements is through speed control.

9.3.15 Screw Compressors

The capacity of screw compressors is normally controlled by a hydraulically operated slide valve, which bypasses gas without compression. However, speed control is the most efficient means of capacity control. Unlike reciprocating and centrifugal compressors, screw compressors develop full pressure regard less of speed. Also, they are more stable at low capacity (up to 10% load)–unlike centrifugal compressors which surge at capacities lower than about 50% of the rated value. The volume handled and the power consumption are directly proportional to speed. Therefore, variable speed drives can be used to efficiently control capacity. Part load power consumption of screw compressors is generally higher than that for reciprocating and centrifugal compressors. Additionally, the discharge pressure of the screw compressor should be closely matched to discharge line pressure to avoid over or under compression that result in higher power consumptions. Therefore, when considering screw compressors, the volume ratio should be properly specified.

19.6 Energy Efficiency Practices in Compressed Air Systems

19.6.1 Location of Compressors

Location of air compressors and the quality of air drawn by the compressors will have a significant bearing on the amount of energy consumed. Compressor performance as a breathing machine improves with cool, clean, dry air at intake.

19.6.2 Cool air intake

Every 4^0C rise in inlet air temperature results in a higher energy consumption by 1% to achieve equivalent output. Hence, cool air intake leads to a more efficient compression.

Table 19.3: Effect of Intake Air temperature on Power Consumption

Inlet Temperature(^{0}C)	Relative Air Delivery (%)	Power Saved (%)
10.0	102.0	+1.4
15.5	100.0	Nil
21.1	98.1	- 1.3
26.6	96.3	- 2.5
32.2	94.1	- 4.0
37.7	92.8	- 5.0
43.3	91.2	- 5.8

It is preferable to draw cold ambient air, as the temperature of air inside the compressor room will be a few degrees higher than the ambient temperature. A sheltered inlet, protected from rain on a north wall is desirable. While extending air intake to the outside of building, care should be taken to minimize excess pressure drop in the suction line, by selecting a bigger diameter duct with minimum number of bends.

19.6.3 Dust Free Air Intake

Dust in the suction air causes excessive wear of moving parts and results in malfunctioning of the valves due to abrasion. Suitable air filters should be provided at the suction side. Air filters should have high dust separation capacity, low pressure drops and robust design to avoid frequent cleaning and replacement.

Table 19.4: Effect of Pressure Drop across Air Inlet Filter on Power consumption

Pressure Drop Across air filter (mmWC)	Increase in Power Consumption (%)
0	0
200	1.6
400	3.2
600	4.7
800	7

Air filters should be selected based on the compressor type and installed as close to the compressor as possible. For every 25mbar pressure lost at the inlet due to choked filters, the compressor performance is reduced by about 2percent. Hence, it is advisable to clean inlet air filters at regular intervals to avoid high-pressure drops. Manometers or differential pressure gauges across filters may be provided for monitoring pressure drops so as to plan filter-cleaning schedules.

Table 19.5: Comparison of Inlet Air Filters

Type	Filter Action Efficiency, %	Particle Size, Microns	Pressure Drop when Clean, inches of Water Column	Comments
Dry	100, 99, 98	10, 5, 3	3 to 8	Recommended for non-lubricated compressors in a high dust environment
Dry type with Silencer	100, 99	10, 5	5, 7	Same as above
Oil wetted (viscous impingement)	95, 85	20, 10	0.25 to 2.0	Not recommended for dusty areas or for non-lubricated
Oil bath	98, 90	10, 3	2, 6 to10	Same as above. Recommended for rotary vane compressors in normal service

19.6.4 Dry Air Intake

Table 19.6: Moisture Levels at Various Humidity Levels

% Relative Humidity	Kg of water vapour compressed per hour for every 1000 m^3/min. of air at 30^0C
50	27.6
80	45
100	68.22

Atmospheric air always contains some amount of water vapour, depending on the relative humidity, being high in foggy or rainy weather. The moisture level will also be high if air is drawn from a damp area, cooling tower exhaust and air conditioner warm outlet air.

It is desirable to draw air with a low relative humidity, as otherwise, energy is consumed to compress the water vapour in the air and again to condense and drain the moisture from inter and after coolers. The moisture-carrying capacity of air increases with a rise in temperature and decreases with increase in pressure.

19.6.5 Pre-Cooled Air Intake

By cooling the air entering the compressor, the efficiency of the compressor can be improved. This cooling, usually to 25^0C is achieved by refrigeration, if the chilled water is available at cheap cost. As the temperature of air is reduced, its volume decreases and a greater mass of air is available for the given compressor. Therefore, due to pre-cooling either more air is delivered for a given power input or the power input is reduced for a required volumetric flow rate. Using pre-cooled dry air can save about 20– 30 % of compressor power requirement. Also, the moisture present inlet air is condensed out giving dry air for compression and saving energy which would otherwise be used for compressing water vapour.

After-coolers and dryers are also eliminated as the pre-cooler performs their functions. This represents another capital cost saving as well as an additional energy saving device. However the economics of cooling the air using chilled water must be viable considering the cost of chilled water available and energy savings in the compressor due the reduced intake air temperature.

19.6.6 Elevation

The altitude of a place has a direct impact on the volumetric efficiency of the compressor. The effect of altitude on volumetric efficiency is given below:

Table 3.7: Effect of Altitude on Volumetric Efficiency

Altitude Meters	Barometric Pressure	Percentage Relative Volumetric Efficiency Compared with Sea Level	
	Mbar	At 4 bars	At 7 bars
Sea level	1013	100	100
500	945	98.7	97.7
1000	894	97	95.2
1500	840	95.5	92.7
2000	789	93.9	90
2500	737	92.1	87

It is evident that compressors located at higher altitudes consume more power to achieve a particular delivery pressure than those at sea level, as the compression ratio is higher.

19.6.7 Cooling Water Circuit

Most of the industrial compressors are water-cooled, where in the heat of compression is removed by circulating cold water to cylinder heads, inter-coolers and after-coolers. The resultant warm water is cooled in a cooling tower and circulated back to compressors. The effect of cooling tower performance, total dissolved solids (TDS) in cooling water, pumps and fans on compressor performance is discussed below:

- **Cooling Tower Performance**

The main purpose of a cooling tower is to reduce the inlet warm water temperature to near the wet bulb temperature of ambient air. Cooling towers are generally designed to have an approach temperature of 2 to 5ºC depending upon the type of cooling tower. In practice, because of microbial growth, scale formation, corrosion and improper maintenance, the intimate contact between air and water is disturbed, resulting in high temperature outlet water which will affect compressor inter cooler effectiveness and compressor performance. Proper maintenance of cooling tower is very important to achieve the desired approach temperature.

- **Effect of air wet bulb temperature on cooling tower performance**

The cooling tower performance is affected by atmospheric conditions–particularly by the wet bulb temperature of inlet air. In a given location, the wet bulb temperature changes throughout the year, reaching its peak value only occasionally. It would, therefore, be uneconomical to operate the tower designed on the basis of the maximum wet bulb temperature. A compromise between peak and average conditions has to be adopted. While designing or selecting a cooling tower, "5 %" wet bulb temperature is used which is the wet bulb temperature not exceeded more than 5% of the total number of hours during summer months. This is estimated from the study of local meteorological data.

- **Cooling Tower Pump**

Cooling water is supplied to compressors through centrifugal pumps at a particular pressure and flow rate. Any change in water flow rate or pressure will affect the compressor performance. High efficiency pumps and motors have to be selected, as they run continuously. Interconnecting pipelines, inter-coolers, and after-coolers have to be selected or designed for minimum pressure drop. Generally pumps in a central compressor house are over-designed for safety reasons, and are capable of catering to more than one compressor. During lean seasons and night shift, only one or two compressors are in operation but cooling water is circulated through even in idle compressors. To avoid this waste of water supply, idle compressors should be closed or a water pressure switch fixed in the water line so that compressor can be tripped off whenever the cooling water pressure falls below a pre-set value.

- **Cooling Tower fans**

Cooling tower fans are provided to facilitate more air throughput thus increasing cooling tower efficacy. A malfunction of fan will result in less air to water ratio, change in air distribution pattern etc., which will affect the cooling tower performance. Hence, proper fan maintenance and fan energy management has to be adopted for lower energy consumption.

- Once the cooling water temperature approaches set temperature, the cooling tower fan can be switched off or operated intermittently by providing an interlock between water outlet temperature and fan operation.
- If two speed motors are used the cooling tower fan power requirement can be reduced substantially, whenever the ambient wet bulb temperature decreases.
- Automatic variable pitch propeller type fans and inverter type devices can be incorporated to permit variable fan speeds. These can track the cooling load for a constant outlet water temperature.
- Heavy fan blades made up of metals can be replaced with light weight, and aerodynamically designed blades such as FRP to reduce the initial torque required and the power consumption.
- Speed control of cooling tower fans by fluid-coupling drives can decrease– power consumption in motors.

- **Cooling Water TDS**

In most of the installations, raw water with high TDS is used for compressor cooling. Because of in adequate attention to water quality, the TDS levels may shoot up to unacceptable levels, due to water loss through evaporation, drift and other losses. This leads to increase of scaling in cylinder heads, inter-coolers and after-coolers, which reduces heat exchanger efficacy and compressor capacity. The scaling in compressor and interconnecting pipelines not only reduce its effectiveness but also increases pressures drop and thus, water pumping power.

Table 19.8: Effect of Scaling on Pressure Drop and Inner Pipe Diameter

Scaling Thickness (mm)	Inside Diameter Reduced		Pressure Drop
	From (mm)	To (mm)	
0.4	64	63.2	6
0.8	64	62.4	14
1.2	64	61.6	21
4.7	64	54.6	134

Use of treated water or purging apportion of cooling water periodically can maintain TDS levels within acceptable limits. It is better to maintain the water pH by addition of chemicals, and avoid microbial growth by addition of fungicides and algaecides.

19.6.8 Efficacy of Inter and After Coolers

Inter-coolers are provided between successive stages of a multi-stage compressor to cool the air, reduce its specific volume and condense out excess water. This reduces the power requirement in consecutive stages. Ideally, the temperature of the inlet air at each stage of a multi-stage machine should be the same as it was at the first stage. This is referred to as "perfect cooling". But in actual practice, because of fouled heat exchangers, due to scaling of dissolved solids in cooling water, the inlet air temperatures at subsequent stages are higher than the normal levels resulting in higher power consumption, as a larger volume is handled for the same duty.

Table 19.9: Effect of Inter-stage Cooling on Specific Power Consumption of a Reciprocating Compressor

Details	Imperfect Cooling	Perfect Cooling	Chilled Water Cooling
1 Stage inlet temperature^{0}C	21.1	21.1	21.1
2 Stage inlet temperature^{0}C	26.6	21.1	15.5
Capacity(m^3/min)	15.5	15.6	15.7
Shaft Power (kW)	76.3	75.3	74.2
Specific energy consumption kW (m^3/min)	4.9	4.8	4.7
Percent Change	+ 2.1	-	- 2.1

It can be seen from the table 3.9 that an increase of 5.5^{0}C in the inlet to the second stage results in a 2% increase in the specific energy consumption. Use of cold water reduces power consumption. However, use of very cold water could result in condensation of moisture in the air leading to cylinder damage. An after-cooler is located after the final stage of the compressor to reduce air temperature and water content, as far as possible, before air enters the receiver. As time passes, dissolved solids in the cooling water coat the after-coolers, thereby reducing the heat transfer effectiveness. So, fouled after- coolers, allow warm, humid air into the receiver, which causes more condensation in air receivers and distribution lines, which in consequence, leads to increased corrosion. Periodic cleaning of both heat exchangers and cylinder heads are therefore necessary.

Table 19.10: Cooling Water Requirement

Compressor Type	Minimum quantity of Cooling Water required for 2.85 m3/min. FAD at 7 bar (lpm)
Single-stage	3.8
Two-stage	7.6
Single-stage with after- cooler	15.1
Two-stage with after- cooler	18.9

Inter-cooler and after-cooler efficacy also depend upon the quantity of cooling water circulated through the heat exchanger.

19.6.9 Pressure Settings

- **Reducing Delivery Pressure:**

The power consumed by a compressor depends on its operating pressure and rated capacity. They should not be operated above their optimum operating pressures as this not only wastes energy, but also leads to excessive wear, leading to further energy wastage. The volumetric efficiency of a compressor is also less at higher delivery pressures. The possibility of down setting the delivery pressure should be explored by careful study of pressure requirements of various equipment, and the pressure drop in the line between the compressed air generation and utilization points. The pressure switches must be adjusted such that the compressor cut-in and cuts-off at optimum levels.

Table 19.11: Table: Power Reduction through Pressure Reduction

Pressure Reduction		Power Reduction (%)		
From(bar)	To (bar)	Single-stage Water-cooled	Two-stage Water-cooled	Two-stage Air-cooled
6.8	6.1	4	4	2.6
6.8	5.5	9	11	6.5

A reduction in the delivery pressure of a compressor would reduce the power consumption. This has been practically achieved, as discussed in the relevant case study.

- **Compressor modulation by Optimum Pressure Settings**

Very often in an industry, different types, capacities and makes of compressors are connected to a common distribution network. In such situations, proper selection of a right combination of compressors and optimal modulation of different compressors can conserve energy. Where more than one compressor feeds a common header, compressors have to be operated in such a way that the cost of compressed air generation is minimal.

If all compressors are similar, the pressure setting can be adjusted such that only one compressor handles the load variation, whereas the others operate more or less at full load.

If compressors are of different sizes, the pressure switch should be set such that only the smallest compressor is allowed to modulate. If different types are operated together, for example, both reciprocating and screw compressors, the reciprocating compressor must be allowed to modulate, while keeping the screw compressor at full load always as its part load operation consumes more power. In general, the compressor with lower no-load power consumption must be modulated. Compressors can be graded according to their specific energy consumption, at different pressures and energy efficient ones must be made to meet most of the demand.

Table 19.12: Expected Specific Power Consumption of Reciprocating Compressors (based on motor input)

Pressure bar	No. of Stages	Specific Power kW/170 CMHg
1	1	6.29
2	1	9.64
3	1	13.04
4	2	14.57
7	2	18.34
8	2	19.16
10	2	21.74
15	2	26.22

- **Mains air pressure reduction**

It is often necessary to reduce the mains pressure when supply groups of plants or complete workshops. This requires a pressure reducing valve of large capacity and good flow characteristics. In these circumstances, a pressure reducing station may be used.

If the low-pressure air requirement is considerable, it is advisable to generate low pressure and high-pressure air separately, and feed to the respective sections instead of reducing the pressure through pressure reducing valves, which invariably waste energy.

- **Minimum pressure drops in air lines**

The air mains and their associated branches, hoses, couplings and other accessories offer considerable opportunities for energy conservation.

Table 19.13: Energy Wastage due to Smaller Pipe Diameter

Pipe Nominal Bore (mm)	Pressure drops (bar) per 100meters	Equivalent power losses (kW)
40	1.80	9.5
50	0.65	3.4
65	0.22	1.2
80	0.04	0.2

100	0.02	0.1

Excess pressure drop due to inadequate pipe sizing, choked filter elements, improperly sized couplings and hoses represent energy wastage. The above table illustrates the energy wastage, if the pipes are of smaller diameter.

- **Equivalent lengths of fittings**

When long runs of distribution mains are involved, the pressure drops maybe higher than acceptable levels; in such cases it is desirable to check for actual pressure drops.

Table 19.14: Resistance of Pipe Fittings in Equivalent Lengths (in meters)

Type of Fitting	Nominal Pipe Size in mm									
	15	20	25	32	40	50	65	80	100	125
Gate Valve	0.11	0.14	0.18	0.27	0.32	0.40	0.49	0.64	0.91	1.20
Run of standard	0.12	0.18	0.24	0.38	0.40	0.52	0.67	0.85	1.20	1.52
Tee 90^o long bend	0.15	0.18	0.24	0.38	0.46	0.61	0.76	0.91	1.20	1.52
Elbow	0.26	0.37	0.49	0.67	0.76	1.07	1.37	1.83	2.44	3.20
Return bend	0.46	0.61	0.76	1.07	1.20	1.68	1.98	2.60	3.66	4.88
Through side	0.52	0.70	0.91	1.37	1.58	2.14	2.74	3.66	4.88	6.40
Outlet of tee globe valve	0.76	1.07	1.37	1.98	2.44	3.36	3.96	5.18	7.32	9.45

19.6.10 Blowers in place of Compressed Air System

Since the compressed air system is already available, facilities engineers may be tempted to use compressed air to provide air for low pressure requirements such as agitating plating tanks or pneumatic conveying. Using a blower that is designed for lower pressure operation will cost only a fraction of compressed air generation cost.

19.6.11 Capacity Control of Compressors

In many installations, the use of air is intermittent. Therefore, some means of controlling the output of the compressor is necessary. This is achieved by regulation of pressure, volume, temperature or some other factors. The type of capacity control employed has a direct impact on the compressor power consumption. Some control schemes commonly used are discussed below:

- **On / Off Control**

Automatic start and stop control, as its name implies, starts or stops the compressor by means of a pressure activated switch as the air demand varies. This is a very efficient method in controlling the capacity of compressor, where the motor idle-running losses are eliminated, as it completely switches off the motor when the set pressure is reached. This is suitable for small compressors (less than 10 kW).

- **Load and Unload**

This is a two-step control where compressor is loaded when there is air demand and unloaded when there is no air demand. During unload, the reciprocating compressor motor runs without air compression, thereby consuming only 20- 30% of the full load power. In screw compressors, the unloading is achieved by closing the inlet valve. The idling power is about 40 to 50 % of the full load power depending configuration, operation and maintenance practices. While in screw compressors, the unload power consumption is marginally higher compared to reciprocating machines.

- **Multi-step Control**

Motor-driven reciprocating compressors above75 kW are usually equipped with a multi-step control. In this type of control, unloading is accomplished in a series of steps, varying from full load down to no-load. A relevant case study has been appended for this opportunity.

Table 19.15: Power Consumption of Reciprocating Compressor at Various Loads

Load %	Power Consumption as % of full load Power
100	100
75	76-77
50	52-53
25	27-29
0	10-12

Five-step control (0%, 25%, 50%, 75% & 100%) is accomplished by means of clearance pockets. In some cases, a movable cylinder head is provided for variable clearance in the cylinder.

- **Throttling Control**

This kind of control is achieved using an inlet valve or a variable–displacement slide valve and is suitable for screw compressors where the capacity can be varied from 40 to 100%. The variable displacement method reduces the volume of air delivered by venting air from a variable portion of the helical screw length to the inlet side of the compressor. The variable displacement method is more efficient than the inlet valve.

The output of centrifugal compressors can be controlled using variable inlet guide vanes to throttle discharge pressure. However, another efficient way to match compressor output to meet varying load requirements is by speed control.

Table 19.16: Typical part load gas compression: Power input for speed and vane control of centrifugal compressors

System Volume	Flow % Speed Control	Power Input (%) Vane Control
111	120	-
100	100	100
80	76	81
60	59	64
40	55	50

20	51	46
0	47	43

At low volumetric flow (below 40 %), vane control may result in lower power input compared to speed control due to low efficiency of the speed control system. For loads more than 40%, speed control is recommended.

19.6.12 Avoiding Misuse of Compressed Air

Misuse of compressed air for purposes like body cleaning, liquid agitation, floor cleaning, drying, equipment cooling and other similar uses must be discouraged. Wherever possible, low-pressure air from a blower should be substituted for compressed air, for example secondary air for combustion in a boiler / furnace.

The following illustrations gives an idea of savings by stopping use of compressed air by choosing alternative methods to perform the same task.

Electric motors can serve more efficiently than air-driven rotary devices. The following table gives the comparison of pneumatic grinders and electrical grinders. Refer table 19.17 below:

Table 19.17: Power Requirements for Pneumatic and Electrical Tools

Tool	Wheel dia (mm)	Speed (rpm)	Air Cons. (m^3/h)	Power (kW)
Pneumatic angle grinder	150	6000	102 m^3/h	10.2
Electric angle grinder	150	5700-8600	N.A.	1.95 –2.90
Pneumatic jet grinder	35	30000	32.3 m^3/h at 6 bar	3.59
Electric straight grinder	25	22900-30500	N.A.	0.18

It may be noted that in some areas uses of electric tools are not permitted due to safety constraints, especially places where inflammable vapours are present in the environment. In those cases, possibility of shifting the machine tool operation to outside the flammable area may be considered when evaluating use of electric tools. It should always be remembered that safety consideration always overrides energy conservation.

- In place of pneumatic hoists, electric hoists can be used. A comparison is given below:

Table 19.18: Comparison of Power Consumption of Pneumatic and Electric Hoists

Capacity	Type	Compressed Air Required CMH	Equivalent Power Consumption at the Compressor, kW	Motor Rating of an Electric Hoist, kW
0.5	Chain	125	12	0.37
1.0	Chain	118	12	0.37
1.5	Chain	118	12	1.125
2	Chain	118	12	1.5
5	Wire rope	200	20.25	2.7

- Material conveying applications can be replaced by blower systems of preferably by a combination of belt/ screw conveyers and bucket elevators. In a paper manufacturing facility, compressed air was used for conveying wood chips.

- For applications like blowing of components, use of compressed air amplifiers, blowers or gravity-based systems may be possible. Brushes can sweep away debris from work in progress as effectively as high-pressure air. Blowers also can be used for this purpose. When moving air really is required for an application, often sources other than compressed air can do the job. Many applications do not require clean, dry, high-pressure and expensive 6 bar or 7 bar compressed air rather, only moving air is needed to blow away debris, provide cooling, or other functions. In these cases, local air fans or blowers may satisfy the need for moving air much economically.
- Use of compressed air for cleaning should be discouraged; use of vacuum cleaners is an alternative for some applications. If absolutely necessary, compressed air should be used only with blow guns to keep the air pressure below 2 bar; higher pressure are not permitted as printer national safety regulations. Use of compressed air amplifiers can also be considered for some cleaning applications.
- For applications where compressed air is indispensable for cleaning internal crevices of machines etc., installation of a separate cleaning air header with a main isolation valve may be considered. The main valve should be opened only for a few, well-defined time periods during the whole day, no connections for cleaning should be provided from process or equipment air lines.
- Replacement of pneumatically operated air cylinders by hydraulic power packs can be considered.
- Use of compressed air for personal comfort cooling can cause grievous injuries and is extremely wasteful; it should be banned from the safety viewpoint alone. Use of man coolers or air washers (in dry areas) may be encouraged. If a ¼" hosepipe is kept open at a 7bar compressed air line for personal cooling for at least 1000 hours/ annum, it can cost about 1,00,000 BDT/ annum.
- Vacuum systems are much more efficient than expensive venture methods, which use expensive compressed air rushing past an orifice to create a vacuum.
- Mechanical stirrers, conveyers, and low-pressure air may mix materials far more economically than high-pressure compressed air.

19.6.13 Avoiding Air Leaks and Energy Wastage

The major opportunity to save energy is in the prevention of leaks in the compressed air system. Leaks frequently occur at air receivers, relief valves, pipe and hose joints, shutoff valves, quick release couplings, tools and equipment. In most cases, they are due to poor maintenance and sometimes, improper installation in underground lines.

Air leakages through Different Size Orifices

The following table gives the amount of free air wasted for different nozzles sizes and pressure:

Table 19.19: Discharge of Air through Orifice (Cd –1.0)

Gauge Pressure Bar	0.5mm	1mm	2mm	3mm	5mm	10mm	12.5mm
0.5	0.06	0.22	0.92	2.1	5.7	22.8	35.5
1.0	0.08	0.33	1.33	3.0	8.4	33.6	52.5
2.5	0.14	0.58	2.33	5.5	14.6	58.6	91.4
5.0	0.25	0.97	3.92	8.8	24.4	97.5	152.0
7.0	0.33	1.31	5.19	11.6	32.5	129.0	202.0

Cost of Compressed Air Leakage

It may be seen from the following table that any expenditure on sealing leaks would be paid back through energy saving.

Table 19.20: Cost of Air Leakage

Orifice Size mm	KW Wasted	* Energy Waste (BDT/Year)
0.8	0.2	8000
1.6	0.8	32000
3.1	3.0	120000
6.4	12.0	480000

* based on BDT 5 / kWh; 8000 operating hours; air at 7.0bar

Steps in simple shop-floor method for leak quantification

- Shut off compressed air operated equipment (or conduct test when no equipment is using compressed air).
- Run the compressor to charge the system to set pressure of operation
- Note the subsequent time taken for 'on load' and 'off load' cycles of the compressors. For accuracy, take ON & OFF times for 8 – 10 cycles continuously. Then calculate total 'ON' Time (T) and Total 'OFF' time (t).
- The system leakage is calculated as

System leakage (m^3/min) = Q × T / (T + t)
Q = Actual free air being supplied during trial, in cubic meters per minute
T = Time on load in minutes
t = Time unload in minutes

Example 19.1

In the leakage test in a process industry, following results were observed

Compressor capacity (m^3/minute)	=	35
Cut in pressure, kg/cm^2(g)	=	6.8
Cut out pressure, kg/cm^2(g)	=	7.5
Load kW drawn	=	188 kW
Unload kW drawn	=	54 kW
Average 'Load' time, T	=	1.5 minutes
Average 'Unload' time, t	=	10.5 minutes

Comment on leakage quantity and avoidable loss of power due to air leakages.

a) Leakage quantity (m^3/minute), q $= \dfrac{(1.5)}{(1.5)+(10.5)} \times 35$

$= 4.375$ m^3/min

b) Leakage quantity per day, (m^3/day) = 4.375 x 24 x 60 = 6300 m^3/day

c) Specific power for compressed air generation = 188 kW /(35 x 60) m^3/hr

= 0.0895 kWh/m^3

d) Energy lost due to leakage/day = 0.0895 x 6300 = 564 kWh

- **Leakage Test by Ultrasonic Leak Detector**

Leakage tests are conducted by a Leak Detector having a sensing probe, which senses when there are leakages. The leak is detected by ultrasonic vibration. Leak testing is done by observing and locating sources of ultrasonic vibrations created by turbulent flow of gases passing through leaks in pressurized or evacuated systems. Use is made of ultrasonic detectors to reveal air borne and structure-borne vibrations, and translators that convert these in audible high frequency sounds to lower frequencies within the range of human hearing. Detection of leaks in compressed air and gas systems at high temperatures, beneath insulated coverings, and in pipelines and manifolds, can be done.

Leak detection and location from a distance through air or other fluids involves remote scanning of suspected leak areas with a directional probe and coordinating the direction of the source of the characteristic hissing sound of the leak with the relative sound intensity. Probably the greatest advantage of ultrasonic leak detection is that this method can be used with any fluid (liquid, gas or vapour) if the physical conditions for sound generation are met in the leak. When leak conditions generate sound in ambient air, leaks can be detected up to and beyond 30 metre (100feet). This offers advantages when extended structures are to be inspected. Ultrasonic mechanical vibration signal energy is converted to electrical signal energy by an appropriate transducer. The single most significant actor to be noted is the frequency distribution of ultrasonic energy from leaks. All leaks possess energy in the30/50 kHz. At lower pressure of 480 and 70 kPa (70and10psi), it is seen that there is a distinct maximum around 40 kHz.

19.6.14 Compressor Capacity Assessment

9.3.16

- **Need for Capacity Assessment**

The compressor capacity is expressed in terms of quantity of free air delivered at a particular pressure. Due to ageing of the compressors and inherent inefficiencies in the internal components, the free air delivered may be less than the design value, despite adherence to good maintenance practices. Sometimes, other factors such as poor maintenance, fouled heat exchanger and effects of altitude also tend to reduce free air delivery. In order to meet the air demand, the inefficient compressor may have to run for more time, thus consuming more power than actually required.

The power wastage depends on the percentage deviation of FAD capacity. For example, a worn-out compressor valve can reduce the compressor capacity by as much as 20 percent. A periodic assessment of the FAD capacity of each compressor has to be carried out to check its actual capacity. If the deviations are more than10%, corrective measures should be taken to rectify the same.

The ideal method of compressor capacity assessment is through a nozzle test where in a calibrated nozzle is used as a load, to vent out the generated compressed air. Flow is assessed, based on the air temperature, stabilization pressure, orifice constant etc.

Simple method of Capacity Assessment in Shop-floor

- Isolate the compressor along with its individual receiver being taken for test from main compressed air system by tightly closing the isolation valve or blank, thus closing the receiver outlet.
- Open water drain valve and drain out water fully and empty the receiver and the pipe line. Make sure that water trap is tightly closed once again to start the test.

- Start the compressor and activate the stopwatch.
- Note the time taken to attain the normal operational pressure P2 (in the receiver) from initial pressure P1.
- Calculate the capacity as per the formulae given below:

Actual Free air discharge $$Q = \frac{P_2 - P_1}{P_0} \times \frac{V}{T} N \frac{M^3}{Min}$$

P_2 = Final pressure after filling (kg/cm^2 a)

P_1 = Initial pressure (kg/cm^{2}a) after bleeding

P_0 = Atmospheric Pressure (kg/cm^{2}a)

V = Storage volume in m^3 which includes receiver, after cooler, and delivery piping
T = Time take to build up pressure to P2 in minutes

Example 19.2

An instrument air compressor capacity test gave the following results – Comment?

Make: ABC
Date: ……………..
Time: ……………..
Test No.:1
Piston displacement: 16.88 m^3/min
Theoretical compressor capacity: 14.75 CMM @ 7 kg/cm^2(g)
Compressor rated rpm 750: Motor rated rpm 1445
Receiver Volume: 7.79 m^3
Additional hold up volume,
i.e., pipe / water cooler, etc., is: 0.4974 m^3 Total volume: 8.322 m^3
Initial pressure P1: 0.5 kg/cm^2(g)
Final pressure P2: 7.03 kg/cm^2(g)
Pump up time: 4.021 min
Atmospheric pressure P_0: 1.026 kg/cm^2(g)

$$\text{Compressor output CMM} = \frac{(\text{P2} - \text{P1}) * \text{Total Volume}}{\text{Atm. Pressure} * \text{Pumpup time}}$$

$$\frac{\mathbf{(7.03 - 0.5) * 8.322}}{\mathbf{1.026 * 4.021}} = \mathbf{13.17}\ \text{m3/min}$$

Comment:
Capacity shortfall with respect to 14.75 m^3/min rating is 1.577 m^3/min i.e., 10.69% Compressor performance needs to be investigated further.

Example 19.3

A free air delivery test was carried out before conducting a leakage test on a reciprocating air compressor in an engineering industry and following were the observations:

Receiver capacity	:	8.0 m^3
Initial pressure	:	0.1 kg / cm^2 gauge

Final pressure	:	7.0 kg / cm^2 gauge
Additional hold-up volume	:	0.3 m^3
Atmospheric pressure	:	1.026 kg / cm^2 abs.
Compressor pump-up time	:	3.5 minutes

Further the following observations were made during the conduct of leakage test during the lunch time when no pneumatic equipment/ control valves were in operation:

a) Compressor on load time is 24 seconds and unloading pressure is 7 kg/cm^2gauage
b) Average power drawn by the compressor during loading is 92 kW
c) Compressor unload time and loading pressure are 79 seconds and 6.6kg/cm^2 gauge respectively.

Find out the following:

(i)Compressor output in m^3/hr (neglect temperature correction)
(ii) Specific Power Consumption, kW/ m^3/hr
(iii) % Air leakage in the system
(iv) Leakage quantity in m^3/hr
(v) Power lost due to leakage

(i) Compressor output m^3/minute : $\dfrac{(P_2 - P_1) \times \text{Total Volume}}{\text{Atm. Pressure} \times \text{Pumpup time}}$

: $\dfrac{(8.026 - 1.126) \times 8.3}{1.026 \times 3.5}$ = 15.948 m^3/minute

: 956.89 m^3/hr

(ii) Output : 956.89 m^3/hr

Power consumption : 92 kW
Specific power consumption : 92/956.89 = 0.09614 kW/m^3/hr

(iii) % Leakage in the system
Load time (T) : 24 s
Unload time (t) : 79 s

% leakage in the system : $\dfrac{T}{(T + t)} x100$

: $\dfrac{24}{(24 + 79)} x100$

: 23.3%

iv) Leakage quantity : 0.233x956.89
: 222.955 m^3/hr

v) Power lost due to leakage : Leakage quantity x specific power consumption
: 222.955 x 0.09614
: 21.43 kW

19.6.15 Line Moisture Separator and Traps

Although, in an ideal system, all cooling and condensing of air should be carried out before the air leaves the receiver, this is not very often achieved in practice. The amount of condensation, which takes place in the lines, depends on the efficiency of moisture extraction before the air leaves the receiver and the temperature in the mains itself. In general, the air main should be given a fall of not less than 1 m in 100 m in the direction of air flow, and the distance between drainage points should not exceed 30m.

Drainage points should be provided using equal tees, as it assists in the separation for water. Whenever a branch line is taken off from the mains it should leave at the top so that any water in the main does not fall straight in to the plant equipment. Further, the bottom of the falling pipe should also be drained.

19.6.16 Compressed Air Filter

Although some water, oil and dirt are removed by the separators and traps in the mains, still some of it is always left, which is being carried over. Moreover, pipe systems accumulate scale and other foreign matters, such as small pieces of gasket material, jointing compounds and so on. Burnt compressor oil may also be carried over in pipe work, and this, with other contaminants, forms a gummy substance. To remove these, all of which are liable to have deleterious effects on pneumatic equipment, the air should be filtered as near as possible to the point of use. Water and oil collected in the filter sump must be drained off because, if its level is allowed to build up, then it is forced through the filter element into the very system it is designed to protect.

19.6.17 Regulators

In many instances, pneumatic operations are to be carried out at a lower pressure than that of the main supply. For these applications, pressure regulators are required to reduce the pressure to the required value and also to ensure that it remains reasonably constant at the usage point. Pilot operated type regulators are energy efficient than direct-acting and self- relieving regulators. In the self-relieving type, a small relief valve is provided which allows excess air to bleed away, should the downs tream pressure exceed the set value. It is suitable for applications where the control pressure has to be varied periodically.

19.6.18 Lubricators

Where air is used to drive prime movers, cylinders and valves, they should be fitted with a lubricator. Essentially, a lubricator is a reservoir of oil and has been designed so that when air is flowing, metered amount of oil is fed in mist form into the air stream. This oil is carried with the motive air, to the point of use to lubricate all moving parts. All lubricators require a certain minimum rate of air flow to induce oil into their stream. Their design should be such that once the air flow is more than this minimum rate, they give satisfactory lubrication without causing an excessive pressure drop. Light free-fogging, lubricating oil with a high velocity index and without lead additives is suitable for lubrication. The ratio of oil to air can be decided experimentally. A rough guide is, one drop of oil per minute for every 5 dm^3/s of free air at 5.5 bar pressure.

It is advisable to fix filters, regulators and lubricators as close as possible to the equipment being served. Where lubricators are used to provide oil for linear actuators or when the direction of air flow is reversed, the volume of pipe work between the lubricator and cylinder should not exceed to 50 % of the volume of free air used by the cylinder per stroke.

19.6.19 Air Dryers

There are certain applications where air must be free from moisture and have a lower dew point. This calls for more sophisticated and expensive methods to lower the dew point of compressed air. Three common types of air dryers used are heat-less (absorption), absorption and chiller dryers. They produce dry air with 10°C–40°C dew point, depending on the type of dryers.

Table 19.21: Moisture Content in Air

Dew point at Atmospheric Pressure (°C)	Moisture Content (ppm)
0	3800
-5	2500
-10	1600
-20	685
-30	234
-40	80
-60	6.5

Table 19.22: Pressure Dew Point and Power Consumption Data for Dryers

Type of Dryer	Atmospheric Dew Point (°C)	First Cost	Operating Cost	Power Cons. For 1000 m^3/hr
Refrigeration	-20	Low	Low	2.9 kW
Desiccant regenerative (by compressed air purging)	-20	Low	High	20.7 kW
Desiccant regenerative (external or internal heating with electrical or steam heater, reduced or no compressed air purging)	-40	Medium	Medium	18.0 kW
Desiccant regenerative (using heated low pressure air, no compressed air loss)	-40	High	Low	12.0 kW
Desiccant regenerative (by recovery of heat of Compression from compressed air)	-40	High	Very low	0.8 kW

19.6.20 Air Receivers

The main purpose of a receiver is to act as a pulsation damper, allowing inter mitten thigh demands for compressed air to be met from a small compressor set, resulting in lesser energy consumption.

If receiver is sized too small for air demand, compressor will run for longer periods. By improving the ability of storage to meet air demand, running time of the compressor is minimised, thereby reducing energy usage as well as wear and tear. Compressed air systems usually have one primary receiver and possibly few secondary receivers near high intermittent air using equipment.

The air receiver should be generously sized to give a large cooling surface and even out the pulsation in delivered air pressure from a reciprocating compressor. As per IS 7938-1976, volume of air in receiver (in m^3) should be $1/10^{th}$ to $1/6^{th}$ of the output in m^3/min.

A simple formula often quoted for air receiver size is to take a value equal to one minute's continuous output of the compressor. However, this should be considered indicative of the minimum size of receiver. A better suggestion is to estimate the peak air consumption likely and allow for the maximum pressure drop that is acceptable at this peak load.

$$Receiver\ capacity\ in\ m^3 = \frac{m^3\ of\ free\ air\ volume\ required}{permissible\ pressure\ drop\ in\ bar}$$

If peaks cannot be quantified, another approximation can be to size the receiver volume to be 5% of the rated hourly free air output. Providing an air receiver n earth load end, where there is sudden high demand lasting for a short period, would avoid the need to provide extra capacity.

19.6.21 Capacity Utilization

In many installations, the use of air is intermittent. This means the compressor will be operated on low load or no-load condition, which increases the specific power consumption per unit of air generated. Hence, for optimum energy consumption, a proper compressor capacity control should be selected. The nature of the control device depends on the function to be regulated. Regulation of pressure, volume, temperature or some of factor determines the type of regulation required and the type of the compressor drive.

CHAPTER 20: FANS AND BLOWERS

20.1 Introduction

Fans and blowers provide air for ventilation and industrial process requirements. Fans generate a pressure to move air (or gases) against a resistance caused by ducts, dampers, or other components in a fan system. The fan rotor receives energy from a rotating shaft and transmits it to the air.

20.1 Difference between Fans, Blowers and Compressors

Fans, blowers and compressors are differentiated by the method used to move the air, and by the system pressure they must operate against. As per American Society of Mechanical Engineers (ASME) the specific ratio - the ratio of the discharge pressure over the suction pressure - is used for defining the fans, blowers and compressors (see Table 20.1).

Table 20.1 Differences between Fans, Blower and Compressor

Equipment	Specific Ratio	Pressure rise (mmWg)
Fans	Up to 1.11	1136
Blowers	1.11 to 1.20	1136 – 2066
Compressors	more than 1.20	-

Table 20.2 Fan Efficiencies

Type of fan	Peak Efficiency Range
Centrifugal Fan	
Airfoil, backward curved/inclined	79-83
Modified radial	72-79
Radial	69-75
Pressure blower	58-68
Forward curved	60-65
Axial fan	
Vanaxial	78-85
Tubeaxial	67-72
Propeller	45-50

20.2 Fan Types

Fan and blower selection depends on the volume flow rate, pressure, type of material handled, space limitations, and efficiency. Fan efficiencies differ from design to design and also by types. Typical ranges of fan efficiencies are given in Table 20.2.

Fans fall into two general categories: centrifugal flow and axial flow.

In centrifugal flow, airflow changes direction twice - once when entering and second when leaving (forward curved, backward curved or inclined, radial) (see Figure 20.1).
In axial flow, air enters and leaves the fan with no change in direction (propeller, tube axial, vane axial) (see Figure 20.2).

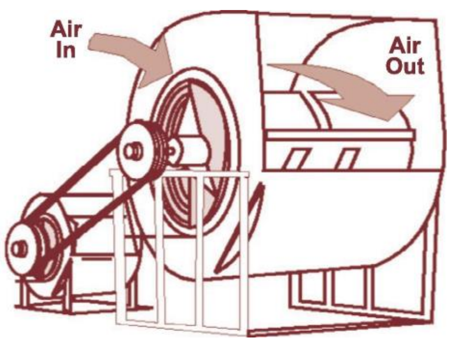


Figure 20.1 Centrifugal Fan

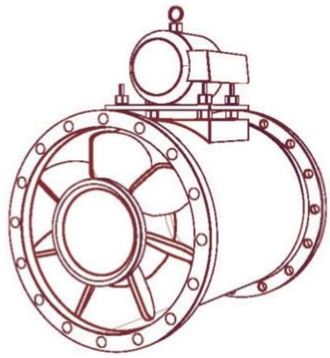


Figure 20.2 Axial Fan

Table 20.3 Types of Fans, Characteristics, and Typical Applications

Centrifugal Fans			Axial-flow Fans		
Type	**Characteristics**	**Typical Applications**	**Type**	**Characteristics**	**Typical Applications**
Radial	High pressure, medium flow, efficiency close to tube-axial fans, power increases continuously	Various industrial applications, suitable for dust laden, moist air/ gases	Propeller	Low pressure, high flow, low efficiency, peak efficiency close to point of free air delivery (zero static pressure)	Air-circulation, ventilation, exhaust
Forward-curved blades	Medium pressure, high flow, dip in pressure curve, efficiency higher than radial fans, power rises continuously	Low pressure HVAC, packaged units, suitable for clean and dust laden air / gases	Tube-axial	Medium pressure, high flow, higher efficiency than propeller type, dip in pressure-flow curve before peak pressure point.	HVAC, drying ovens, exhaust systems
Backward curved blades	High pressure, high flow, high efficiency, power reduces as flow increases beyond point of highest efficiency	HVAC, various industrial applications, forced draft fans, etc.	Vane-axial	High pressure, medium flow, dip in pressure-flow curve, use of guide vanes improves efficiency	High pressure applications including HVAC systems, exhausts
Airfoil type	Same as backward curved type, highest efficiency	Same as backward curved, but for clean air applications			

20.3 Fan Performance Evaluation and Efficient System Operation

The term "system resistance" is used when referring to the static pressure. The system resistance is the sum of static pressure losses in the system. The system resistance is a function of the configuration of ducts, pickups, elbows and the pressure drops across equipment-for example bag filter or cyclone. A Fan Characteristics Curve by Manufacturer is given in figure 20.3.

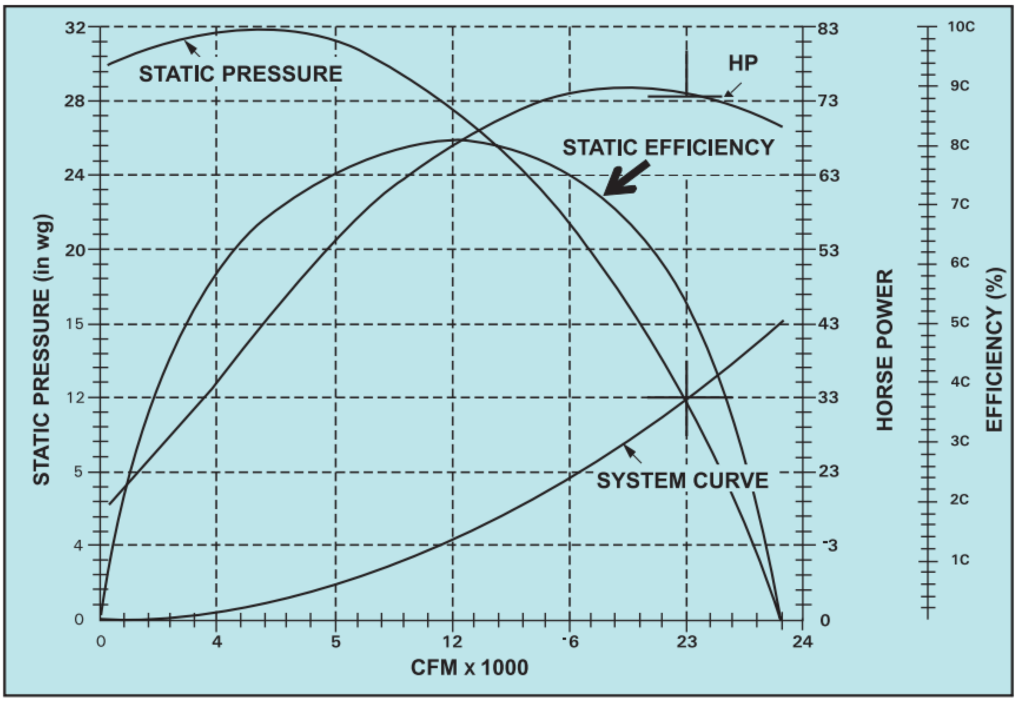


Figure 20.3 Fan Characteristics Curve by Manufacturer

9.3.17 System Characteristics and Fan Curves

In any fan system, the resistance to air flow (pressure) increases when the flow of air is increased. It varies as the square of the flow. The pressure required by a system over a range of flows can be determined and a "system performance curve" can be developed (shown as SC) (see Figure 20.4).
This system curve can then be plotted on the fan curve to show the fan's actual operating point at "A" where the two curves (N_1 and SC_1) intersect. This operating point is at air flow Q_1 delivered against pressure $\mathbf{P_1}$.

A fan operates along a performance given by the manufacturer for a particular fan speed. (The fan performance chart shows performance curves for a series of fan speeds.) At fan speed N_1, the fan will operate along the N_1 performance curve as shown in Figure 5.7. The fan's actual operating point on this curve will depend on the system resistance; fan's operating point at "A" is flow (Q_1) against pressure (P_1).

Two methods can be used to reduce air flow from Q_1 to Q_2:

First method is to restrict the air flow by partially closing a damper in the system. This action causes a new system performance curve (SC_2) where the required pressure is greater for any given air flow. The fan will now operate at **"B"** to provide the reduced air flow $\mathbf{Q_2}$ against higher pressure $\mathbf{P_2}$.

Second method to reduce air flow is by reducing the speed from N_1 to $\mathbf{N_2}$, keeping the damper fully open. The fan would operate at "C" to provide the same $\mathbf{Q_2}$ air flow, but at a lower pressure $\mathbf{P_3}$.

Thus, reducing the fan speed is a much more efficient method to decrease airflow since less power is required and less energy is consumed.

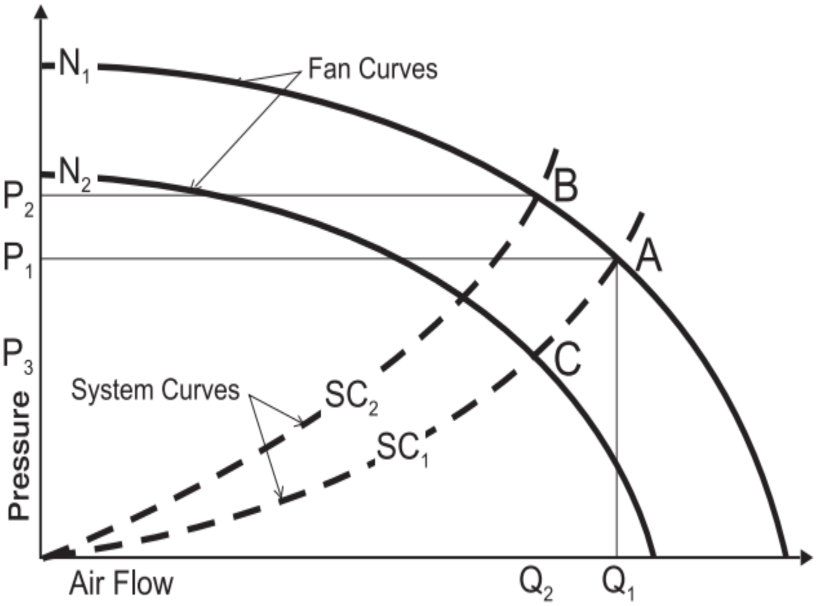
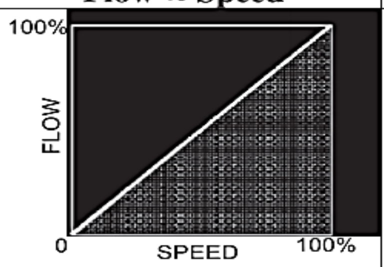
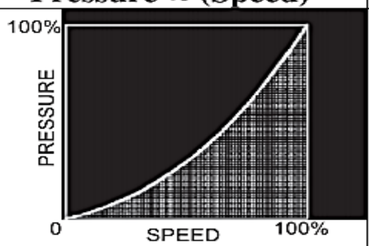
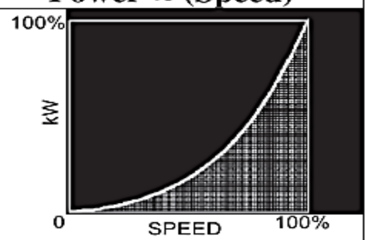


Figure 20.4 System Curve

9.3.18 Fan Laws

The fans operate under a predictable set of laws concerning speed, power and pressure. A change in speed (RPM) of any fan will predictably change the pressure rise and power necessary to operate it at the new RPM.

Flow ∞ Speed	**Pressure ∞ (Speed)^2**	**Power ∞ (Speed)^3**
		
$\frac{Q_1}{Q_2} = \frac{N_1}{N_2}$	$\frac{SP_1}{SP_2} = \left(\frac{N_1}{N_2}\right)^2$	$\frac{kW_1}{kW_2} = \left(\frac{N_1}{N_2}\right)^3$
Varying the RPM by 10% decreases or increases air delivery by 10%.	***Reducing the RPM by 10% decreases the static pressure by 19% and an increase in RPM by 10% increases the static pressure by 21%.***	***Reducing the RPM by 10% decreases the power requirement by 27% and an increase in RPM by 10% increases the power requirement by 33%.***

Where Q - Flow, SP - Static Pressure, kW - Power and N - Speed **(RPM)**

20.4 Fan Design and Selection Criteria

Precise determination of air-flow and required outlet pressure are most important in proper selection of fan type and size. The air-flow required depends on the process requirements; normally determined from heat transfer rates, or combustion air or flue gas quantity to be handled. System pressure requirement is usually more difficult to compute or predict. Detailed analysis should be carried out to determine pressure drop across the length, bends, contractions and expansions in the ducting system, pressure drop across filters, drop in branch lines, etc. These pressure drops should be added to any fixed pressure required by the process (in the case of ventilation fans there is no fixed pressure requirement). Frequently, a very conservative approach is adopted allocating large safety margins, resulting in over-sized fans which operate at flow rates much below their design values and, consequently, at very poor efficiency.

Once the system flow and pressure requirements are determined, the fan and impeller type are then selected. For best results, values should be obtained from the manufacturer for specific fans and impellers.

The choice of fan type for a given application depends on the magnitudes of required flow and static pressure. For a given fan type, the selection of the appropriate impeller depends additionally on rotational speed. Speed of operation varies with the application. High speed small units are generally more economical because of their higher hydraulic efficiency and relatively low cost. However, at low pressure ratios, large, low-speed units are preferable.

9.3.19 Fan Performance and Efficiency

Typical static pressures and power requirements for different types of fans are given in the Figure 20.4.

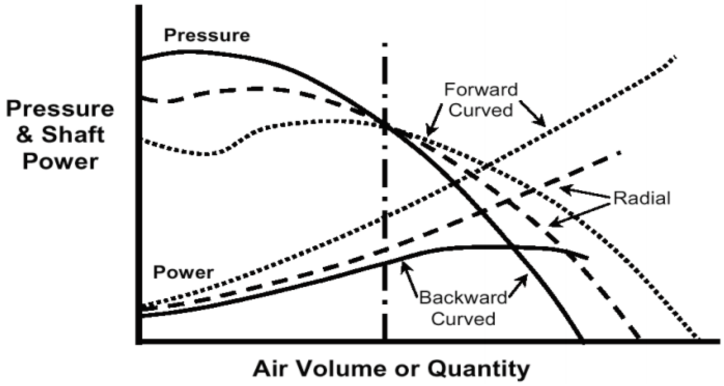


Figure 20.4 Fan Static Pressure and Power Requirements for Different Fans

Fan performance characteristics and efficiency differ based on fan and impeller type (See Figure 20.5). In the case of centrifugal fans, the hub- to-tip ratios (ratio of inner-to-outer impeller diameter) the tip angles (angle at which forward or backward curved blades are curved at the blade tip - at the base the blades are always oriented in the direction of flow), and the blade width determine the pressure developed by the fan.

Forward curved fans have large hub-to-tip ratios compared to backward curved fans and produce lower pressure.

Radial fans can be made with different heel-to-tip ratios to produce different pressures.

At both design and off-design points, backward-curved fans provide the most stable operation. Also, the power required by most backward - curved fans will decrease at flow higher than design values. A similar effect can be obtained by using inlet guide vanes instead of replacing the impeller with different tip angles. Radial fans are simple in construction and are preferable for high-pressure applications.

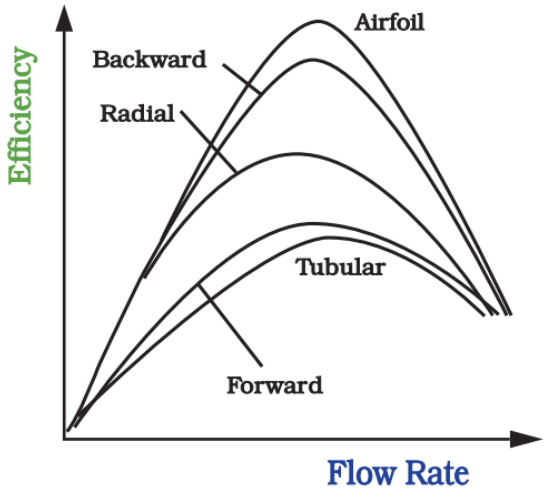


Figure 20.5: Fan Performance Characteristics based on Fans/ Impellers

Forward curved fans, however, are less efficient than backward curved fans and power rises continuously with flow. Thus, they are generally more expensive to operate despite their lower first cost.

Among centrifugal fan designs, aerofoil designs provide the highest efficiency (up to 10% higher than backward curved blades), but their use is limited to clean, dust-free air. Axial-flow fans produce lower pressure than centrifugal fans, and exhibit a dip in pressure before reaching the peak pressure point. Axial-flow fans equipped with adjustable / variable pitch blades are also available to meet varying flow requirements.

Propeller-type fans are capable of high-flow rates at low pressures. Tube-axial fans have medium pressure, high flow capability and are not equipped with guide vanes.

Vane-axial fans are equipped with inlet or outlet guide vanes, and are characterized by high pressure, medium flow-rate capabilities.

Performance is also dependent on the fan enclosure and duct design. Spiral housing designs with inducers, diffusers are more efficient as compared to square housings. Density of inlet air is another important consideration, since it affects both volume flow-rate and capacity of the fan to develop pressure. Inlet and outlet conditions (whirl and turbulence created by grills, dampers, etc.) can significantly alter fan performance curves from that provided by the manufacturer (which are developed under controlled conditions). Bends and elbows in the inlet or outlet ducting can change the velocity of air, thereby changing fan characteristics (the pressure drop in these elements is attributed to the system resistance). All these factors, termed as System Effect Factors, should, therefore, be carefully evaluated during fan selection since they would modify the fan performance curve.

Centrifugal fans are suitable for low to moderate flow at high pressures, while axial-flow fans are suitable for low to high flows at low pressures. Centrifugal fans are generally more expensive than axial fans. Fan prices vary widely based on the impeller type and the mounting (direct-or-belt-coupled, wall-or-duct-mounted). Among centrifugal fans, aerofoil and backward-curved blade designs tend to be somewhat more expensive than forward-curved blade designs and will typically provide more favourable economics on a lifecycle basis. Reliable cost comparisons are difficult since costs vary with a number of application-specific factors. A careful technical and economic evaluation of available options is important in identifying the fan that will minimize lifecycle costs in any specific application.

Safety margin

The choice of safety margin also affects the efficient operation of the fan. In all cases where the fan requirement is linked to the process/other equipment, the safety margin is to be decided, based on the discussions with the process equipment supplier. In general, the safety margin can be 5 % over the maximum requirement on flow rate.

In the case of boilers, the induced draft (ID) fan can be designed with a safety margin of 20 % on volume and 30 % on head. The forced draft (FD) fans and primary air (PA) fans do not require any safety margins. However, safety margins of 10 % on volume and 20 % on pressure are maintained for FD and PA fans.

System Resistance and Pressure Drop

The system resistance has a major role in determining the performance and efficiency of a fan. The system resistance also changes depending on the process. For example, the formation of the coatings / erosion of the lining in the ducts, changes the system resistance marginally. In some cases, the change of equipment (e.g. Replacement of Multi-cyclones with ESP / Installation of low pressure drop cyclones in cement industry) duct modifications, drastically shift the operating point, resulting in lower efficiency. In such cases, to maintain the efficiency as before, the fan has to be changed.
Hence, the system resistance has to be periodically checked, more so when modifications are introduced and action taken accordingly, for efficient operation of the fan.

System resistance in the application of centrifugal fan is the resistance offered by all the process equipment and duct line connected to the inlet of the fan as well as at the outlet of the fan, usually stacks. In the Figure 20.6 draft required to overcome the resistance offered by the boiler to draw the flue gases -10 mmWc (- ve sign indicates the suction), the draft required to draw the flue gases through the economiser, Air heater and dust control system are added to estimate the total resistance at the inlet of the ID fan (i.e., -10 - 30 - 40 - 150 = - 230 mmWc). However, the ID fan requires a minimum of 10 mmWc pressure to push the gases to the bottom of the stack from where the gases will be taken care by natural draft into atmosphere. Hence the overall resistance (pressure drop) to be build up by the ID fan is the difference between the outlet pressure and the inlet pressure [i.e., 10 - (-230) = 240 mmWc].

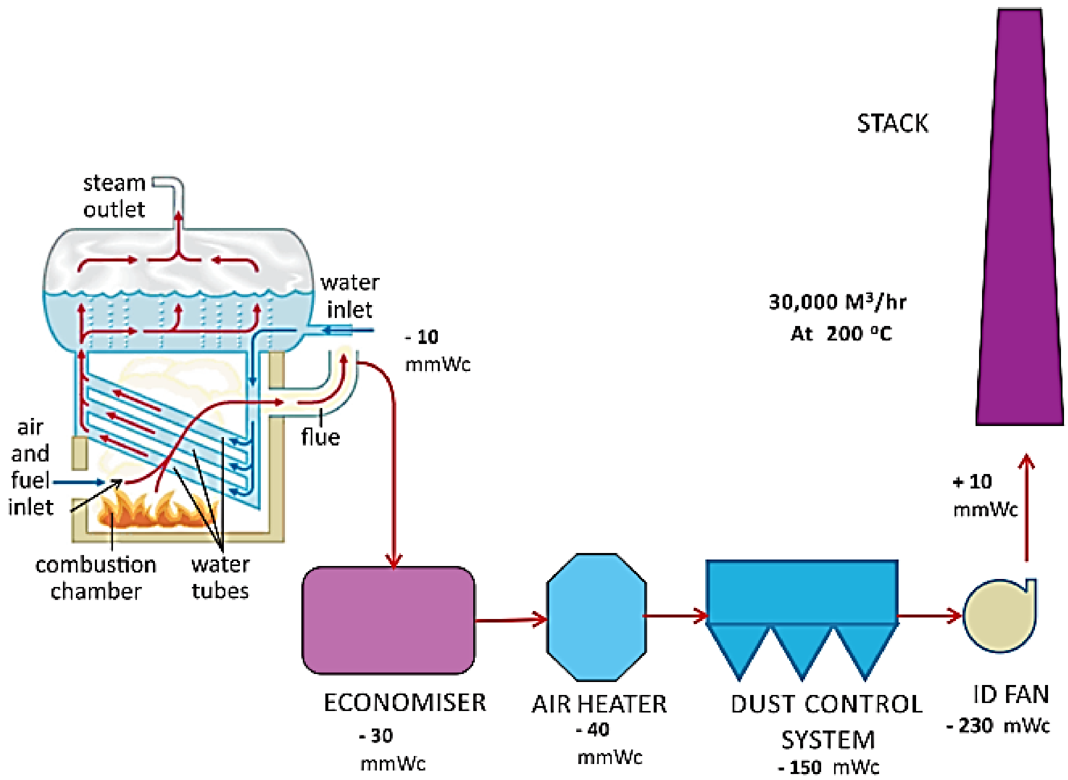


Figure 20.6: Pressure Drop across Various Equipment

System resistance is a function of gas density and the velocity of the gas. In the Figure 20.6 initially when there is no flue gas generation, there is no gas velocity in the process equipment and the ducts and hence the resistance (pressure drop) is zero (see Figure 20.7). After the boiler firing is started, there is continuous increase in the generation of flue gases and accordingly there is continuous increase in the velocity of the gases and continuous increase in draft. When the boiler is fired at rated capacity, the generation of flue gases are maximum resulting in corresponding pressure drop, which is the "operating point" (30,000 m^3/hr, 240 mmWc) of the boiler (Figure 20.7). Accordingly, the ID fan with a characteristic (Performance) curve passing through the "operating point" of the system at the highest possible fan efficiency has to be selected for better utilisation of energy.

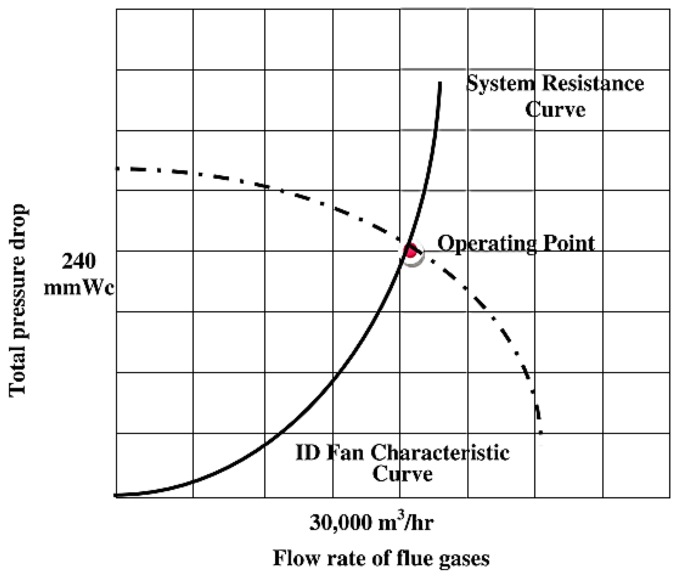


Figure 20.7 Fan System Curve

20.5 Flow Control Strategies

Typically, once a fan system is designed and installed, the fan operates at a constant speed. There may be occasions when a speed change is desirable, i.e., when adding a new run of duct that requires an increase in air flow (volume) through the fan. There are also instances when the fan is oversized and flow reductions are required.

Various ways to achieve change in flow are: pulley change, damper control, inlet guide vane control, variable speed drive and series and parallel operation of fans.

9.3.20 Pulley Change

When a fan volume change is required on a permanent basis, and the existing fan can handle the change in capacity, the volume change can be achieved with a speed change. The simplest way to change the speed is with a pulley change. For this, the fan must be driven by a motor through a v-belt system. The fan speed can be increased or decreased with a change in the drive pulley or the driven pulley or in some cases, both pulleys. As shown in the Figure 20.8, a higher sized fan operating with damper control was downsized by reducing the motor (drive) pulley size from 8" to 6". The power reduction was 12 kW.

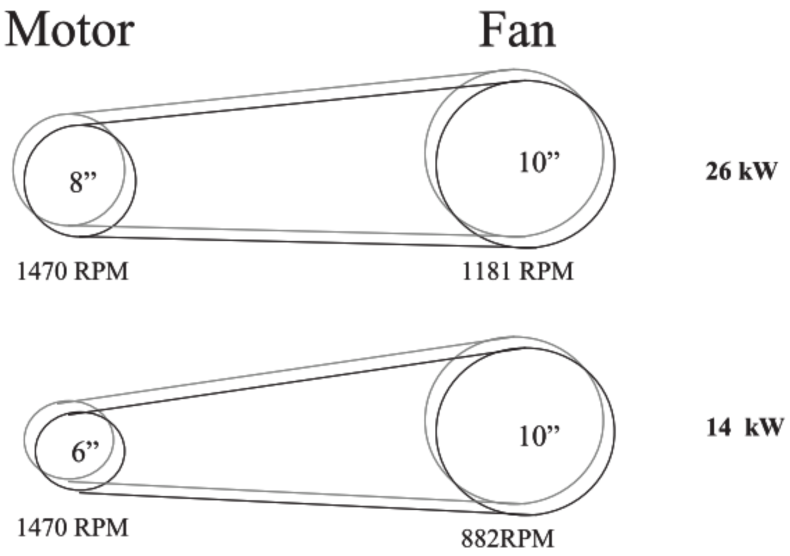


Figure 20.8 Pulley Change

9.3.21 Damper Controls

Some fans are designed with damper controls (see Figure 20.8). Dampers can be located at inlet or outlet. Dampers provide a means of changing air volume by adding or removing system resistance. This resistance forces the fan to move up or down along its characteristic curve, generating more or less air without changing fan speed. However, dampers provide a limited amount of adjustment, and they are not particularly energy efficient.

Figure 20.8 Damper change

9.3.22 Inlet Guide Vanes

Inlet guide vanes are another mechanism that can be used to meet variable air demand (see Figure 20.9). Guide vanes are curved sections that lay against the inlet of the fan when they are open. When they are closed, they extend out into the air stream. As they are closed, guide vanes pre-swirl the air entering the fan housing. This changes the angle at which the air is presented to the fan blades, which, in turn, changes the characteristics of the fan curve. Guide vanes are energy efficient for modest flow reductions — from 100 percent flow to about 80 percent. Below 80 percent flow, energy efficiency drops sharply.

Figure 20.9 Inlet Guide Vanes

Axial-flow fans can be equipped with variable pitch blades, which can be hydraulically or pneumatically controlled to change blade pitch, while the fan is at stationary. Variable-pitch blades modify the fan characteristics substantially and thereby provide dramatically higher energy efficiency than the other options discussed thus far.

9.3.23 Variable Speed Drives

Although, variable speed drives are expensive, they provide almost infinite variability in speed control. Variable speed operation involves reducing the speed of the fan to meet reduced flow requirements. Fan performance can be predicted at different speeds using the fan laws. Since power input to the fan changes as the cube of the flow, this will usually be the most efficient form of capacity control. However, variable speed control may not be economical for systems, which have infrequent flow variations. When considering variable speed drive, the efficiency of the control system (fluid coupling, eddy-current, VFD, etc.) should be accounted for, in the analysis of power consumption.

9.3.24 Series and Parallel Operation

Parallel operation of fans is another useful form of capacity control. Fans in parallel can be additionally equipped with dampers, variable inlet vanes, variable-pitch blades, or speed controls to provide a high degree of flexibility and reliability.

Combining fans in series or parallel can achieve the desired airflow without greatly increasing the system package size or fan diameter. Parallel operation is defined as having two or more fans blowing together side by side.

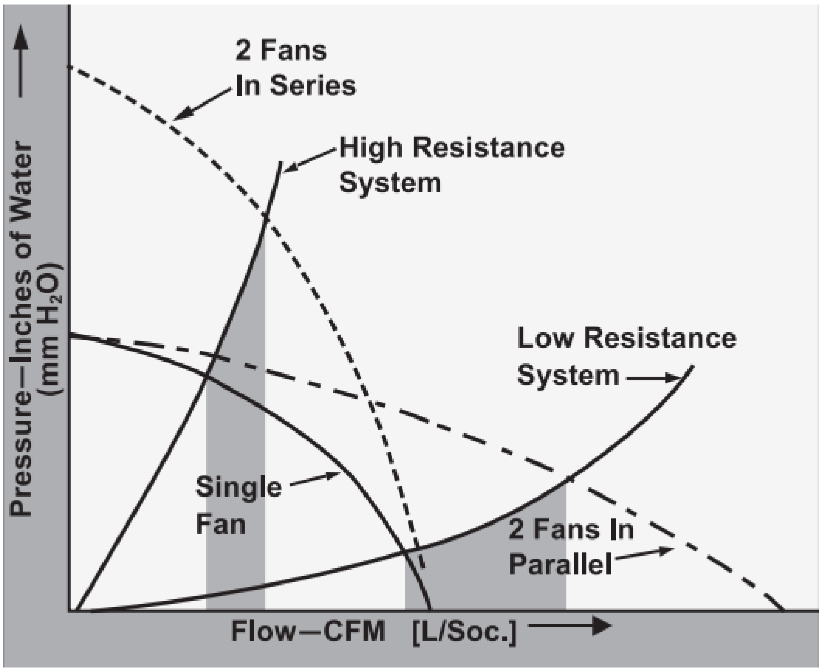


Figure 20.10: Series and Parallel Operation

The performance of two fans in parallel will result in doubling the volume flow, but only at free delivery. As Figure 20.10 shows, when a system curve is overlaid on the parallel performance curves, the higher the system resistance, the less increase in flow results with parallel fan operation. Thus, this type of application should only be used when the fans can operate in a low resistance almost in a free delivery condition.

Series operation can be defined as using multiple fans in a push-pull arrangement. By staging two fans in series, the static pressure capability at a given airflow can be increased, but again, not to double at every flow point, as the above Figure displays. In series operation, the best results are achieved in systems with high resistances.

In both series and parallel operation, particularly with multiple fans certain areas of the combined performance curve will be unstable and should be avoided. This instability is unpredictable and is a function of the fan and motor construction and the operating point.

Factors to be considered in the selection of flow control methods

Comparison on of various volume control methods with respect to power consumption (%) required power is shown in Figure 20.11.
All methods of capacity control mentioned above have turn-down ratios (ratio of maximum—to minimum flow rate) determined by the amount of leakage (slip) through the control elements. For example, even with dampers fully closed, the flow may not be zero due to leakage through the damper. In the case of variable-speed drives the turn-down ratio is limited by the control system. In many cases, the minimum possible flow will be determined by the characteristics of the fan itself. Stable operation of a fan requires that it operate in a region where the system curve has a positive slope and the fan curve has a negative slope.

The range of operation and the time duration at each operating point also serves as a guide to selection of the most suitable capacity control system. Outlet damper control due to its simplicity, ease of operation, and low investment cost, is the most prevalent form of capacity control. However, it is the most inefficient of all methods and is best suited for situations where only small, infrequent changes are required (for example, minor process variations due to seasonal changes. The economic advantage of one method over the other is determined by the time duration over which the fan operates at different operating points. The frequency of flow change is another important determinant. For systems requiring frequent flow control, damper adjustment may not be convenient. Indeed, in many plants, dampers are not easily accessible and are left at some intermediate position to avoid frequent control.

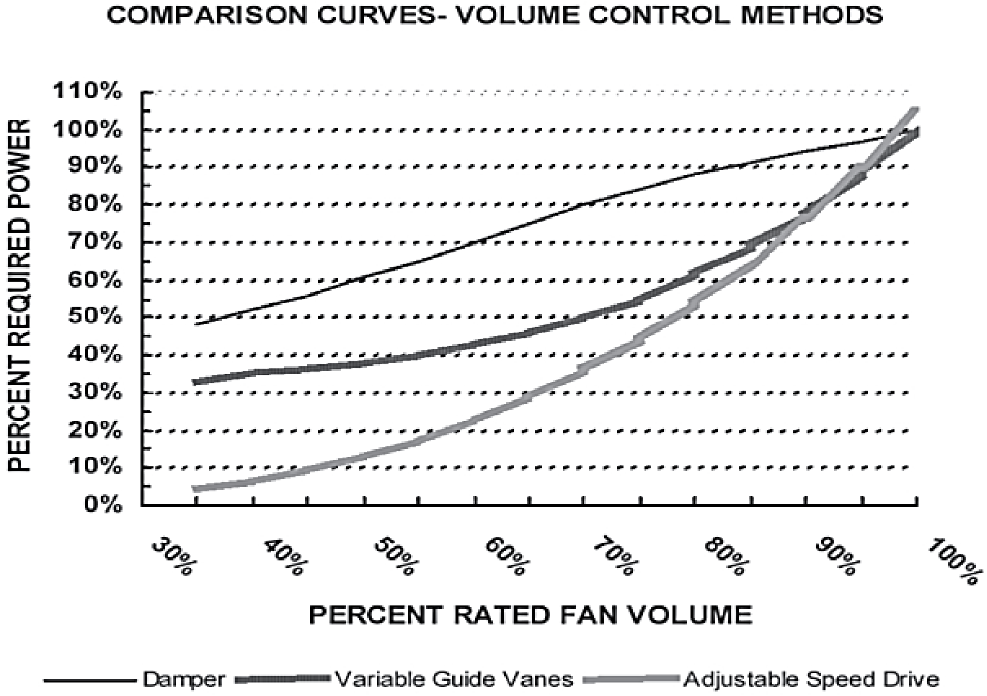


Figure- 20.11: Comparison: Various Volume Control Methods

20.6 Fan Performance Assessment

The fans are tested for field performance by measurement of flow, head and temperature on the fan side and electrical motor kW input on the motor side.

9.3.25 Air flow measurement Static pressure

Static pressure is the potential energy put into the system by the fan. It is given up to friction in the ducts and at the duct inlet as it is converted to velocity pressure. At the inlet to the duct, the static pressure produces an area of low pressure (see Figure 20.12).

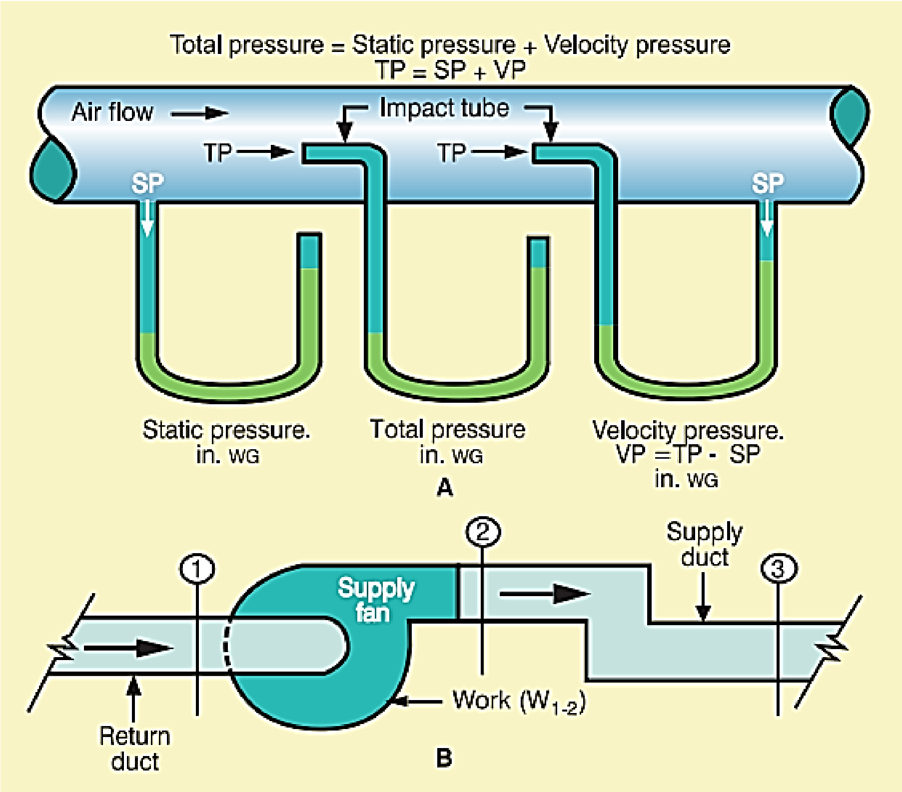


Figure 20.12: Static, Total and Velocity Pressure

9.3.26 Velocity pressure

Velocity pressure is the pressure along the line of the flow that results from the air flowing through the duct. The velocity pressure is used to calculate air velocity.

9.3.27 Total pressure

Total pressure is the sum of the static and velocity pressure. Velocity pressure and static pressure can change as the air flows though different size ducts accelerating and de-accelerating the velocity. The total pressure stays constant, changing only with friction losses. The illustration that follows shows how the total pressure changes in a system.
The fan flow is measured using pitot tube manometer combination, or a flow sensor (differential pressure instrument) or an accurate anemometer. Care needs to be taken regarding number of traverse points, straight length section (to avoid turbulent flow regimes of measurement) upstream and downstream of measurement location. The measurements can be on the suction or discharge side of the fan and preferably both where feasible.

9.3.28 Measurement by Pitot tube

The Figure 20.13 shows how velocity pressure is measured using a pitot tube and a manometer. Total pressure is measured using the inner tube of pitot tube and static pressure is measured using the outer tube of pitot tube. When the inner and outer tube ends are connected to a manometer, we get the velocity pressure. For measuring low velocities, it is preferable to use an inclined tube manometer instead of U tube manometer.

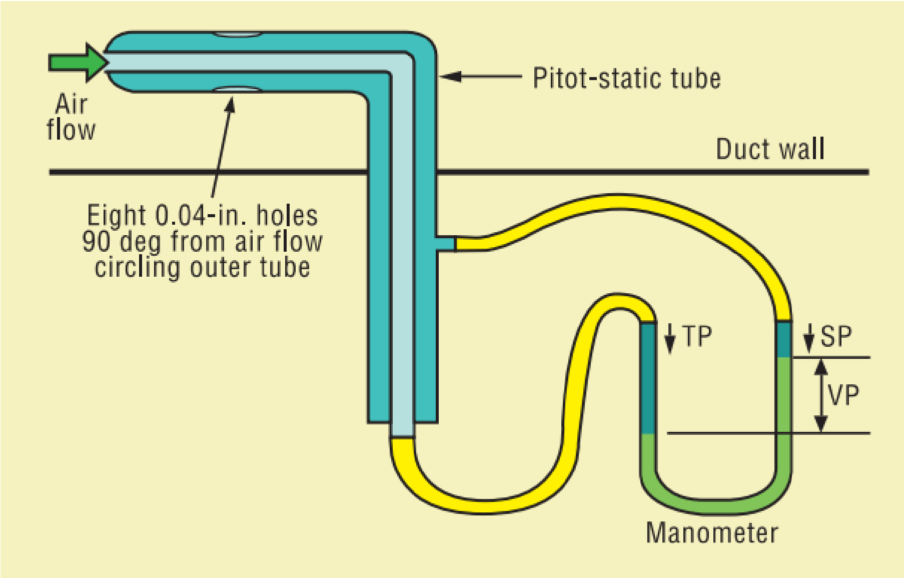


Figure 20.13 Velocity Measurement Using Pitot Tube

9.3.29 Measurements and Calculations

Velocity pressure/velocity calculation: When measuring velocity pressure, the duct diameter (or the circumference from which to calculate the diameter) should be measured as well. This will allow us to calculate the velocity and the volume of air in the duct. In most cases, velocity must be measured at several places in the same system.

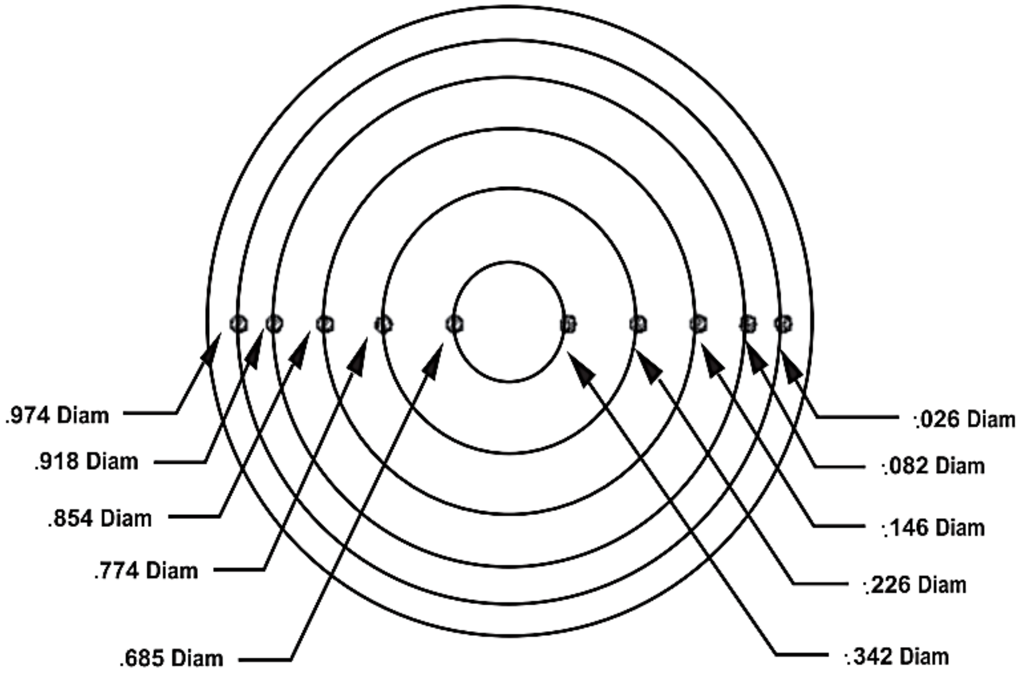


Figure 20.14 Traverse Points for Circular Duct

The velocity pressure varies across the duct. Friction slows the air near the duct walls, so the velocity is greater in the centre of the duct. The velocity is affected by changes in the ducting configuration such as bends and curves. The best place to take measurements is in a section of duct that is straight for at least 3-5 diameters after any elbows, branch entries or duct size changes.

To determine the average velocity, it is necessary to take a number of velocity pressure readings across the cross-section of the duct. The velocity should be calculated for each velocity pressure reading, and the average of the velocities should be used. Do not average the velocity pressure; average the velocities. For round ducts over 6 inches diameter, the following locations will give areas of equal concentric area (see Figure 20.14).

For best results, one set of readings should be taken in one direction and another set at a 90° angle to the first. For square ducts, the readings can be taken in 16 equally spaced areas. If it is impossible to traverse the duct, an approximate average velocity can be calculated by measuring the velocity pressure in the centre of the duct and calculating the velocity. This value is reduced to an approximate average by multiplying by 0 .9.

Calculation of Velocity: After taking velocity pressures readings, at various traverse points, the velocity corresponding to each point is calculated using the following expression.

$$\text{Velocity (m/s)} = C_p \times \sqrt{\frac{2 \times 9.81 \times \Delta p}{\gamma}}$$

Where C_P, = The pitot tube coefficient (Take manufacturer's value or assume 0.85)

ΔP = The average velocity pressure measured using pitot tube and inclined manometer by taking number of points over the entire cross-section of the duct, mm Water Column

γ = Gas density at flow conditions, kg/m^3

Example 20.1

Air flow measurements using the pitot tube, in the primary air fan of a coal fired boiler gave the following data, calculate the velocity of air.
Air temperature = 38°C
Velocity pressure = 47 mmWC
Pitot tube constant, Cp = 0.9
Air density at 38°C = 1.135 kg /m^3
Find out the velocity of air in m/sec.

$$\text{Velocity (m/s)} = C_p \times \sqrt{\frac{2 \times 9.81 \times \Delta p}{\gamma}}$$

$$= 0.9 \times \sqrt{\frac{2 \times 9.81 \times 47}{1.135}}$$

$$= 25.6 \text{ m/s}$$

Calculation of gas density: To calculate the velocity and volume from the velocity pressure measurements, it is necessary to know the density of gas. The density is dependent on altitude, temperature, molecular weight and pressure.

$$Density\,(\gamma), kg/m^3 = \frac{P \times M}{R \times T}$$

P – Absolute gas pressure, mmWC
M – Molecular weight of the gas, kg/kg mole (in the case of air M = 28.92 kg/kg mole)
T – Gas temperature, K
R – Gas constant, 847.84 mmWC m^3/kg mole K

Calculation of molecular weight for flue gas consisting of CO_2, CO, O_2, N_2 (M) (dry basis), kg/kg mole

$$= \{\%\, CO_2 \text{ x } M_{CO2} + \%\, O_2 \text{ x } M_{O2} + \%\, CO \text{ x } M_{CO} + \%\, N_2 \text{ x } M_{N2}\}/100$$

Volume calculation

The volume in a duct can be calculated for the velocity using the equation:

$$Volumetric\ flow(Q), m^3/\text{sec} = Velocity, V\,(m/\text{sec})\ x\ Area\,(m^2)$$

Fan efficiency

Fan manufacturers generally use two ways to mention fan efficiency: mechanical efficiency (sometimes called the total efficiency) and static efficiency. Both measure how well the fan converts horsepower into flow and pressure.

The equation for determining mechanical efficiency is:

$$Fan\ Mechanical\ Efficiency\,(\eta_{mechanical}),\% = \frac{Volume\ in\ m^3/\sec \times \Delta p\,(total\ pressure)\ in\ mmWC}{102 \times Power\ input\ to\ fan\ shaft\ in\ kW}\ x\ 100$$

The static efficiency equation is the same except that the outlet velocity pressure is not added to the fan static pressure

$$Fan\ Static\ Efficiency\,(\eta_{static}),\% = \frac{Volume\ in\ m^3/\sec \times \Delta p\,(static\ pressure)\ in\ mmWC}{102 \times Power\ input\ to\ fan\ shaft\ in\ kW}\ x\ 100$$

Drive motor kW can be measured by a load analyzer. This kW multiplied by motor efficiency gives the shaft power to the fan.

20.7 Energy Savings Opportunities

Minimizing demands on the fan-

1. Minimising excess air level in combustion systems to reduce FD fan and ID fan load.
2. Minimising air in-leaks in hot flue gas path to reduce ID fan load, especially in case of kilns, boiler plants, furnaces, etc. Cold air in-leaks increase ID fan load tremendously, due to density increase of flue gases and in-fact choke up the capacity of fan, resulting as a bottleneck for boiler / furnace itself.
3. In-leaks / out-leaks in air conditioning systems also have a major impact on energy efficiency and fan power consumption and need to be minimized.

The findings of performance assessment trials will automatically indicate potential areas for improvement, which could be one or a more of the following:

1. Change of impeller by a high efficiency impeller along with cone.
2. Change of fan assembly as a whole, by a higher efficiency fan
3. Impeller derating (by a smaller dia impeller)
4. Change of metallic / Glass reinforced Plastic (GRP) impeller by the more energy efficient hollow FRP impeller with aerofoil design, in case of axial flow fans, where significant savings have been reported
5. Fan speed reduction by pulley dia modifications for derating
6. Option of two speed motors or variable speed drives for variable duty conditions
7. Option of energy efficient flat belts, or, cogged raw edged V belts, in place of conventional V belt systems, for reducing transmission losses.
8. Adopting inlet guide vanes in place of discharge damper control
9. Minimizing system resistance and pressure drops by improvements in duct system

20.8 Factors that Could Affect Fan System Performance

- Leakage, re-circulation or other defects in the system
- Excessive loss in a system component located too close to the fan outlet
- Disturbance of the fan performance due to a bender other system component located too close to the fan inlet

20.9 Case Study on Pressure Drop Reduction Across the Bag Filter

One of the Cement filter bag houses is experiencing high Differential Pressure (DP) across the bag house while producing one particular type of cement. This high DP is resulting in high power consumption and puffing from the bag house. Upon examination it has been found that particle size distribution for this particular type of Cement associated with the fineness is creating high DP.

The results of this replacement are self-explanatory in the details given below:

Application	Bag Filter for Cement Mill	
Problem	High DP across the bag house while producing one particular type of Cement Product	
Reason for the Problem	Characteristics of particle size distribution associated with its fineness is creating high DP across the bag house	
Solution	Replace the existing filter bags with PTFE Membrane filter bags	
Results	Reduction of 50mm WC in DP across the bag house Reduction of 5kWh in power consumption	
	Existing Bag	Bag with membrane
	40000	41600
	96.8/86.9	98.2/88.7
	Mixed Felt	Mixed Felt with PTFE membrane
	165	115
	51	46
Conclusion	The above results are categorically demonstrating that by changing the filter fabric we can achieve significant performance improvement of the bag house	

20.10 Case Studies VSD Applications

Case 1: Cement plants use a large number of high-capacity fans. By using liners on the impellers, which can be replaced when they are eroded by the abrasive particles in the dust-laden air, the plants have been able to switch from radial blades to forward-curved and backward-curved centrifugal fans. This has vastly improved system efficiency without requiring frequent impeller changes.

For example, a careful study of the clinker cooler fans at a cement plant showed that the flow was much higher than required and also the old straight blade impeller resulted in low system efficiency. It was decided to replace the impeller with a backward-curved blade and use liners to prevent erosion of the blade. This simple measure resulted in a 53 % reduction in power consumption, which amounted to annual savings of BDT. 2.1 million.

Case 2: Another cement plant found that a large primary air fan which was belt driven through an arrangement of bearings was operating at system efficiency of 23 %. The fan was replaced with a direct coupled fan with a more efficient impeller. Power consumption reduced from 57 kW to 22 kW. Since cement plants use a large number of fans, it is generally possible to integrate the system such that air can be supplied from a common duct in many cases.

For example, a study indicated that one of the fans was operated with the damper open to only 5 %. By re-ducting to allow air to be supplied from another duct where flow was being throttled, it was possible to totally eliminate the use of a 55 kW fan.

Case 3: The use of variable-speed drives for capacity control can result in significant power savings. A 25 ton-per-hour capacity boiler was equipped with both an induced-draft and forced-draft fan. Outlet dampers were used to control the airflow. After a study of the air-flow pattern, it was decided to install a variable speed drive to control air flow. The average power consumption was reduced by nearly 41 kW resulting in annual savings of BDT. 0.33 million. The investment of BDT. 0.65 million for the variable-speed drive was paid back in under 2 years.

Case 4: The type of variable-speed drive employed also significantly impacts power consumption. Thermal power stations install a hydraulic coupling to control the capacity of the induced-draft fan. It was decided to install a VFD on ID fans in a 200 MW thermal power plant. A comparison of the power consumption of the two fan systems indicated that for similar operating conditions of flow and plant power generation, the unit equipped with the VFD control unit consumed, on average, 4 million units / annum less than the unit equipped with the hydraulic coupling.

Example 20.2

A V-belt centrifugal fan is supplying air to a process plant. The performance test on the fan gave the following parameters.

Density of air at 0 °C	1.293 kg/m^3
Ambient air temperature	40 °C
Diameter of the discharge air duct	0.8 m
Velocity pressure measured by Pitot tube in discharge duct	45 mmWC
Pitot tube coefficient	0.9
Static pressure at fan inlet	- 20 mmWC
Static pressure at fan outlet	185 mmWC
Power drawn by the motor coupled with the fan	75 kW
Belt transmission efficiency	97 %
Motor efficiency at the operating load	93 %

Find out the static fan efficiency.

Solution

Air temperature	40 °C
Diameter of the discharge air duct	0.8 m
Velocity pressure measured by Pitot tube	45 mmWC
Static pressure at fan inlet	- 20 mmWC
Static pressure at fan outlet	185 mmWC
Power drawn by the motor	75 kW
Transmission efficiency	97%
Motor efficiency	93 %
Area of the discharge duct	3.14 x 0.8 x 0.8 x 1/4
	0.5024 m^2
Pitot tube coefficient	0.9
Corrected gas density	(273 x 1.293) / (273 + 40) = 1.1277
Volume	$\dfrac{C_p \times A\sqrt{2 \times 9.81 \times \Delta p \times \gamma}}{\gamma}$

	$\frac{0.9 \times 0.5024 \times \text{Sq rt.}(2 \times 9.81 \times 45 \times 1.1277)}{1.1277}$
	12.65 m^3/s
Power input to the shaft	75 x 0.97 x 0.93
	67.65 kW
$\text{Static Fan Efficiency } \% = \frac{\text{Volume in } m^3/\text{Sec} \times \text{total static pressure in mmwc}}{102 \times \text{Power input to the shaft in (kW)}}$	
Fan static Efficiency	$\frac{12.65 \times (185 - (-20))}{102 \times 67.65}$
	37.58 %

Example 20.3

An energy audit of a fan was carried out. It was observed that the fan was delivering 18,500 Nm^3/hr of air with static pressure rise of 45 mm WC. The power measurement of the motor coupled with the fan recorded 8.7 kW. The motor operating efficiency was taken as 88%from the motor performance curves. Assess the fan static efficiency.

Q	= 18,500 Nm^3/hr
	= 5.13888 m^3/sec
Static pressure rises across the fan, ΔP_{st}	= 45 mmWC
Power input to motor	= 8.7 kW
	=8.7 kW
Power input to fan shaft	=8.7 x0.88=7.656 kW
Fan static	= Volume in m^3/sec x ΔP_{st} in mmWc
	102 x Power input to shaft
	= 5.13888 x 45
	102 x 7.656
	= 0.296
	= 29.6%

CHAPTER 21: LIGHTING SYSTEMS

21.1 Introduction

Most natural light comes from the sun, including moon light. Its origin makes it completely clean and it consumes no natural resources. But man-made sources generally require consumption of resources, such as fossil fuels, to convert stored energy into light energy.

Light is usually described as the type of electromagnetic radiation that has a wavelength visible to the human eye, roughly 400 to 700 nanometers. Light exists as tiny "packets" called photons and exhibits the properties of both particles and waves. Visible light, as can be seen on the electromagnetic spectrum, as given in Figure 8.1, represents a narrow band between ultraviolet light (UV) and infrared energy (heat). These light waves are capable of exciting the eye's retina, which results in a visual sensation called sight. Therefore, seeing requires a functioning eye and visible light.

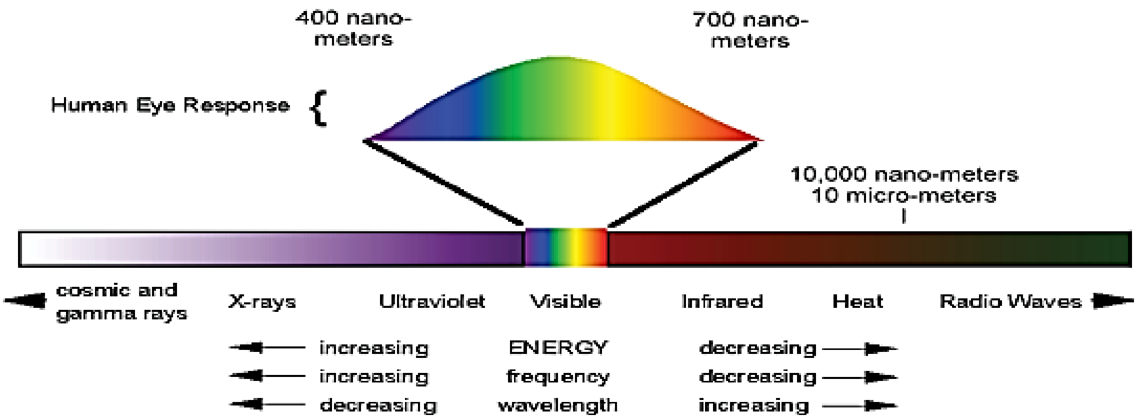


Figure 21.1: Visible Radiation

The lumen (1m) is the photometric equivalent of the Watt, weighted to match the eye response of the "standard observer". Yellowish-green light receives the greatest weight because it stimulates the eye more than blue or red light of equal radiometric power:

1 Watt = 683 lumens at 555 nm wavelength

The best eye sensitivity, as seen from Figure 21.2 is at 555 nm wavelength having greenish yellow colour with a luminous efficacy of 683 lm/Watt.

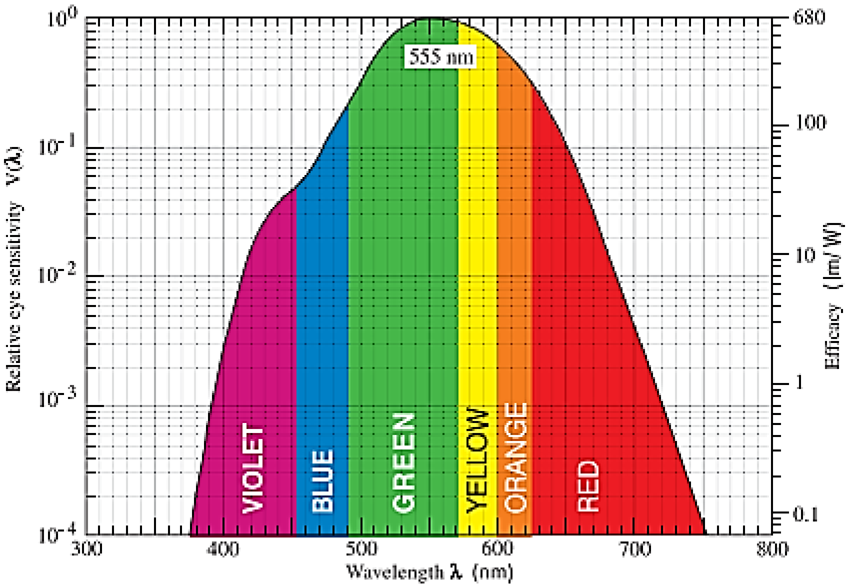


Figure 21.2: Relative Eye Sensitivity and Luminous Efficacy

Three primary considerations to ensure energy efficiency in lighting systems are:

i. Selection of the most efficient light source possible in order to minimize electricity consumption and cost.
ii. Matching the proper lamp type to the intended work task or aesthetic application, consistent with colour, brightness control and other requirements.
iii. Establishing adequate light levels without compromising productivity improve security and increase safety.

21.2 Basic Parameters and Terms in Lighting System

Luminous flux: The luminous flux describes the quantity of light emitted by a light source. It is a measure of a lamp's economic efficiency.

The most common measurement or unit of luminous flux is the lumen (lm).

The lumen rating of a lamp is a measure of the total light output of the lamp. Light sources are labelled with an output rating in lumens.

Illuminance (E): is the quotient of the luminous flux incident on an element of the surface at a point of surface containing the point, by the area of that element.
The lighting level produced by a lighting installation is usually qualified by the illuminance produced on a specified plane. In most cases, this plane is the major plane of the tasks carried out in the interior and is commonly called the working plane. The illuminance provided by an installation affects both the performance of the tasks and the appearance of the space. Lux (1X) is the metric unit of measure for illuminance of a surface. One lux is equal to one lumen per square meter. Illuminance decreases by the square of the distance (inverse square law).

The inverse square law defines the relationship between the illuminance from a point source and distance. It states that the intensity of light per unit area is inversely proportional to the square of the distance from the source (essentially the radius).

$$\mathbf{E} = \frac{\mathbf{I}}{\mathbf{d}^2}$$

Where, E = Illuminance in lux (lm/mz), I = Luminous flux in lumen (1m) and
d = distance in m
An alternate form of this equation which is sometimes more convenient is:

$$E_1 d_1^2 = E_2 d_2^2$$

Distance is measured from the test point to the first luminating surface - the filament of a clear bulb or the glass envelope of a frosted bulb.

Example 21.1

The illuminance is 10 lm/m^2 from a lamp at 1 meter distance. What will be the illuminance at half the distance?

Solution:

$$\begin{aligned} E_{(1m)} &= (d_2 / d_1)^2 * E_2 \\ &= (1.0 / 0.5)^2 * 10.0 \\ &= 40 \text{ lm/m}^2 \end{aligned}$$

Average maintained illuminance: is the average of illuminance (lux) levels measured at various points in a defined area.

Circuit Watts: is the total power drawn by lamps and ballasts in a lighting circuit under assessment.

Luminous Efficacy (lm/W): is the ratio of luminous flux emitted by a lamp to the power consumed by the lamp. It is a reflection of efficiency of energy conversion from electricity to light form. Unit: lumens per lamp Watt (lm/W).

Lamp Circuit Efficacy: is the amount of light (lumens) emitted by a lamp for each Watt of power consumed by the lamp circuit, i.e., including control gear losses. This is a more meaningful measure for those lamps that require control gear. Unit: lumens per circuit Watt (lm/W).

Installed Load Efficacy: is the average maintained illuminance provided on a horizontal working plane per circuit watt with general lighting of an interior. Unit: lux per Watt per square metre (lux/W/m²).

Installed Power Density: The installed power density per 100 lux is the power needed per square meter of floor area to achieve 100 lux of average maintained illuminance on a horizontal working plane with general lighting of an interior. Unit: Watts per square metre per 100 lux ($W/m^2/100$ lux)

Colour rendering index (CRI): is a measure of the effect of light on the perceived colour of objects. To determine the CR1 of a lamp, the colour appearances of a set of standard colour chips are measured with special equipment under a reference light source with the same correlated colour temperature as the lamp being evaluated. If the lamp renders the colour of the chips identical to the reference light source, its CR1 is 100. If the colour rendering differs from the reference light source, the CR1 is less than 100. A low CR1 indicates that some colours may appear unnatural when illuminated by the lamp.

Luminaire: is a device that distributes filters or transforms the light emitted from one or more lamps. The luminaire includes all the parts necessary for fixing and protecting the lamps, except the lamps themselves. In some cases, luminaires also include the necessary circuit auxiliaries, together with the means for connecting them to the electric supply. The basic physical principles used in optical luminaire are reflection, absorption, transmission and refraction.

Control gear: The gears used in the lighting equipment are as follows:

- Ballast is a current limiting device, to counter negative resistance characteristics of any discharge lamps. In case of fluorescent lamps, it aids the initial voltage build-up, required for starting. In an electric circuit the ballast acts as a stabilizer. Fluorescent lamp is basically an electric discharge lamp with two electrodes separated inside a tube with no apparent connection between them. When sufficient voltage is impressed on these electrodes, electrons are driven from one electrode and attracted to the other. The current flow takes place through an atmosphere of low-pressure mercury vapor.
- Since the fluorescent lamps cannot produce light by direct connection to the power source, they need an ancillary circuit and device to get started and remain illuminated. The auxiliary circuit housed in a casing is known as ballast.
- Ignitors are used for starting high intensity discharge lamps such as metal halide and sodium vapor lamps. Ignitors generate a high voltage pulse or a series of pulses to initiate the discharge.

21.3 Light Source and Lamp Types

Lamp is equipment, which produces light. Light is that part of the electromagnetic spectrum that is perceived by our eyes. A number of light sources are available, each with its own unique combination of operating characteristics viz., efficacy, colour, lamp life, and the percent of output that a lamp loses over its life.

Based on the construction and operating characteristics, the lamps can be categorized into three groups: incandescent, fluorescent and high intensity discharge (HID) lamps. HID lamps can be further classified as sodium vapor, mercury vapor and metal halide lamps. The most commonly used lamps are described briefly as follows

i. Incandescent lamp

The principal parts of an incandescent lamp also known as GLS lamp (General Lighting Service lamp) include the filament, the bulb, the fill gas or vacuum and the cap. Incandescent lamps (Figure 21.3 A&B) produce light by means of a wire or filament heated to incandescence by the flow of electric current through it. The filament is enclosed in an evacuated glass bulb filled with inert gas such as argon, krypton, or nitrogen that helps to increase the brilliance of lamp and to prevent the filament from burning out.

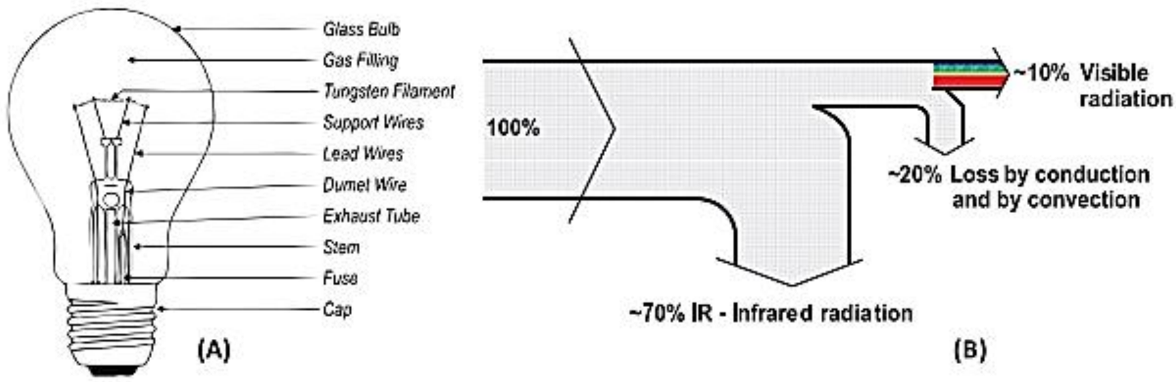


Figure 21.3: Incandescent Lamp and Energy Flow Diagram

Reflector lamps: Reflector lamps are basically incandescent, provided with a high-quality internal mirror, which follows exactly the parabolic shape of the lamp. The reflector is resistant to corrosion, thus making the lamp maintenance free and output efficient.

ii. Halogen lamp

It has a tungsten filament and the bulb filled with halogen gas (Figure 21.4). Current flows through the filament and heats it up, as in incandescent lamps. These lamps therefore generate a relatively large amount of heat. The use of halogen increases the efficiency and extends the service life compared with traditional incandescent lamps. Low-voltage types are very small and are ideal for precise direction of light, but they require a transformer.

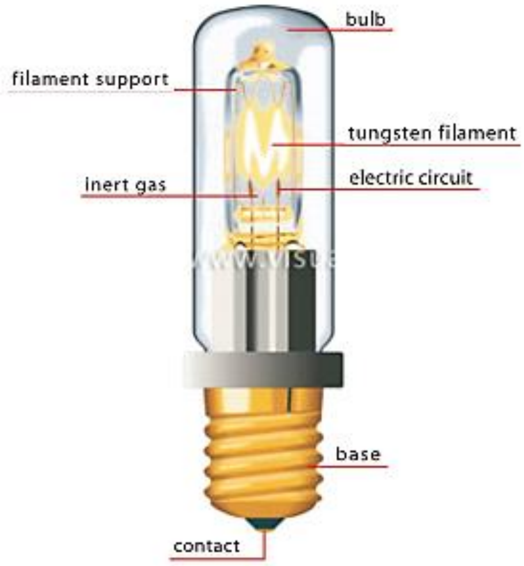


Figure 21.4: Halogen Lamp

Tungsten atoms evaporate from the hot filament and move toward the cooler wall of the bulb. Tungsten, oxygen and halogen atoms combine at the bulb-wall to form tungsten oxyhalide molecules. The bulb-wall temperature keeps the tungsten oxyhalide molecules in a vapor. The molecules move toward the hot filament where the higher temperature breaks them apart. Tungsten atoms are re-deposited on the cooler regions of the filament - not in the exact places from which they evaporated. Breaks usually occur near the connections between the tungsten filament and its molybdenum lead-in wires where the temperature drops sharply.

iii. Fluorescent tube lamp (FTL)

It works by the fluorescence principle. A fluorescent lamp (Figure 21.5 A&B) is a glass tube containing a small trace of a gas such as mercury vapor (for a white colour), carbon dioxide (for green), neon (for red colour), etc., with a special fluorescent / phosphorescent coating on the interior surface of the tube.

It contains two filaments, one at each end of the tube and when the electrical supply is switched ON, the contacts of the starter open and the filaments glow to heat up the gas contained inside the tube.

This action provides a voltage across its electrodes that set off an electric (gaseous mercury) arc discharge in the tube. This generates invisible UV radiation that is high enough to ionize the warmed-up gas inside the tube. This ionized gas also called as "plasma", excites the fluorescent coating so that it gives out visible light. Ballast is needed to start and operate fluorescent lamps, because of the characteristics of a gaseous arc. The luminous flux is highly dependent on the ambient temperature. Fluorescent Lamps are about 3 to 5 times as efficient as standard incandescent lamps and can last about 10 to 20 times longer.

The different types of fluorescent lamps and their reference are given below:

Linear tubes

- T12 - 38 mm (1.5″diameter)
- T8 - 25 mm (1″diameter)

- T5 - 16mm (5/8″diameter)
- T2 - 6 mm (l/4″diameter

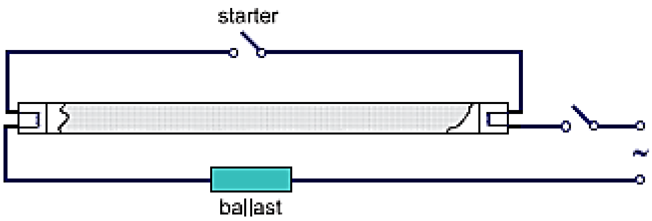


Figure 21.5 (A): Fluorescent Tube Lamp

U-bent tubes

- T12- 38 mm (1.5″diameter)
- T8 - 25 mm (1″ diameter)

Circular tubes

- T9 - 38 mm (1.5″diameter)
- T5 - 16 mm (5/8″diameter)

These four lamps vary in diameter (ranging from 1.5 inches that is 12/8 of an inch for T12 to 0.625 or 5/8 of an inch in diameter for T5 lamps). Efficacy is another area that distinguishes one from another. T5 & T8 lamps offer a 5-percent increase in efficacy over 40-watt T12 lamps, and have become the most popular choice for new installations.

iv. Compact fluorescent lamp (CFL)

Compact Fluorescent lamps (Figure 8.6) are compact / miniature versions of the linear or circular fluorescent lamps and operate in a very similar way. The luminous flux depends on temperature. CFL’s use less power and have a longer rated life compared to an incandescent lamp.

Figure 21.6: Compact Fluorescent Lamp

They are designed to replace an incandescent lamp and can fit into most existing light fixtures formerly used for incandescent. CFL’s are available in screw type/ pin type which fit into standard sockets, and gives off light that is similar to common fluorescent lamps.

v. Sodium vapour lamp

Low pressure sodium vapour lamp

Although low pressure sodium vapour (LPSV) lamps (Figure 8.7) are similar to fluorescent systems (because they are low pressure systems), they are commonly included in the HID family. LPSV lamps are the most efficacious light sources, but they produce the poorest quality light of all the lamp types. Being a monochromatic light source, all colours appear black, white, or shades of grey under an LPSV source. LPSV lamps are available in wattages ranging from 18-180.

Figure 21.7: LOW Pressure Sodium Vapour Lamp

LPSV lamp use has been generally limited to outdoor applications such as security or street lighting and indoor, low-wattage applications where colour quality is not important (e. g. stairwells). However, because the colour rendition is so poor, many municipalities do not allow them for roadway lighting.

High pressure sodium Vapour lamp

The high pressure sodium vapour (HPSV) lamp (Figure 21.8 A&B) is widely used for outdoor and industrial applications as the light is yellowish. Its higher efficacy makes it a better choice than metal halide for these applications, especially when good colour rendering is not a priority. HPSV lamps differ from mercury and metal-halide lamps in that they do not contain starting electrodes; the ballast circuit includes a high-voltage electronic starter. The arc tube is made of a ceramic material, which can withstand temperatures up to 1300 °C. It is filled with xenon to help start the arc, as well as a sodium-mercury gas mixture.

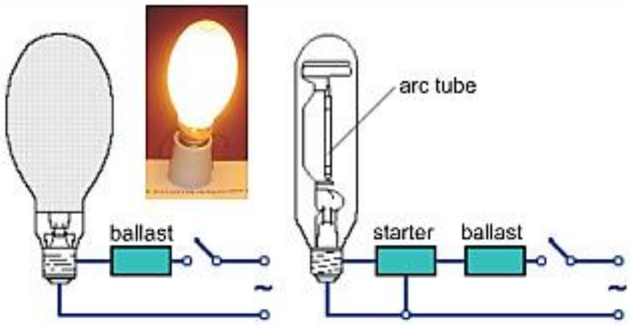


Figure 21.8 (A): High Pressure Sodium Vapour Lamp

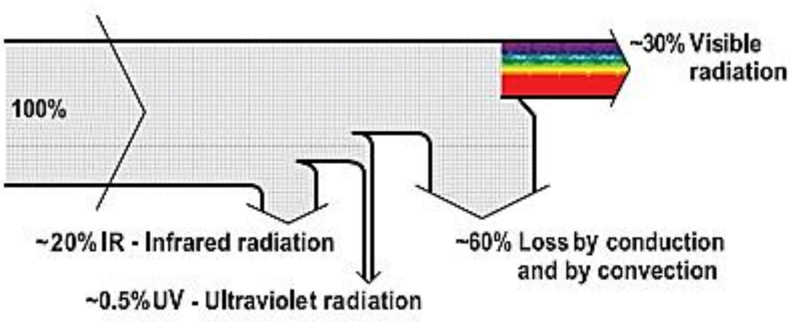


Figure 21.8 (B): Energy Flow diagram of High-Pressure Sodium Vapour Lamp

vi. Mercury vapour lamp

In a mercury vapour lamp (Figure 21.9) electromagnetic radiation is created from discharge within mercury vapour, but the regime is different than that found in the normal fluorescent lamp. During operation, the pressure within the lamp is in the range of 200 – 400 kPa (compared with only 1 Pa). It is not possible to achieve the mercury vapour discharge in a cold lamp. For this reason, the lamp also includes argon, and the initial arc is struck as an argon arc. The energy from this discharge vaporises the mercury to get the main discharge going.

The mercury vapour lamp produces a much greater proportion of visible light than fluorescent lamp and gives off a bluish white light. Phosphor coating can be given to improve the colour rendering index.

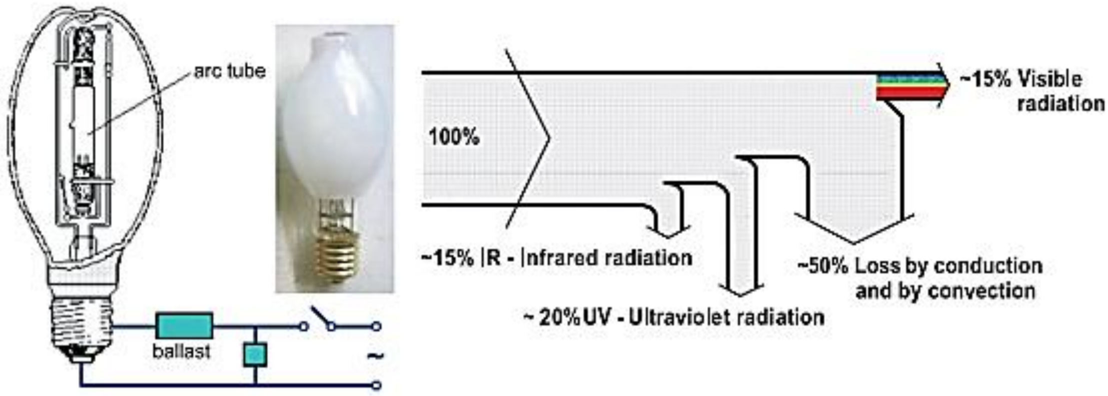


Figure 21.9: Mercury Vapour Lamp and Energy Flow Diagram

vii. Metal halide lamp:

Metal halide lamp (Figure 21.10 A&B) can be considered as a variant of high pressure mercury vapour lamp (HPMV). In addition to mercury vapour and argon, this lamp contains metal halide. The halides can be a mixture of rare earth halides, usually iodides or a mixture of sodium and scandium iodide. The mercury vapour radiation is augmented by that of the metals.

A highly compact electric arc is produced in a discharge tube. A starter is needed to switch on the lamp. The use of ceramic discharge tubes further improves the lamp properties. The halides act in a similar manner to the tungsten halogen cycle. As the temperature increases there is disassociation of the halide compound releasing the metal into the arc. The halides prevent the quartz wall getting attacked by the alkali metals. By adding other metals to the mercury different spectrum can be emitted. Some lamps use a third electrode for starting, but others, especially the smaller display lamps, require a high voltage ignition pulse.

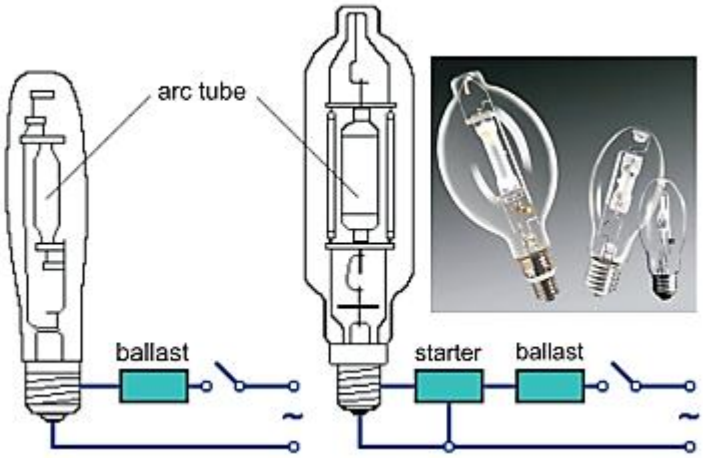


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Figure 21.10 (A): Metal Halide Lamp

Metal halide lamps have a significantly better colour rendering index than mercury vapour and can be tailored by the choice of halides.

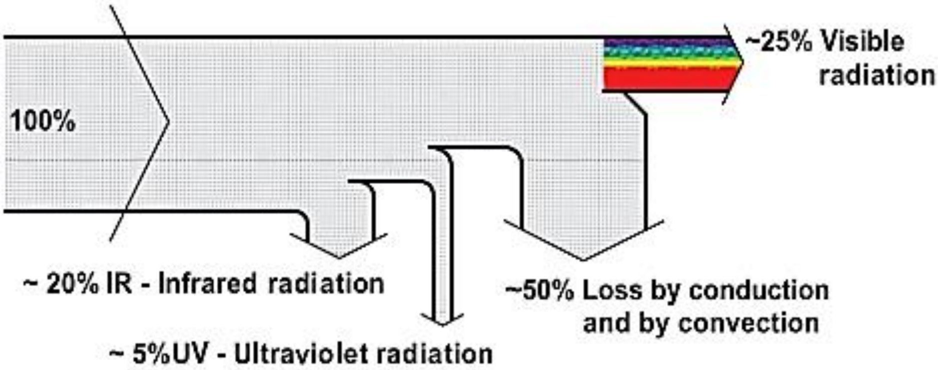


Figure 21.10 (B): Energy Flow Diagram of Metal Halide Lamp

viii. Light emitting diode (LED) lamp

LEDs produce light in a very unique way; they produce light via a process called electro-luminescence

(Figure 8.11), a process that starts by turning a semiconductor material into a conducting material. A semiconductor with extra electrons is called N-type (negative) material, since it has extra negatively-charged electrons. In N-type material, free electrons can move from a negatively-charged area to a positively charged area. A semiconductor with extra holes is called P-type (positive) material since it has extra positively-charged gaps called holes. When excited with current the negative electron leaves its atom and the P-type material's positive attraction draws the free negative electron into its hole, and the hole also moves toward the electron, so on and so forth.

As an electron travels to a hole, it carries energy, but in order to fit into the hole it must release any extra energy, and when it does, the extra energy is released in the form of light. When we maintain a steady flow of electrical current to the diode, it continues the process of allowing electrons to flow from the negative charged material and fall into the positive charged holes which maintains a steady stream of light out of the LED. The actual LED is quite small in size, usually less than one square millimetre. Additional optical components are added to shape and direct the light. LED's are made of number of inorganic semiconductor materials, many of which produce different colour of light.

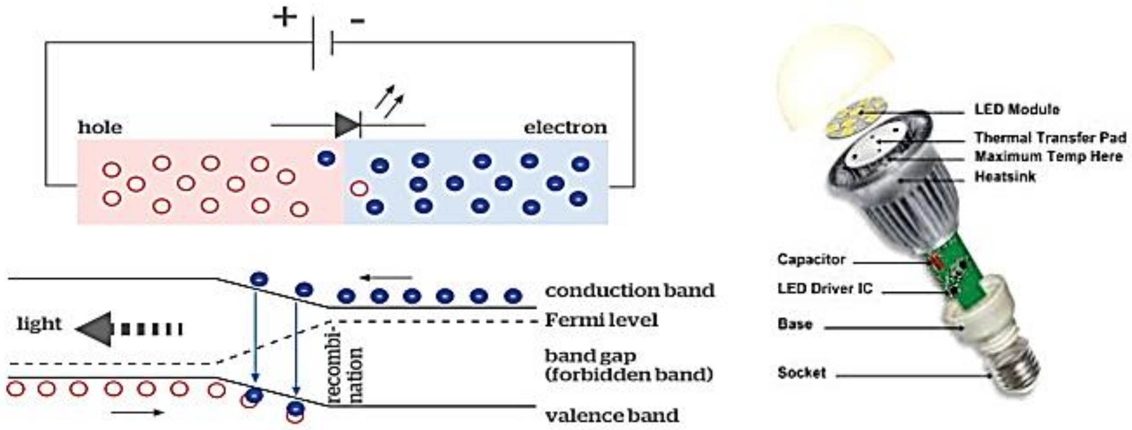


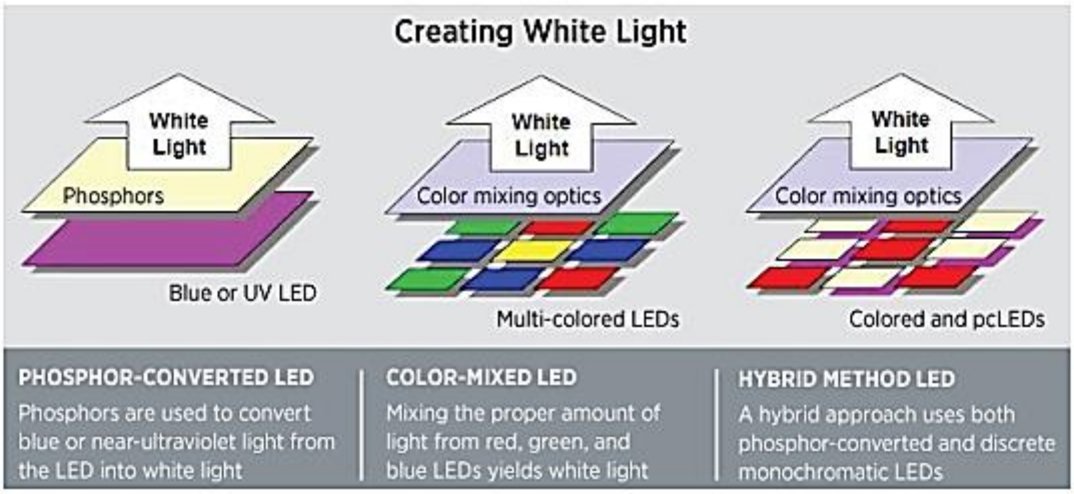
Figure 21.11(A): Representation of LED light

The efficiency of LED's has now risen sharply and is currently up to 200 lumens per watt in the laboratory and in some products available on the market (although more typical LED's average output varies from 50 to 130 lumens per watt).

Because of the low power requirement for LED's, using solar panels becomes more practical and less expensive than running an electrical wire or using a generator. Hence LED with battery backup for remote application is very economical. They do not radiate light in 360 degrees as an incandescent does. The light will be bright wherever it is focused.

Unlike incandescent and fluorescent lamps, LEDs are not inherently white light sources. Instead, LEDs emit nearly monochromatic light, making them highly efficient for coloured light applications such as traffic lights and exit signs. However, to be used as a general light source, white light is needed. White light can be achieved with LEDs in three ways:

Phosphor conversion, in which a phosphor is used on or near the LED to convert the coloured light to white light; RGB systems, in which light from multiple monochromatic LEDs (red, green, and blue) is mixed, resulting in white light; and a hybrid method, which uses both phosphor-converted and monochromatic LEDs.



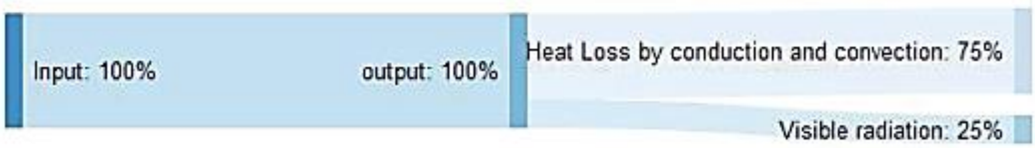


Figure 21.11 (B): Energy Flow diagram of LED Lamp

Advantages of LED technology is as follows Low power consumption, Directional light output, High efficiency level, Long life: up to ~100,000 hour life if junction temperature can be controlled, Instant switching on with no warm up time, High resistance to switching cycles, High impact and vibration resistance, No UV or IR radiation, Colour control ability, allows dimming and Mercury free

LED's also offer a number of promising environmental benefits, and they are often viewed as the future of green lighting.

ix. Induction lamp

Induction lamp is noted for 'crisp white light output'. Uses a magnetic field to excite gases — has no lamp parts to wear out. It consists of two main components: ballast and a sealed gas-filled bulb. Light is produced via electromagnetic induction, without an electrode or any electrical connection inside the bulb. Instead, high frequency electromagnetic fields are induced from outside the sealed chamber. To produce light, the ballast supplies the electric coils with high frequency electrical current. The ferrite magnets on either side of the bulb then emit electromagnetic fields which excite electrons within the bulb.

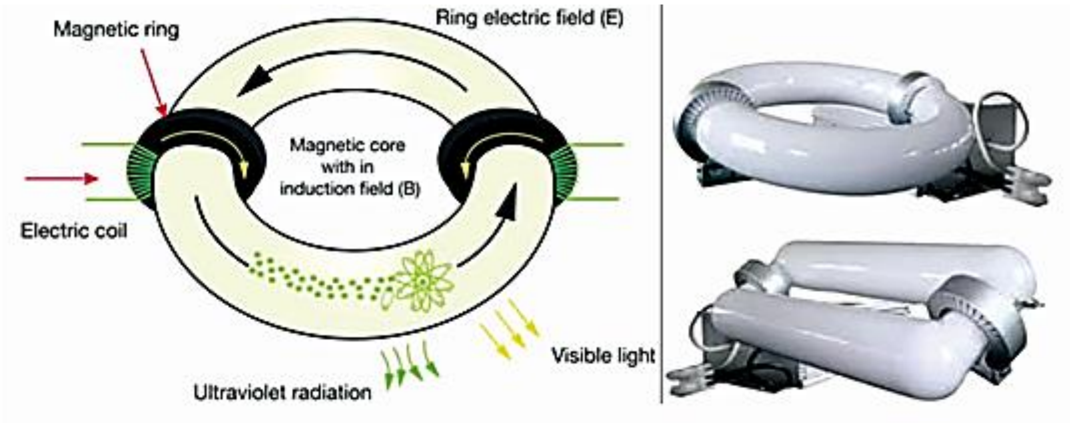


Figure 21.12: Representation of Induction Lamp

As the electrons accelerate inside the bulb, they collide with mercury atoms and produce ultraviolet (UV) light radiation. The UV light then causes the special phosphor coating inside the glass to react in a way that produces fluorescent light within the visible spectrum. The light produced by Induction Lighting (Figure 21.12) achieves good Colour Rendering Index (CR1), with a Correlated Colour Temperature.

Advantages of Induction lamps is as follows long burning hours, very less maintenance required, instant on/ instant re—strike and energy efficient lighting.

Lamp features: The Table 21.1 shows the lamp features of different lamps.

Table 21.1 Luminous performance characteristic of commonly used Luminaries

Type of Lamp	Lumens / Watt		Colour Rendering Index	Typical Application	Typical life (hours)
	Range	Avg.			
Incandescent	8-18	14	Excellent (100)	Homes, restaurants, general lighting,	1000

				emergency lighting	
Fluorescent lamps	46-60	50	Good w.r.t. coating (67-77)	Offices, shops, hospitals, homes	5000
Compact fluorescent lamps (CFL)	40-70	60	Very good (85)	Hotels, shops, homes, offices	8000-10000
High pressure mercury (HPMV)	44-57	50	Fair (45)	General lighting in factories, garages, car parking, flood lighting	5000
Halogen lamps	18-24	20	Excellent (100)	Display, flood lighting, stadium exhibition grounds, construction areas	2000-4000
High pressure sodium (HPSV) SON	67-121	90	Fair (22)	General lighting in factories, ware houses, street lighting	6000-12000
Low pressure sodium (LPSV) SOX	101-175	150	Poor (10)	Roadways, tunnels, canals, street lighting	6000-12000
Metal halide lamps	75-125	100	Good (70)	Industrial bays, spot lighting, flood lighting, retail stores	8000
LED lamps	50-130	90	Very good (80)	Office, industry, outdoor, retail, hospitality, etc	30,000- 60,000
Induction Lamps	65-90	75	Very good (80)	General lighting, factories, warehouse, street lighting, flood lighting, etc	60,000- 1,00,000

21.4 Recommended Illuminance Levels for Various Tasks/Activities/Locations

Recommendations on Illuminance

Scale of Illuminance:	The minimum illuminance for all non-working interiors, has been mentioned as 20 Lux (as per IS 3646). A factor of approximately 1.5 represents the smallest significant difference in subjective effect of illuminance. Therefore, the following scale of illuminances is recommended. 20—30—50—75—100—150—200—300—500—750—1000—1500—2000, ... Lux
Illuminance ranges:	Because circumstances may be significantly different for different interiors used for the same application or for different conditions for the same kind of activity, a range of illuminances is recommended for each type of interior or activity intended of a single value of illuminance. Each range consists of three successive steps of the recommended scale of illuminances. For working interiors the middle value (R) of each range represents the recommended service illuminance that would be used unless one or more of the factors mentioned below apply.

The higher value (H) of the range should be used at exceptional cases where low reflectance or contrasts are present in the task, errors are costly to rectify, visual work is critical, accuracy or higher productivity is of great importance and the visual capacity of the worker makes it necessary. Similarly, lower value

(L) of the range may be used when reflectances or contrasts are unusually high, speed and accuracy is not important and the task is executed only occasionally.

Recommended Illumination

The following Table 8.2 gives the recommended illuminance range for different tasks and activities for chemical sector. The values are related to the visual requirements of the task, to user's satisfaction, to practical experience and to the need for cost effective use of energy (Source IS 3646 (Part I): 1992).

For recommended illumination in other sectors, reader may refer Illuminating Engineers Society *Recommendations Handbook.*

Table 21.2 Recommended illuminance range for different tasks and activities for chemical sector

Petroleum, Chemical and Petrochemical works	
Exterior walkways, platforms, stairs and ladders	30-50-100
Exterior pump and valve areas	50-100-150
Pump and compressor houses	100-150-200
Process plant with remote control	30-50-100
Process plant requiring occasional manual intervention	50-100-150
Permanently occupied work stations in process plant	150-200-300
Control rooms for process plant	200-300-500

Pharmaceuticals Manufacturer and Fine chemicals manufacturer	
Pharmaceutical manufacturer	
Grinding, granulating, mixing, drying, tableting, sterilising, washing, preparation of solutions, filling, capping, wrapping, hardening	300-500-750
Fine chemical manufacturers	
Exterior walkways, platforms, stairs and ladders	30-50-100
Process plant	50-100-150
Fine chemical finishing	300-500-750
Inspection	300-500-750
Soap manufacture	
General area	200-300-500
Automatic processes	100-200-300
Control panels	200-300-500
Machines	200-300-500
Paint works	
General	200-300-500
Automatic processes	150-200-300
Control panels	200-300-500
Special batch mixing	500-750-1000
Colour matching	750-100-1500

21.5 Methods of Calculating Illuminance - Lighting Design for Interiors

In order to design a luminaire layout that best meets the illuminance and uniformity requirements of the job, two types of information are generally needed: average illuminance level and illuminance level at a given point. Calculation of illuminance at specific points is often done to help the designer evaluate the lighting uniformity, especially when using luminaires where maximum spacing recommendations are not supplied, or where task lighting levels must be checked against ambient level.

If average levels are to be calculated, two methods can be applied:

1. For indoor lighting situations, the Zonal Cavity Method is used with data from a coefficient of utilization table.
2. For outdoor lighting applications, a coefficient of utilization curve is provided, the CU is read directly from the curve and the standard lumen formula is used.

9.3.30 Calculation of the Installed Load Efficacy and Installed Load Efficacy Ratio of a General Lighting Installation in an Interior

STEP 1	Measure the floor area of the interior:	Area = m^2
STEP 2	Calculate the Room Index:	RI =
STEP 3	Determine the total circuit watts of the installation by a power meter if a separate feeder for lighting is available: (If the actual value is not known a reasonable approximation can be obtained by totalling up the lamp wattages including the ballasts)	Total circuit watts =
STEP 4	Calculate Watts per square metre: (Value of step 3 ÷ value of step 1)	W/m^2 =
STEP 5	Ascertain the average maintained illuminance by using lux meter, Eav. Maintained:	E_{av}.maint. =
STEP 6	Divide 5 by 4 to calculate lux per watt per square Metre:	$Lux/W/m^2$ =
STEP 7	Obtain target $Lux/W/m^2$ for type of the interior/application and RI (2):	Target $Lux/W/m^2$ =
STEP 8	Calculate Installed Load Efficacy Ratio (ILER) (6÷ 7):	ILER =

Table 21.3: Target Values for Maintained illuminance on Horizontal Plane

Room Index	Commercial lighting. (Offices, Retail stores etc.) & very clean industrial applications. Standard or good colour rendering. Ra: 40-85	Industrial lighting (Manufacturing areas, Workshops, Warehousing etc.) Standard or good colour rendering. Ra: 40-85	Industrial lighting installations where standard or good colour rendering is not essential but some colour discrimination is required. Ra: 20-40
5	53 (1.89)	49 (2.04)	67 (1.49)
4	52 (1.92)	48 (2.08)	66 (1.52)
3	50 (2.00)	46 (2.17)	65 (1.54)
2.5	48 (2.08)	44 (2.27)	64 (1.56)
2	46 (2.17)	42 (2.38)	61 (1.64)
1.5	43 (2.33)	39 (2.56)	58 (1.72)
1.25	40 (2.50)	36 (2.78)	55 (1.82)
1	36 (2.78)	33 (3.03)	52 (1.92)

The principal difference between the targets for Commercial and Industrial Ra: 40-85 (Cols.2 & 3) of Table 21.3 is the provision for a slightly lower maintenance factor for the latter. The targets for very clean industrial applications, with Ra: of 40 - 85, are as column2.

ILER Assessment

Compare the calculated ILER with the information in Table 21.4.

Table 21.4: Indicators of Performance

ILER	Assessment
0.75 and above	Satisfactory to Good
0.51 – 0.74	Review suggested
0.5 or less	Urgent action required

ILER ratios of 0.75 and above are considered to be satisfactory. ILER ratios of 0.51 - 0.74 need investigation to assess if improvements are possible. There may be reasons for a low ratio, such as use of lower efficacy lamps or less efficient luminaires to achieve the required lighting effects. In such cases, more efficient alternatives can be suggested. ILER ratio of 0.5 or less certainly suggests scope for installation of more efficient lighting equipment.

After determining the ILER for the existing lighting installation, the difference between the actual ILER and the best possible (1.0) can be calculated to estimate the energy wastage.

Annual Energy Wastage (in kWh) = (1.0 - ILER) x Total load (kW) x annual operating hours (h)

Sample Calculations

STEP 1 Measure the floor area of the interior: Area = 45 m^2

STEP 2 Calculate the Room Index RI = 1.93

STEP 3 Determine the total circuit watts of the installation by a power meter if a separate feeder for lighting is available. If the actual value is not known a reasonable approximation can be obtained by totalling up the lamp wattages including the ballasts: Total circuit watts = 990 W

STEP 4 Calculate Watts per square metre, 3 ÷1 : W/m^2 = 22

STEP 5	Ascertain the average maintained illuminance, Eav.Maintained (average lux levels measured at 18 points) Eav.maint. = 700
STEP 6	Divide 5 by 4 to calculate the actual lux per watt per square Metre Lux/W/m^2 = 31.8
STEP 7	Obtain target Lux/W/m^2 for the type of interior/ application and RI (2):(Refer Table 3) Target Lux/W/m^2 = 46
STEP 8	Calculate Installed Load Efficacy Ratio (ILER) (6÷ 7). = 0.7

ILER of 0.7 means that there is scope for review of the lighting system as per Table 21.4.

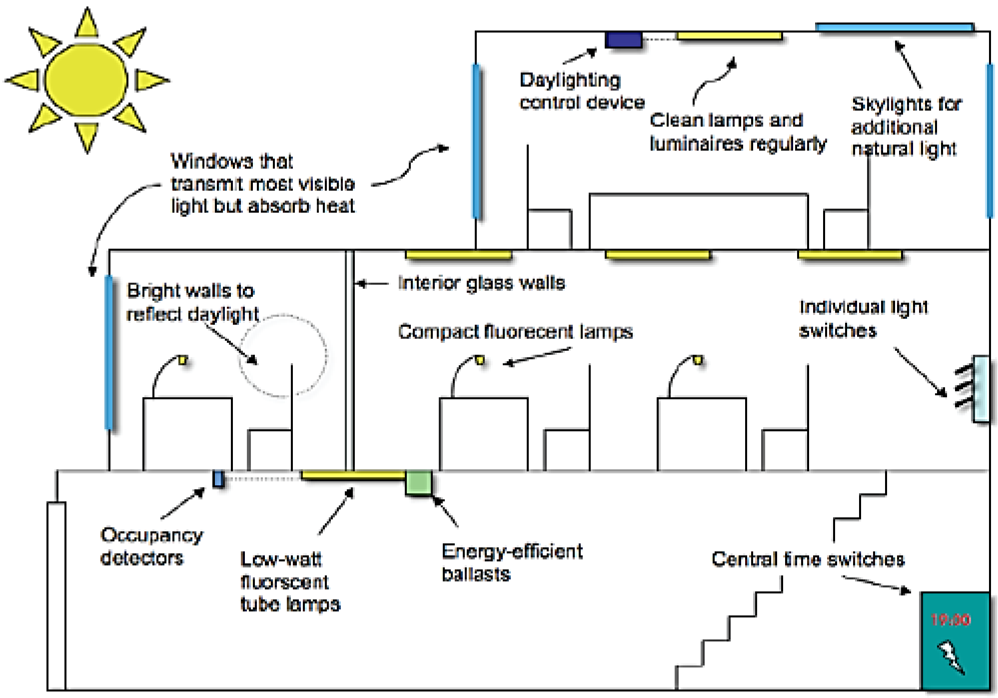
Annual energy loss = (1 - ILER) x watts x no. of operating hours
= (1 - 0.7) x 990 x 8 hrs/day x 300 days = 712 kWh/annum

Areas of Improvement

- Identify natural lighting opportunities such as windows and other openings
- For industrial lighting, explore the scope for introducing translucent sheets
- Assess scope for more energy efficient lamps and luminaries
- Assess scope for rearrangement of lighting fixtures

21.6 General Energy Saving Opportunities

Changing the light bulbs is not the only way to improve the use of lighting. Below are some examples of many other options available:



a) Use natural day lighting

The utility of using natural day lighting instead of electric lighting during the day is well known, but is being increasingly ignored especially in modern air-conditioned office spaces and commercial establishments like hotels, shopping plazas etc. Industrial plants generally use daylight in some fashion, but improperly designed day lighting systems can result in complaints from personnel or supplementary use of electric lights during daytime.

Some of the methods to incorporate day lighting are:

i. North lighting by use if single-pitched truss of the saw-tooth type is a common industrial practice; this design is suitable for latitudes north of 23 i.e. in North India. In South India, north lighting may not be appropriate unless diffusing glasses are used to cut out the direct sunlight.
ii. Innovative designs are possible which eliminates the glare of daylight and blend well with the interiors. Glass strips, running continuously across the breadth of the roof at regular intervals, can provide good, uniform lighting on industrial shop floors and storage bays.
iii. A good design incorporating sky lights with FRP material along with transparent or translucent false ceiling can provide good glare-free lighting; the false ceiling will also cut out the heat that comes with natural light.
iv. Use of atrium with FRP dome in the basic architecture can eliminate the use of electric lights in passages of tall buildings.
v. Natural Light from windows should also be used. However, it should be well designed to avoid glare. Light shelves can be used to provide natural light without glare.
vi. Mounting Solar tube on the roof, with the help of advanced optics and special duct work to direct sunlight deep into the buildings and spreading out over large internal spaces providing heat and glare free day lighting for 8-10 hrs in a day

b) De-lamping to reduce excess lighting

De—lamping is an effective method to reduce lighting energy consumption. In some industries, reducing the mounting height of lamps, providing efficient luminaires and then de-lamping has ensured that the illuminance is hardly affected. De—lamping at empty spaces where active work is not being performed is also a useful concept.

c) Task lighting

Task Lighting implies providing the required good illuminance only in the actual small area where the task is being performed, while the general illuminance of the shop floor or office is kept at a lower level; e. g. Machine mounted lamps or table lamps. Energy saving takes place because good task lighting can be achieved with low wattage lamps. The concept of task lighting if sensibly implemented, can reduce the no of general lighting fixtures, reduce the wattage of lamps, save considerable energy and provide better illuminance and also provide aesthetically pleasing ambience.

d) Selection of high efficiency lamps and luminaries

The details of common types of lamps are summarised in Table 8.1 above. It is possible to identify energy saving potential for lamps by replacing with more efficient types. The following examples of lamp replacements are common. There may be some limitations if colour rendering is an important factor. It may be noted that, in most cases, the luminaires and the control gear would also have to be changed. The savings are large if the lighting scheme is redesigned with higher efficacy lamps and luminaires.

e) Reduction of lighting feeder voltage

Figure 21.15 shows the effect of variation of voltage on light output and power consumption for fluorescent tube lights. Similar variations are observed on other gas discharge lamps like mercury vapour lamps, metal halide lamps and sodium vapour lamps (Table 8.3 summarises the effects). Hence reduction in lighting feeder voltage can save energy, provided the drop in light output is acceptable.

In many areas, night time grid voltages are higher than normal; hence reduction in voltage can save energy and also provide the rated light output. Some manufacturers are supplying reactors and transformers as standard products. A large number of industries have used these devices and have reported saving to the tune of 5% to 15%. Industries having a problem of higher night time voltage can get an additional benefit of reduced premature lamp failures.

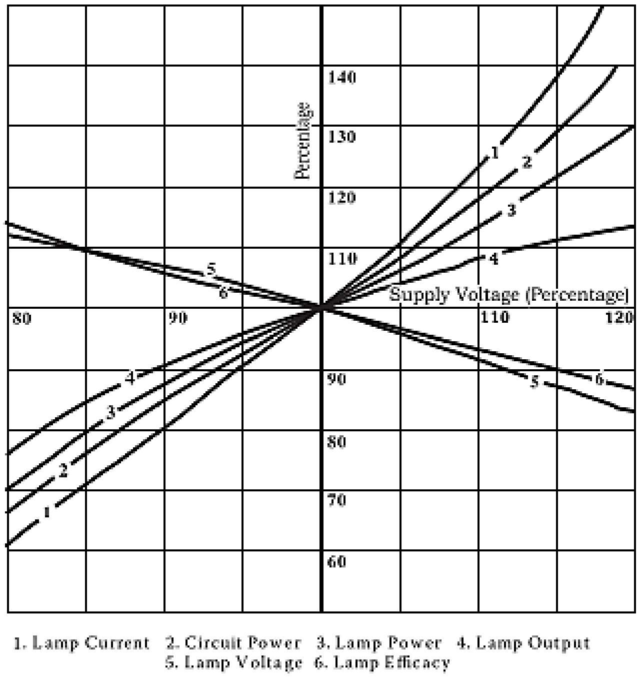


Figure 21.15 Effect of Voltage Variation on Fluorescent Tube light Parameters

Table 21.3 Variation in Light Output and Power Consumption

Particulars	10% lower voltage	10% higher voltage
Fluorescent lamps		
Light output	Decreases by 9 %	Increases by 8 %
Power input	Decreases by 15 %	Increases by 8 1%
HPMV lamps		
Light output	Decreases by 20 %	Increases by 20 %
Power input	Decreases by 16 %	Increases by 17 %
Mercury Blended lamps		
Light output	Decreases by 24 %	Increases by 30 %
Power input	Decreases by 20 %	Increases by 20 %
Metal Halide lamps		

f) Electronic ballasts

Conventional electromagnetic ballasts (chokes) are used to provide higher voltage to start the tube light and subsequently limit the current during normal operation. Electronic ballasts are oscillators that convert the supply frequency to about 20,000 Hz to 30,000 Hz. The basic functions of electronic ballast are:

- To ignite the lamp
- To stabilize the gas discharge
- To supply the power to the lamp

The losses in electronic ballasts for tube lights are only about 1 Watt, in place of 10 to 15 Watts in standard electromagnetic chokes.
The additional advantage is that the efficacy of tube lights improves at higher frequencies, resulting in additional savings if the ballast is optimised to provide the same light output as with the conventional choke. Hence a saving of about 15 to 20 Watts per tube light can be achieved by use of electronic ballasts. With electronic ballast, the starter is eliminated and the tube light lights up instantly without flickering.

g) Lighting controllers

Automatic control for switching off unnecessary lights can lead to good energy savings. This includes dimmers, motion & occupancy sensors, photo sensors and timers.

h) Lighting maintenance

Maintenance is vital to lighting efficiency. Light levels decrease over time because of aging lamps and dirt on fixtures, lamps and room surfaces. Together, these factors can reduce total illumination by 50 percent or more, while lights continue drawing full power. The basic maintenance includes cleaning of lamps and fixtures, cleaning and repainting interiors, re-lamping etc.

21.7 Energy Efficient Lighting Controls

Occupancy Sensors

Occupancy-linked control can be achieved using infra-red, acoustic, ultrasonic or microwave sensors, which detect either movement or noise in room spaces. These sensors switch lighting on when occupancy is detected, and off again after a set time period, when no occupancy movement detected. They are designed to override manual switches and to prevent a situation where lighting is left on in unoccupied spaces. With this type of system, it is important to incorporate a built-in time delay, since occupants often remain still or quiet for short periods and do not appreciate being plunged into darkness if not constantly moving around.

Timed Based Control

Timed-turnoff switches are the least expensive type of automatic lighting control. In some cases, their low cost and ease of installation makes it desirable to use them where more efficient controls would be too expensive.

Types and features

The oldest and most common type of timed-turnoff switch is the “dial timer,” a spring-wound mechanical timer that is set by twisting the knob to the desired time. Typical units of this type are vulnerable to damage because the shaft is weak and the knob is not securely attached to the shaft. Some spring- wound units make an annoying ticking sound as they operate. Newer types of timed-turnoff switches are completely electronic and silent. Electronic switches can be made much more rugged than the spring-wound dial timer. These units typically have a spring-loaded toggle switch that turns on the circuit for a pre-set time interval. Some electronic models provide a choice of time intervals, which you select by adjusting a knob located behind the faceplate. Most models allow occupants to turn off the lights manually. Some models allow occupants to keep the lights on, overriding the timer. Timed-turnoff switches are available with a wide range of time spans. The choice of time span is a compromise. Shorter time spans waste less energy but increase the probability that the lights will turn off while someone is in the space. Dial timers allow the occupant to set the time span, but this is not likely to be done with a view toward optimising efficiency. For most applications, the best choice is an electronic unit that allows the engineering staff to set a fixed time interval behind the cover plate.

Daylight Linked Control

Photoelectric cells can be used either simply to switch lighting on and off, or for dimming. They may be mounted either externally or internally. It is however important to incorporate time delays into the control system to avoid repeated rapid switching caused, for example, by fast moving clouds. By using an internally mounted photoelectric dimming control system, it is possible to ensure that the sum of daylight and electric lighting always reaches the design level by sensing the total light in the controlled area and adjusting the output of the electric lighting accordingly. If daylight alone is able to meet the design requirements, then the electric lighting can be turned off. The energy saving potential of dimming control is greater than a simple photoelectric switching system. Dimming control is also more likely to be acceptable to room occupants.

Localized Switching

Localized switching should be used in applications which contain large spaces. Local switches give individual occupants control over their visual environment and also facilitate energy savings. By using localized switching, it is possible to turn off artificial lighting in specific areas, while still operating it in other areas where it is required, a situation which is impossible if the lighting for an entire space is controlled from a single switch.

Street Lighting Systems and Controls

Street lighting /Public lighting is one of the major electrical loads in municipal areas. Number of street lights used in a Municipal area varies from 20000 — 50000 in numbers depending on the kilometres of road illuminated within the municipal limits. Typical electrical load of municipal lighting system varies 2MW to 7 MW. The type of lamps used in Municipal area includes Fluorescent Tube light/ Mercury Vapor Lamps/ Sodium Vapor Lamps and Metal Halide Lamps. High Mast towers are also used at strategic junctions in the Municipal area. LEDs are also used for traffic signalling purpose in municipal areas.

Following controls are adopted to reduce energy consumption in street lighting system:

1. Timer control (Switch ON/OFF as per set timing)
2. Day light control(Based on illumination level)
3. Selective switching/alternate switching of street lights low traffic density areas (after midnight).
4. Switching control based on lux levels. (after midnight)
5. Installations of Voltage controllers to be operated after midnight.
6. Installation of PLC controlled Lighting panels for effective control and monitoring.

21.8 Lighting Case Study

Replacement of existing T12 Fluorescent lamps in street lighting system with LED lamps

Existing: Fluorescent lamp (T12) fixture of40 numbers is connected to the entire campus for security purpose. All the lights remain in operation for around 12 hours at night (6 pm. to 6 am) every day throughout the year. All the light fixtures are equipped with electromagnetic ballast which consumes around 12 to 14 watts of additional power while in operation. Hence the power consumption of a single fluorescent light fixture considering minimum ballast loss is 40+12=52 watts. The total light output of all the fluorescent light fixtures is around 2400 lumen.

Proposed: It was proposed to replace existing lamps with high efficient LED lamps of 18 W with a luminous efficacy of around 120-140 lm/w. The total luminous output of these lamps is around 2340 lumen.

Calculation

Existing Fittings			
No of FTL-T12 lamps installed	=	40	No's
Wattage Consumed			
40 No's of (40W+12W (Ballast)=52 W)	=	2.1	kW
Average operating hours per day	=	12	hrs/day

Total energy consumed by operating the lights	=	25	kWh/day
Annual energy consumption by operating the lights (365 days/year)	=	9125	kWh/annum
Proposed option			
Replacement of all 40 no's of 40 Watts T12-FTL with 18 Watts LED lamps			
Total energy consumed by operating with LED	=	0.72	kW
Average operating hours per day	=	12	hrs/day
Total kWh/day consumed by operating the lights	=	9	kWh/day
Annual energy consumption by operating the lights (365 days/year)	=	3285	kWh/annum
Savings			
Total energy reduction per annum	=	5840	kWh/annum
Annual monetary savings (@ BDT 5/unit)	=	***29,200***	BDT/annum
Investment @ BDT 2500/ Lamp	=	1.0	Lakhs
Simple payback period	=	3.4	Years

CHAPTER 22: HVAC & REFRIGERATION SYSTEM

22.1 Introduction

The Heating, Ventilation and Air Conditioning (HVAC) and refrigeration system transfers the heat energy from or to the products, or building environment. Energy in form of electricity or heat is used to power mechanical equipment designed to transfer heat from a colder, low-energy level to a warmer, high-energy level.

Refrigeration deals with the transfer of heat from a low temperature level at the heat source to a high temperature level at the heat sink by using a low boiling refrigerant.

There are several heat transfers loops in refrigeration system as described below:

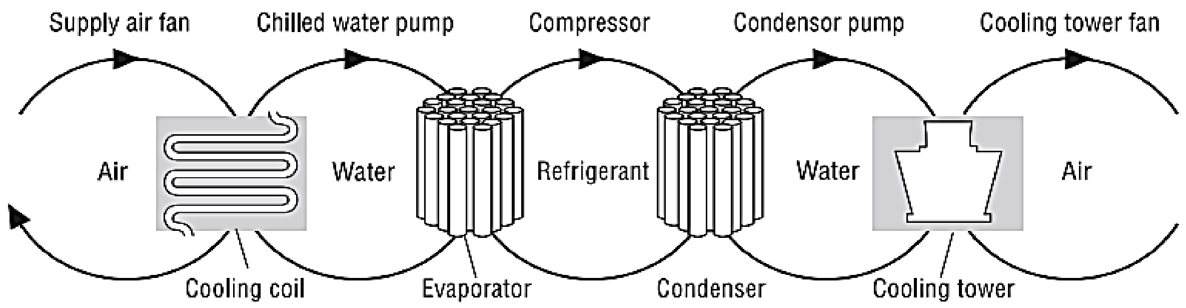


Figure 22.1: Heat Transfer Loops in Refrigeration System

In the Figure 22.1, thermal energy moves from left to right as it is extracted from the space and expelled into the outdoors through five loops of heat transfer:

Indoor air loop. In the leftmost loop, indoor air is driven by the supply air fan through a cooling coil, where it transfers its heat to chilled water. The cool air then cools the building space.

Chilled water loop. Driven by the chilled water pump, water returns from the cooling coil to the chiller's evaporator to be re-cooled.

Refrigerant loop. Using a phase-change refrigerant, the chiller's compressor pumps heat from the chilled water to the condenser water.

Condenser water loop. Water absorbs heat from the chiller's condenser, and the condenser water pump sends it to the cooling tower.

Cooling tower loop. The cooling tower's fan drives air across an open flow of the hot condenser water, transferring the heat to the outdoors.

22.2 Psychometrics and Air-Conditioning Processes

Psychometrics is the science of moist air properties and processes, which is used to illustrate and analyse air-conditioning cycles. It translates the knowledge of heating or cooling loads (which are in kW or tons) into volume flow rates (in m^3/s or cfm) for the air to be circulated into the duct system.

Water vapor is lighter than dry air. The amount of water vapor that the air can carry increases with its temperature. Any amount of moisture that is present beyond what the air can carry at the prevailing temperature can only exist in the liquid phase as suspended liquid droplets (if the air temperature is above the freezing point of water), or in the solid state as suspended ice crystals (if the temperature is below the freezing point).

The most commonly used psychrometric quantities include the dry and wet bulb temperatures, dew point, specific humidity, relative humidity.

Psychrometric Chart:

Psychrometric chart (Figure 22.2) is a chart indicating the psychrometric properties of air such as dry-bulb temperature, wet-bulb temperature, specific humidity, enthalpy of air in kJ/kg dry air, specific volume of air in 111 m^3/kg and relative humidity ø in %. It helps in quantifying and understanding air conditioning process.

Example 22.1

Assume that the outside air temperature is 32°C with a relative humidity of ø = 60%. Use the psychrometric chart to determine the air properties. See Figure 22.2.

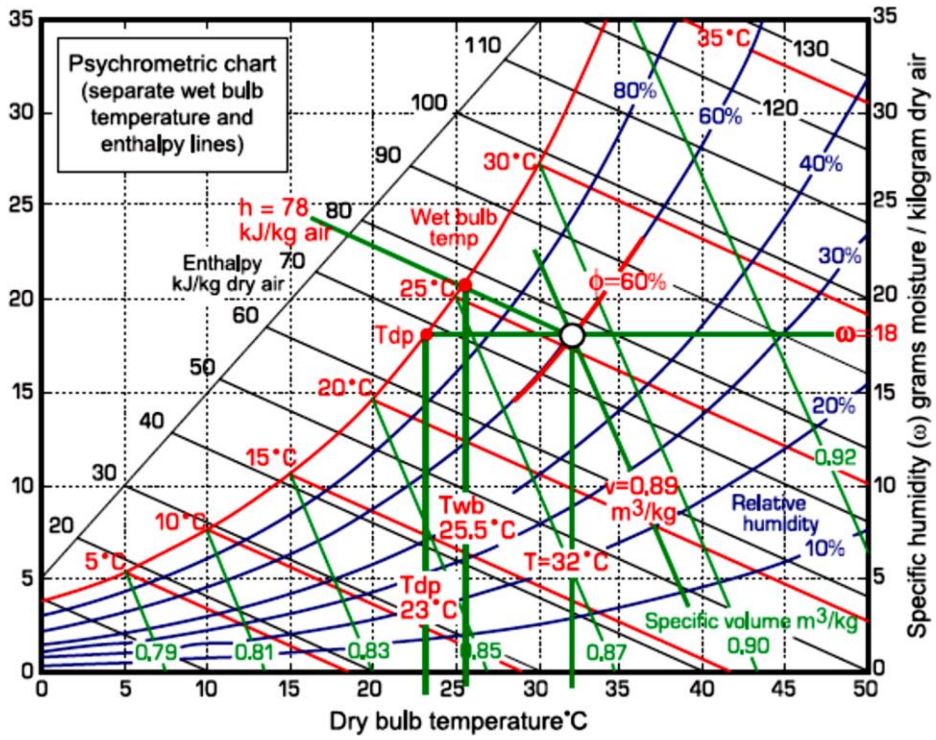


Figure 22.2 Properties of Air at 32°C Dry Bulb Temperature and RH of 60%

Solution

Air properties of air at 32°C dry bulb temperature and RH of 60 %

Specific humidity, $\acute{\omega}$	=	18 gm-moisture/kg-air
Enthalpy, h	=	78 kJ/kg-air
Wet-bulb temperature, T_{wb}	=	25.5°C
Dew-point temperature, T_{dp}	=	23°C
The specific volume of the dry air, v	=	0.89m3/kg

Comfort Zone

One of the major applications of the Psychrometric Chart is in air conditioning, and we find that most humans feel comfortable when the temperature is between 22°C and 27°C, and the relative humidity ϕ between 40% and 60%. This defines the "comfort zone" which is portrayed on the Psychrometric Chart as shown in Figure 22.3. Thus, with the aid of the chart we either heat or cool, add moisture or dehumidify as required in order to bring the air into the comfort zone.

Example 22.2

Outside air at 35°C and 60% relative humidity is to be conditioned by cooling and reheating so as to bring the air to the "comfort zone" with the exit temperature of 24°C and 53% RH. Using the Psychrometric Chart neatly plot the required air conditioning process and estimate

(a) the amount of moisture removed, (b) the heat removed, and (c) the amount of heat added.
See Figure 22.3.

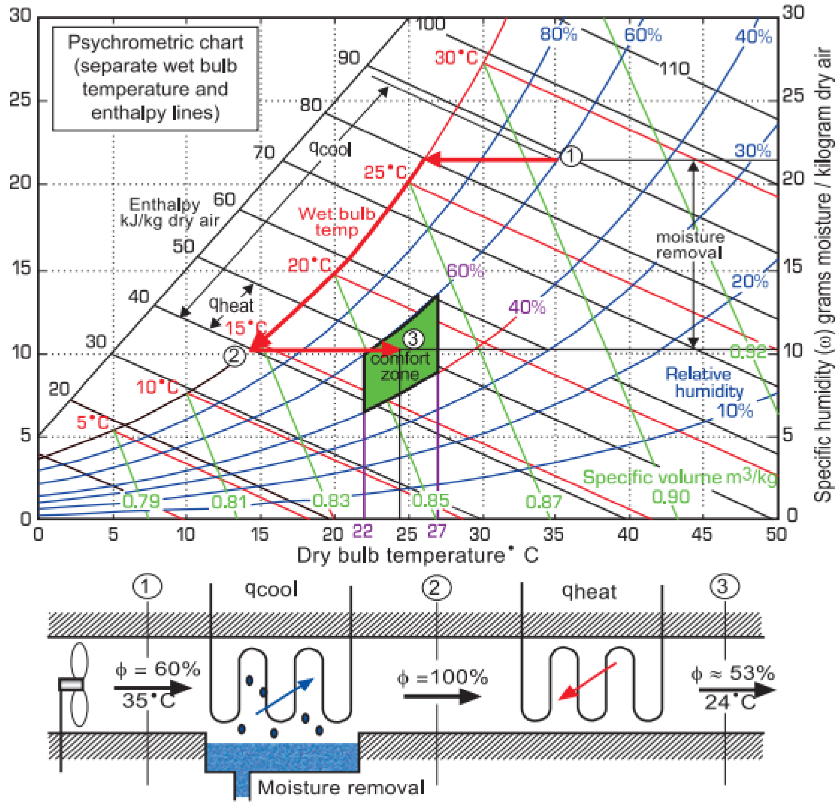


Figure-22.3: Properties of Air

Solution
Using the Figure 22.3

a) The amount of moisture removed = 11.5g-H_20 /kg-dry-air
b) The heat removed = (1)-(2), q_{cool}= 48 kJ/kg-dry-air

The amount of heat added = (2)-(3), q_{heat} = 10 kJ/kg-dry-air Air-

Conditioning Systems

Depending on applications, there are several options / combinations, which are available for use as given below:

- Air Conditioning (for comfort / machine)
- Split air conditioners
- Fan coil units in a larger system
- Air handling units in a larger system Refrigeration Systems (for processes)

•Small capacity modular units of direct expansion type similar to domestic refrigerators, small capacity refrigeration units.

•Centralized chilled water plants with chilled water as a secondary coolant for temperature range over 5 °C typically. They can also be used for ice bank formation.

•Brine plants, which use brines as lower temperature, secondary coolant, for typically sub-zero temperature applications, which come as modular unit capacities as well as large centralized plant capacities.

•The plant capacities up to 50 TR are usually considered as small capacity, 50 - 250 TR as medium capacity and over 250 TR as large capacity units.

A large industry may have a bank of such units, often with common chilled water pumps, condenser water pumps, cooling towers, as an offsite utility. The same industry may also have two or three levels of refrigeration & air conditioning such as:

- Comfort air conditioning (20 - 25 °C)
- Chilled water system (8 - 10 °C)
- Brine system (sub-zero applications)

Two principal types of refrigeration plants found in industrial use are: Vapour Compression Refrigeration (VCR) and Vapour Absorption Refrigeration (VAR). VCR uses mechanical energy as the driving force for refrigeration, while VAR uses thermal energy as the driving force for refrigeration.

22.3 Types of Refrigeration System

Vapour Compression Refrigeration

Heat flows naturally from a hot to a colder body. In refrigeration system the opposite must occur i.e. heat flows from a cold to a hotter body. This is achieved by using a substance called a refrigerant, which absorbs heat and hence boils or evaporates at a low pressure to form a gas. This gas is then compressed to a higher pressure, such that it transfers the heat it has gained to ambient air or water and turns back (condenses) into a liquid. In this way heat is absorbed, or removed, from a low temperature source and transferred to a higher temperature source.

The refrigeration cycle can be broken down into the following stages (see Figure 22.4):

1- 2 Low pressure liquid refrigerant in the evaporator absorbs heat from its surroundings, usually air, water or some other process liquid. During this process it changes its state from a liquid to a gas, and at the evaporator exit is slightly superheated.

2 - 3 The superheated vapour enters the compressor where its pressure is raised. There will also be a big increase in temperature, because a proportion of the energy input into the compression process is transferred to the refrigerant.

3 - 4 The high pressure superheated gas passes from the compressor into the condenser. The initial part of the cooling process (3 - 3a) de-super heats the gas before it is then turned back into liquid (3a - 3b). The cooling for this process is usually achieved by using air or water. A further reduction in temperature happens in the pipe work and liquid receiver (3b - 4), so that the refrigerant liquid is sub-cooled as it enters the expansion device.

4 -1 The high-pressure sub-cooled liquid passes through the expansion device, which both reduces its pressure and controls the flow into the evaporator.

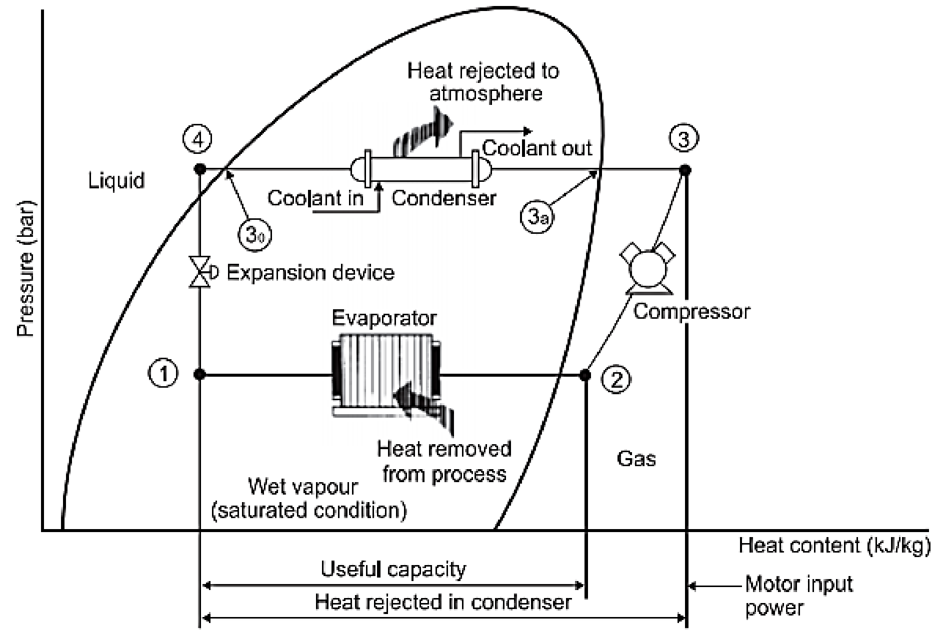


Figure 22.4: Schematic of a Basic Vapour Compression Refrigeration System

It can be seen that the condenser has to be capable of rejecting the combined heat inputs of the evaporator and the compressor; i.e. (1 - 2) + (2 - 3) has to be the same as (3 - 4). There is no heat loss or gain through the expansion device.

Alternative Refrigerants for Vapour Compression Systems

The use of CFCs is phased out due to their damaging impact on the protective tropospheric ozone layer around the earth. The Montreal Protocol of 1987 and the subsequent Copenhagen agreement of 1992 mandate a reduction in the production of ozone depleting Chlorinated Fluorocarbon (CFC) refrigerants in a phased manner, with an eventual stop to all production by the year 1996. As part of the accelerated phase-out of CFCs, India has completely phased out CFCs by 1st August. 2008.

In response, the refrigeration industry has developed two alternative refrigerants; one based on Hydrochloro Fluorocarbon (HCFC), and another based on Hydro Fluorocarbon (HFC). The HCFCs have a 2 to 10% ozone depleting potential as compared to CFCs and also, they have an atmospheric lifetime between 2 to 25 years as compared to 100 or more years for CFCs (Brandt, 1992). However, even HCFCs are mandated to be phased out, and only the chlorine free (zero ozone depletion) HFCs would be acceptable.

The 19th MOP (Meeting of Parties) took a decision to accelerate the phase-out of HCFC production and consumption for developed and developing countries. The new phase-out schedule for Article 5 parties as per the decision taken at the 19th MOP is as follows:

Base-level for production & consumption: the average of 2009 and 2010
Freeze= 2013 at the base-level
10% reduction in 2015
35% reduction in 2020
67.5% reduction in 2025

100% reduction in 2030 with a service tail of 2.5% annual average during the period 2030-2040(Source: Ministry of Environment and Forest, Ozone Cell)

Until now, only one HFC based refrigerant, HFC 134a, has been developed. HCFCs are comparatively

Absorption Refrigeration

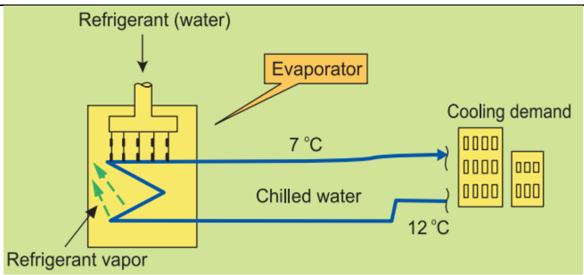
The absorption chiller is a machine, which produces chilled water by using heat such as steam, hot water, gas, oil etc. Chilled water is produced by the principle that liquid (refrigerant), which evaporates at low temperature, absorbs heat from surrounding when it evaporates. Pure water is used as refrigerant and lithium bromide solution is used as absorbent

Heat for the vapour absorption refrigeration system can be provided by waste heat extracted from process, diesel generator sets etc. Absorption systems require electricity to run pumps only. Depending on the temperature required and the power cost, it may even be economical to generate heat / steam to operate the absorption system.

Description of the absorption refrigeration concept is given below:

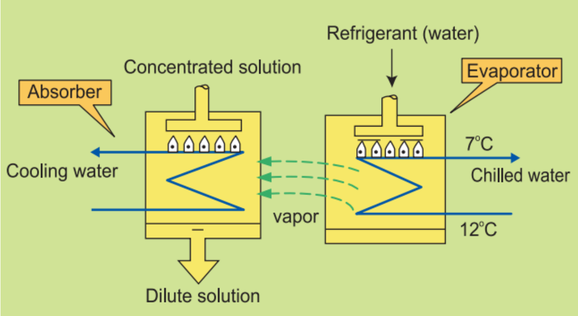
The refrigerant (water) evaporates at around 4 °C under the high vacuum condition of 754 mmHg in the evaporator. When the refrigerant (water) evaporates, the latent heat of vaporization takes the heat from incoming chilled water.

This latent heat of vaporization can cool the chilled water which runs into the heat exchanger tubes in the evaporator by transfer of heat to the refrigerant (water).



EVAPORATOR

In order to keep evaporating, the refrigerant vapor must be discharged from the evaporator and refrigerant (water) must be supplied. The refrigerant vapor is absorbed into lithium bromide solution which is convenient to absorb the refrigerant vapor in the absorber. The heat generated in the absorption process is led out of system by cooling water continually. The absorption also maintains the vacuum inside the evaporator.

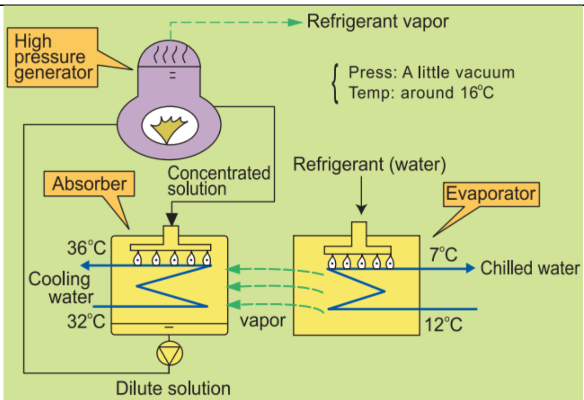


ABSORBER

As lithium bromide solution is diluted, the effect to absorb the refrigerant vapor reduces. In order to keep absorption process, the diluted lithium bromide solution must be made concentrated lithium bromide.

Absorption chiller is provided with the solution concentrating system by the heating media such as steam, hot water, gas, oil, which performs such function is called generator.

The concentrated solution flows into the absorber and absorbs the refrigerant vapor again.



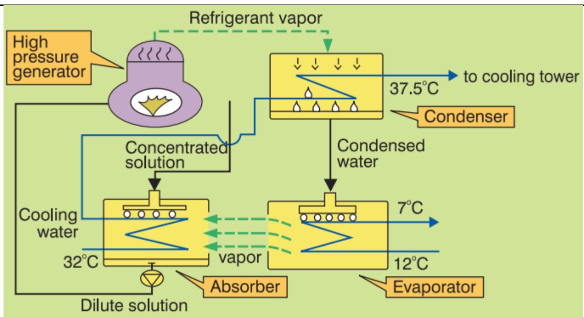
HIGH PRESSURE GENERATOR

In order to carryout above works continually and to make complete cycle, the following two functions are required.

1. To concentrate and liquefy the evaporated refrigerant vapor, which is generated in the high pressure generator.

2. To supply the condensed water to the evaporator as refrigerant (water).

For this function, condenser is installed.



CONDENSER

A typical schematic of the absorption refrigeration system is given in the Figure 22.5.

Li-Br-water absorption refrigeration systems have a Coefficient of Performance (COP) in the range of 0.65 - 0.70 and can provide chilled water at 6.7 °C with a cooling water temperature of 30 °C. Systems capable of providing chilled water at 3 °C are also available. Ammonia based systems operate at above atmospheric pressures and are capable of low temperature operation (below 0°C). Absorption machines of capacities in the range of 10-1500 tons are available. Although the initial cost of absorption system is higher than compression system, operational cost is much lower-if waste heat is used.

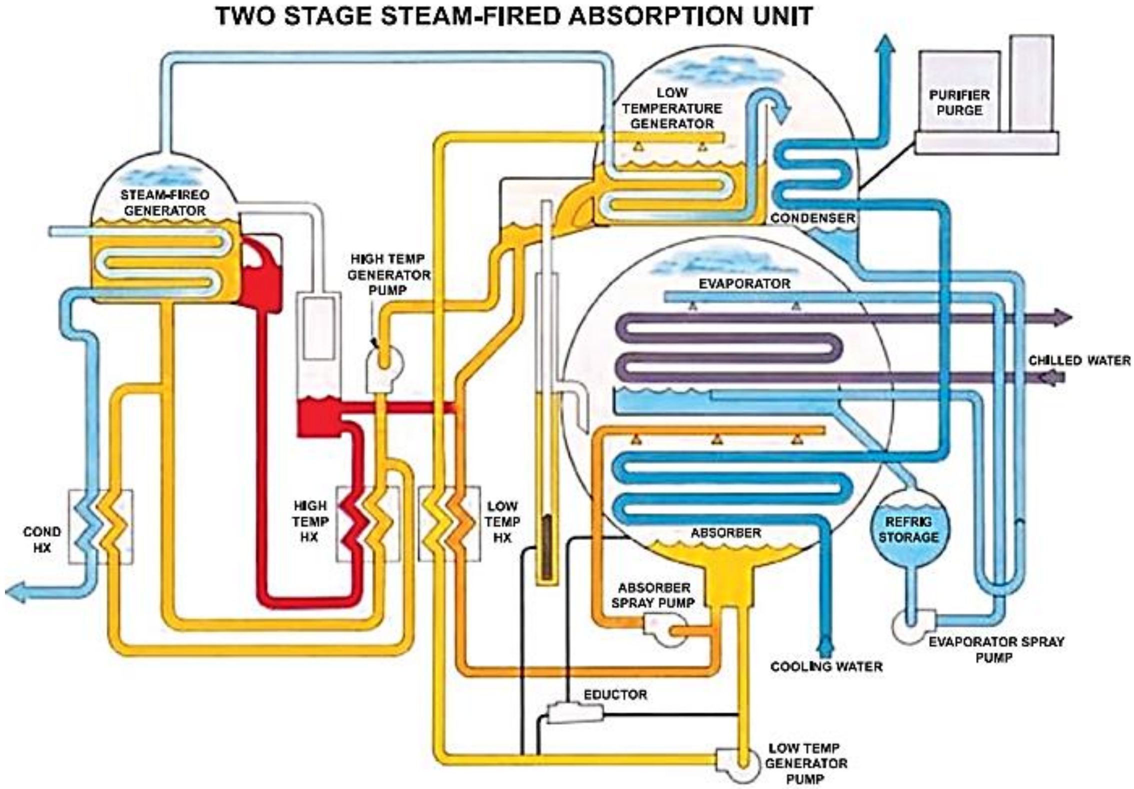


Figure 22.5: Schematic of Absorption Refrigeration System

Evaporative Cooling

There are occasions where air conditioning, which stipulates control of humidity up to 50 % for human comfort or for process, can be replaced by a much cheaper and less energy intensive evaporative cooling.

The concept is very simple and is the same as that used in a cooling tower. Air is brought in close contact with water to cool it to a temperature close to the wet bulb temperature. The cool air can be used for comfort or process cooling. The disadvantage is that the air is rich in moisture. Nevertheless, it is an extremely efficient means of cooling at very low cost. Large commercial systems employ cellulose filled pads over which water is sprayed. The temperature can be controlled by controlling the airflow and the water circulation rate. The possibility of evaporative cooling is especially attractive for comfort cooling in dry regions. This principle is practiced in textile industries for certain processes.

22.4 Common Refrigerants and Properties

A variety of refrigerants are used in vapor compression systems. The choice of fluid is determined largely by the cooling temperature required. Commonly used refrigerants are in the family of chlorinated fluorocarbons (CFCs, also called Freons): R-11, R-12, R-21, R-22 and R-502. The properties of these refrigerants are summarized in Table 22.1 and the performance of these refrigerants is given in Table 22.2.

Table 22.1 Properties of Commonly used Refrigerants

Refrigerant	Boiling Point ** (°C)	Freezing Point (°C)	Vapor Pressure * (kPa)	Vapor Volume * (m^3 / kg)	Enthalpy *	
					Liquid (kJ / kg)	Vapor (kJ / kg)
R - 11	-23.82	-111.0	25.73	0.61170	191.40	385.43
R - 12	-29.79	-158.0	219.28	0.07702	190.72	347.96
R - 22	-40.76	-160.0	354.74	0.06513	188.55	400.83
R - 502	-45.40	---	414.30	0.04234	188.87	342.31
R - 7 (Ammonia)	-33.30	-77.7	289.93	0.41949	808.71	487.76

* At -10 °C ** At Standard Atmospheric Pressure (101.325 kPa)

*Table 22.2 Performance of Commonly used Refrigerants**

Refrigerant	Evaporating Press (kPa)	Condensing Press (kPa)	Pressure Ratio	Vapor Enthalpy (kJ / kg)	COP^{**}_{cam}
R - 11	20.4	125.5	6.15	155.4	5.03
R - 12	182.7	744.6	4.08	116.3	4.70
R - 22	295.8	1192.1	4.03	162.8	4.66
R - 502	349.6	1308.6	3.74	106.2	4.37
R - 717	236.5	1166.5	4.93	103.4	4.78

* At -15 °C Evaporator Temperature, and 30 °C Condenser Temperature
** COP_{carnot} = Coefficient of Performance = $Temp._{Evap.}$ / ($Temp._{Cond}$ -$TeMP_{Evap}$)

The choice of refrigerant and the required cooling temperature and load determine the choice of compressor, as well as the design of the condenser, evaporator, and other auxiliaries. Additional factors such as ease of maintenance, physical space requirements and availability of utilities for auxiliaries (water, power, etc.) also influence component selection.

22.5 Compressor Types and Application

For industrial use, open type systems (compressor and motor as separate units) are normally used, though hermetic systems (motor and compressor in a sealed unit) also find service in some low-capacity applications. Hermetic systems are used in refrigerators, air conditioners, and other low-capacity applications. Industrial applications largely employ reciprocating, centrifugal and, more recently, screw compressors, and scroll compressors. Water-cooled systems are more efficient than air-cooled alternatives because the temperatures produced by refrigerant condensation are lower with water than with air. The features of various refrigeration compressors and application criteria are given in the Table 22.3.

Table 22.3: Comparison of Different Types of Refrigeration Plants

(Source : ASHRAE & Vendor Information)

S. No.	Parameters	Vapour Compression Chillers			Vapour Absorption Chiller				
					LiBr				Ammonia
		Reciprocating	**Centrifugal**	**Screw**	**Single Effect**	**Double Effect**	**Half Effect**	**Triple Effect**	**Single Stage**
1	Refrigeration Temp. Range (Brine / Water)	+7 to -30°C	+7 to -0°C	+7 to -25°C	Above 6°C				Upto –33°C
2	Energy Input	Electricity	Electricity	Electricity	Heat (Steam / Hot Water / Hot Oil/ Direct Fired)	Heat (Steam / Hot Water / Hot Oil/ Direct Fired)	Heat (Hot Water)	Heat (Steam /Hot Oil / Direct Fired)	Heat (Steam/ Hot Water / Hot Oil)
3	Heat Input Temp. Range - Maximum -Minimum	-	-	-	Minimum 85°C	Minimum 130°C	Minimum 55°C	Minimum 190°C	Minimum 85°C
4	Typical Energy to TR Ratio								
	Air Conditioning Temp. Range	0.7-0.9 kW/TR	0.63kW/TR	0.65 kW/TR	5000 kcal/TR	2575 kcal/TR	7500 kcal/TR	2000 kcal/TR	4615 kcal/TR
	Subzero Temp. Range	1.25 to 2.5 kW/TR	—	1.25 to 2.5 kW/TR	—	—	—	—	6666 kcal/hr
5	Refrigerant	R11,R123,R134a Ammonia	R22, R12	R22, R134a Ammonia	Pure Water	Pure Water	Pure Water	Pure Water	Pure Ammonia
6	Absorbent	—	—	—	Water-LiBr solution	Water-LiBr solution	Water-LiBr solution	Water-LiBr solution	Ammonia-LiBr solution
7	Typical single unit capacity range								
	Air Condition temp. range	1-150 TR	300 TR & above	50-200 TR	30 TR & above	30 TR & above	30 TR & above	50 TR & above	30 TR & above
	Subzero temp. range	10-50 TR	—	50-200 TR	—	—	—	—	30 TR & above
8	Typical COP at Part Load up to 50%	Reduces at part load	Reduces at part load	Improves by 15-20%	Marginal Improvement at Part Load				No variation
9	Typical Internal Pressure Levels - Low -High Typical Internal Temp. Levels	0.15-0.40 bar a 1.20-1.50 bar a -25 to 50°C	2.5-3.5 bar a 11-12 bar -5 to 50°C	2-5.5 bar 18-20 bar -25 to 50°C	5-6 mm Hg (abs) 60-70 mm Hg (abs) +4 to 75°C	5-6 mm Hg (abs) 370-390 mm Hg (abs) +4 to +130°C	5-6 mm Hg (abs) 60-70 mm Hg (abs) +4 to 130°C	5-6 mm Hg (abs) 2 kg/cm^2 (a) +4 to 160°C	1.2kg/cm^2(a) 18 kg/cm2(a) -25 to +150°C

S. No.	Parameters	Vapour Compression Chillers			Vapour Absorption Chiller				
					LiBr				Ammonia
		Reciprocating	Centrifugal	Screw	Single Effect	Double Effect	Half Effect	Triple Effect	Single Stage
10	-Typical Cooling tower capacity range per 100 TR of chillers - Air-conditioning Temperature Range - Subzero temp. range	130 190	120 —	120 160	260 —	200 —	370 —	170 —	290 290
11	Typical Make-up water quantity range in Ltrs/Hr. -Air Conditioning temperature range -Subzero temp. range	672 983	620 —	620 830	1345 —	1035 —	1914 —	880 —	1500 1500
12	Material of construction -Generator	—	—	—	Cu-Ni or Stainless Steel				Carbon Steel
	-Absorber	—	—	—	Cu-Ni				Carbon Steel
	-Evaporator	Copper / Carbon steel	copper / Carbon steel	Copper/ Carbon steel	Cu-Ni				Carbon Steel
	-Condenser	Copper / Carbon steel	Copper / Carbon steel	Copper / Carbon steel	Cu-Ni				Carbon Steel
	-Solution Heat Exchange	—	—	—	Carbon Steel				Carbon Steel
	-Solution Pump	—	—	—	Cast Iron Hermatically Sealed (Canned motor type)				Cast Iron with Meh.Seal
	-Refrigerant pump	—	—	—	Cast Iron Hermatically Sealed (Canned motor type)				Not needed
13	Expected Life	25-30 years			15-20 years				50 years
14	Normally Expected Repairs / Maintenance	Periodic Compressor Overhaul Tube Replacement after 1-12 years			Tube Replacement due to Corrosion				Practically no repairs
15	Factory Assembled packaged Or Site Assembled	Factory Assembled							Factory Assembled upto 230 TR in A/C & subzero range
16	Beneficial Energy Sources	Low cost Electricity	Low cost Electricity	Low cost Electricity	a) Waste Heat b) Low cost steam / Low cost fuels				

S. No.	Parameters	Vapour Compression Chillers			Vapour Absorption Chiller				
					LiBr				Ammonia
		Reciprocating	Centrifugal	Screw	Single Effect	Double Effect	Half Effect	Triple Effect	Single Stage
17	Critical Parameters	-Electricity supply	-Lubrication System -Compressor Operation & Maintenance -Electrical Power Panel Maintenance	--	a) Vacuum in Chiller b) Purge System for Vacuum c) Corrosion Inhibitors in Absorbent d) Surfactants in Absorbent e) Cooling Water Treatment f) Cooling Water Temperature g) Heat Source Temperature				Sudden Power failure for 45-60 min. or more can disturb the distillation column for continuous operation. Needs D.G. set if there is frequent power failure for periods longer than 30 min.

22.6 Performance Assessment of Refrigeration Plants

The cooling effect produced is quantified as tons of refrigeration (TR).

1 TR of refrigeration = 3024 kcal/hr heat rejected. The refrigeration TR is assessed as

$TR = Q\ C_p\ (T_i — T_o) / 3024$

Where,
Q is mass flow rate of coolant in kg/hr
C_P is coolant specific heat in kcal /kg ºC
T_i is inlet, temperature of coolant to evaporator (chiller) in °C
T_o is outlet temperature of coolant from evaporator (chiller) in °C The above TR is also called as chiller tonnage.

The specific power consumption kW/TR is a useful indicator of the performance of refrigeration system. By measuring refrigeration duty performed in TR and the kilowatt inputs, kW/TR is used as a reference energy performance indicator.

In a centralized chilled water system, apart from the compressor unit, power is also consumed by the chilled water (secondary) coolant pump as well condenser water (for heat rejection to cooling tower) pump and cooling tower fan in the cooling tower. Effectively, the overall energy consumption would be towards:

- Compressor kW
- Chilled water pump kW
- Condenser water pump kW
- Cooling tower fan kW, for induced / forced draft towers

The specific power consumption for certain TR output would therefore have to include:

- Compressor kW/TR
- Chilled water pump kW/TR
- Condenser water pump kW/TR
- Cooling tower fan kW/TR

The overall kW/TR is the sum of the above.
The theoretical Coefficient of Performance (Carnot), COP_{carnot} - a standard measure of refrigeration efficiency of an ideal refrigeration system- depends on two key system temperatures, namely, evaporator temperature T_e and condenser temperature T with COP being given as:

$COP_{carnot} = T_e / (T_c - T_e)$

This expression also indicates that higher COP_{carnot} is achieved with higher evaporator temperature and lower condenser temperature.

But COP_{carnot} is only a ratio of temperatures, and hence does not take into account the type of compressor. Hence the COP normally used in the industry is given by

$$COP = \frac{\text{Cooling effect (kW)}}{\text{Power input to compressor (kW)}}$$

Where the cooling effect is the difference in enthalpy across the evaporator and expressed as kW. The effect of evaporating and condensing temperatures are given in the Figure 22.6 and Figure 22.7 below:

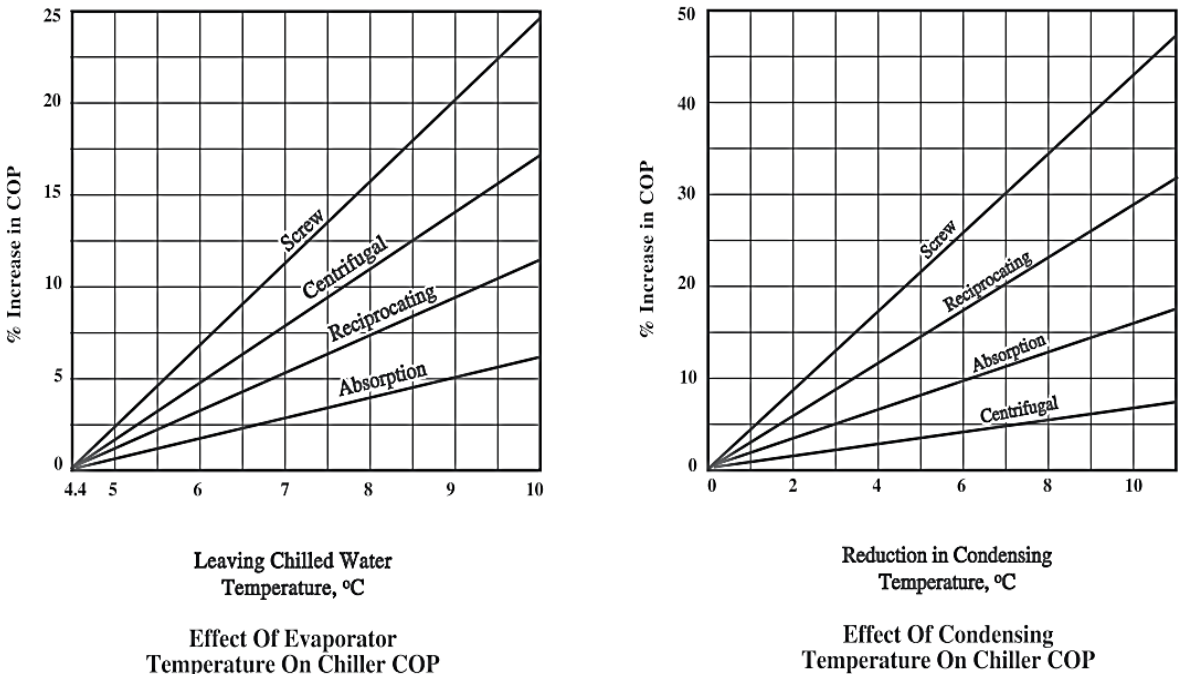


Figure 22.6 & 22.7 Effect of Evaporator and Temperature on Chiller COP

In the field performance assessment, accurate instruments for inlet and outlet chilled water temperature and condenser water temperature measurement are required, preferably with a least count of 0.1°C. Flow measurements of chilled water can be made by an ultrasonic flow meter directly or inferred from pump duty parameters. Adequacy check of chilled water is needed often and most units are designed for a typical 0.68 m^3/hr per TR (3 gpm/TR) chilled water flow. Condenser water flow measurement can also be made by a non-contact flow meter directly or inferred from pump duty parameters. Adequacy check of condenser water is also needed often, and most units are designed for a typical 0.91 m^3/hr per TR (4 gpm / TR) condenser water flow.

In case of air conditioning units, the airflow at the Fan Coil Units (FCU) or the Air Handling Units (AHU) can be measured with an anemometer. Dry bulb and wet bulb temperatures are measured at the inlet and outlet of AHU or the FCU and the refrigeration load in TR is assessed as;

$$TR = \frac{Q \times \rho \times (h_{in} - h_{out})}{3024}$$

Where,
Q is the air flow in m^3/h
ρ is density of air kg/m^3
h_{in} is enthalpy of inlet air kcal/kg
h_{out} is enthalpy of outlet air kcal/kg

Use of psychrometric charts can help to calculate h_{in} and h_{our} from dry bulb, wet bulb temperature values which are, in-turn measured, during trials, by a whirling psychrometer.
Power measurements at, compressor, pumps, AHU fans, cooling tower fans can be accomplished by a portable load analyzer.

Estimation of air conditioning load is also possible by calculating various heat loads, sensible and latent based on inlet and outlet air parameters, air ingress factors, air flow, no. of people and type of materials stored.

An indicative TR load profile for air conditioning is presented as follows:

- Small office cabins = 0.1 TR /m^2
- Medium size office i.e., 10-30 people occupancy with central AC= 0.06 TR/ m^2
- Large multi-storeyed office complexes with central AC= 0.04 TR/ m^2

Integrated Part Load Value (IPLV)

Although the kW/ TR can serve as an initial reference, it should not be taken as an absolute since this value is derived from 100% of the equipment's capacity level and is based on design conditions that are considered the most critical. These conditions occur may be, for example, during only 1% of the total time the equipment is in operation throughout the year. Consequently, it is essential to have data that reflects how the equipment operates with partial loads or in conditions that demand less than 100% of its capacity. To overcome this, an average of kW/TR with partial loads i.e., Integrated Part Load Value (IPLV) have to be formulated.

The IPLV is the most appropriate reference, although not considered the best, because it only captures four points within the operational cycle: 100%, 75%, 50% and 25%. Furthermore, it assigns the same weight to each value, and most equipment usually operates at between 50 % and 75% of its capacity. This is why it is so important to prepare specific analysis for each case that addresses the four points already mentioned, as well as developing a profile of the heat exchanger's operations during the year.

System Design Features

In overall plant design, adoption of good practices improves the energy efficiency significantly. Some areas for consideration are:

- Design of cooling towers with FRP impellers and film fills, PVC drift eliminators, etc.
- Use of softened water for condensers in place of raw water.
- Use of economic insulation thickness on cold lines, heat exchangers, considering cost of heat gains and adopting practices like infrared thermography for monitoring - applicable especially in large chemical / fertilizer / process industry.
- Adoption of roof coatings / cooling systems, false ceilings / as applicable, to minimize refrigeration load.
- Adoption of energy efficient heat recovery devices like air-to-air heat exchangers to pre-cool the fresh air by indirect heat exchange; control of relative humidity through indirect heat exchange rather than use of duct heaters after chilling.
- Adopting of variable air volume systems; adopting of sun film application for heat reflection; optimizing lighting loads in the air-conditioned areas; optimizing number of air changes in the air-conditioned areas are few other examples.

22.7 Cold Storage Systems

A Refrigerated storage which includes cold storage and frozen food storage is the best-known method of preservation of food to retain its value and flavour.

The refrigeration system in a cold storage is usually a vapour compression system comprising the compressor, condenser, receiver, air cooling units and associate piping and controls.

In smaller cold rooms and walk-ins, the practice is to use air cooled condensing units with sealed, semi-sealed or open type compressors. In the light of the CFC phase out the trend now is to use HCFC22, HFC-134a or other substitute refrigerants. In the medium and large sized units, the practice is to use a central plant with ammonia as the refrigerant.

In some present day medium and large sized units with pre-fabricated (insulated) panel construction, the trend is to use modular HCFC-22/HFC units which are compact, lightweight and easy to maintain.

22.7.1 Energy Saving Opportunities in Cold Storage Systems:

Energy cost constitutes a major part of the running cost of a cold store. Apart from the problems of the availability of electrical energy, the ever-increasing rate of electrical energy seriously affects the economic viability of cold store units.

Following are some of the measures adopted to achieve energy efficient operation.

- Cold Store Building Design: Proper orientation, compact arrangement of chambers, shading of exposed walls, adequate insulation etc. are some of the important factors.
- Refrigeration System: The system must be designed for optimum operating conditions like evaporating and condensing temperatures, as these conditions have a direct bearing on energy consumption.
- Compressor capacity control system helps in energy savings during partial load operation.
- Control System: The proper control systems for refrigerant level, room temperature, compressor capacity etc., are required to further optimize energy consumption.
- Air Curtain or Strip Curtain: The use of air curtains and strip curtains is a common feature in present day cold stores as they help reduce air infiltration due to frequent and sometimes long door openings. Fan operated air curtains are expensive and work on electrical power whereas strip curtains are cheaper and need no energy for operation.
- Heat Recovery System: In processing plant cold stores, a heat reclaim system can be installed to recover a part of the heat rejected by the refrigeration system. This can be gainfully utilised in generating hot water free of cost.

22.8 Heat Pumps and their Applications

A heat pump is same as an air conditioner except that the heat rejected in an air conditioner becomes the useful heat output. Heat flows naturally from a higher to a lower temperature. Heat pumps, however, are able to force the heat flow in the other direction, using a relatively small amount of high-quality drive energy (electricity, fuel, or high-temperature waste heat). For the example shown in 22.8 the heat pump takes three units of energy from atmosphere and with an additional one unit by way of compressor work is able to provide four units of energy at a higher temperature. Thus, heat pumps can transfer heat from natural heat sources in the surroundings, such as the air, ground or water, or from man-made heat sources such as industrial or domestic waste, to a building or an industrial application.

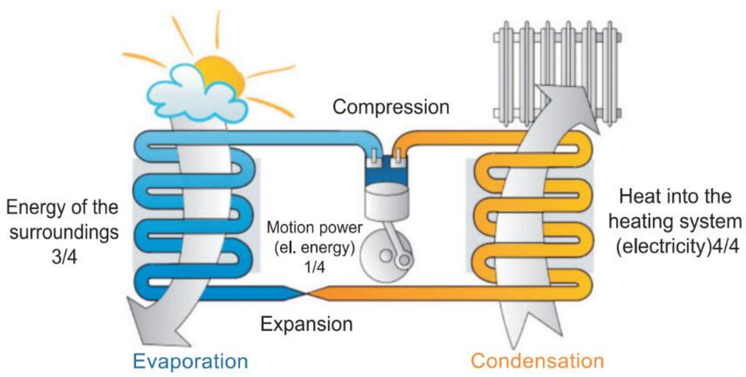


Figure 22.8: Heat Pump

In order to transport heat from a heat source to a heat sink, external energy is needed to drive the heat pump.

Theoretically, the total heat delivered by the heat pump is equal to the heat extracted from the heat source, plus the amount of drive energy supplied. Electrically-driven heat pumps for heating buildings typically supply 100 kWh of heat with just 20-40 kWh of electricity. Many industrial heat pumps can achieve even higher performance, and supply the same amount of heat with only 3-10 kWh of electricity. The principle of operation of heat pump is shown in the Figure 22.9.

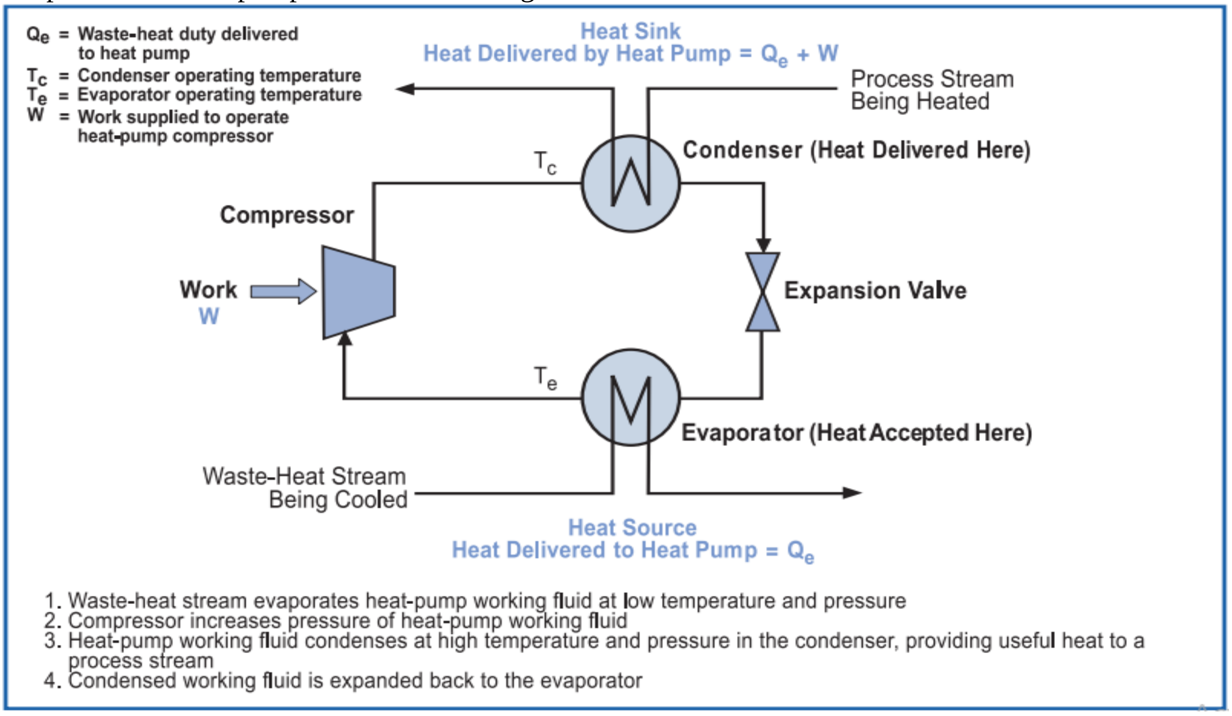


Figure 22.9 Principle of Operation

Heat Pump Applications

Industrial heat pumps are mainly used for:
- Space heating
- Heating of process streams
- Water heating for washing, sanitation and cleaning
- Steam production
- Drying/dehumidification
- Evaporation
- Distillation
- Concentration

When heat pumps are used in drying, evaporation and distillation processes, heat is recycled within the process. For heating of the space, process streams and steam production, the heat pumps utilise (waste) heat sources between 20°C and 100°C.

22.9 Ventilation Systems

Ventilation can be simply described as air circulation, the extraction of stale, overheated and contaminated air and supply and distribution of fresh air in amounts necessary to provide healthy and comfortable conditions for the occupants of the room. The ventilation effectiveness is dictated by number of Air Changes per Hour (ACH). The number air changes depend on the purpose and function. Typical air changes are given in Table 22.4 for various operations.

Table 22.4 Typical Air Changes per Hour

Location	Air changes per hour

Boiler room	15 - 30
Compressor room	10 - 12
Conference rooms	10-20
Engine rooms	15 - 30
Lavatories	6 - 15
Offices	6 - 10
Welding shops	15 - 30

Calculation of ventilation rate: If the compressor room size is 15 m (L) X 10 m (B) X 4 m (H) then the ventilation rate is = L x B X H X A C

=15 X10 X 4 X10

= 6000 m^3/hr

22.10 Ice Bank Systems

Ice Bank System is a proven technology that has been utilized for decades Thermal energy storage takes advantage of low cost, off-peak electricity, produced more efficiently throughout the night, to create and store cooling energy for use when electricity tariffs are higher, typically during the day. There are full- and partial- load Off-Peak Cooling systems. The essential element for either full- or partial- storage configurations are thermal- energy storage tanks. Each tank contains a spiral-wound, polyethylene-tube heat exchanger surrounded with water. ICEBANK tanks are available in a variety of sizes ranging from 45 to over 500 ton-hours. These systems are economical based on the electricity tariff of particular utility. These systems can be employed to meet the air conditioning requirements in the commercial buildings as well as to meet the chilling requirements in Diary and process industry. The main advantage of these systems is to reduce the peak demand of the utility and also reduce the cost of operation for the end user.

How Ice Bank Works?

With a partial-storage system, the chiller can be 40 to 50 percent smaller than other HVAC systems, because the chiller works in conjunction with the ICEBANK tanks during on-peak daytime hours to manage the building's cooling load. During off-peak night time hours, the chiller charges the ICEBANK tanks for use during the next day's cooling. The lowest possible average load is obtained by extending the chiller hours of operation.

22.11 Humidification Systems

This is a process involving reduction in dry bulb temperature and increase in specific humidity. The atmospheric conditions with respect to humidity play a very important part in many manufacturing processes. For example, in textile processing the properties like dimensions, weight, tensile strength, elastic recovery, electrical resistance, rigidity etc. of all textile fibre are influenced by humidity maintained. Temperature does not have a great effect on the fibres but the temperature dictates the amount of moisture the air will hold in suspension and, therefore, temperature and humidity must be considered together. Humidification system without chilling helps to maintain only the RH% without much difficulty.

Adiabatic saturation or evaporative cooling

In this process (Figure 22.10) air comes in direct contact with water in the air washer. There is heat and mass transfer between air and water. The humidity ratio of air increases. If the time of contact is sufficient, the air gets saturated. Latent heat of evaporation required for conversion of water into water vapor is taken from the remaining water. When equilibrium conditions are reached, water cools down to the wet bulb temperature of the air. If the air washer is ideal, the dry bulb temperature and wet bulb temperature of the air would be equal. Dry bulb temperature of the air goes down in the process and the effect of cooling is due to the evaporation of some part of the water. That is why it is called **Evaporative Cooling.**

The sensible heat is decreased as the temperature goes down but the latent heat goes up as water vapour is added to the air. The latent heat required by the water which is evaporated in the air is drawn from the sensible heat of the same air. Thus, it is transformation of sensible heat to latent heat. During this process the enthalpy of air remains the same. If humidity ratios of saturated air and of the air before saturation are known, then the difference between the two would be the amount of water vapour absorbed by unit weight of dry air.

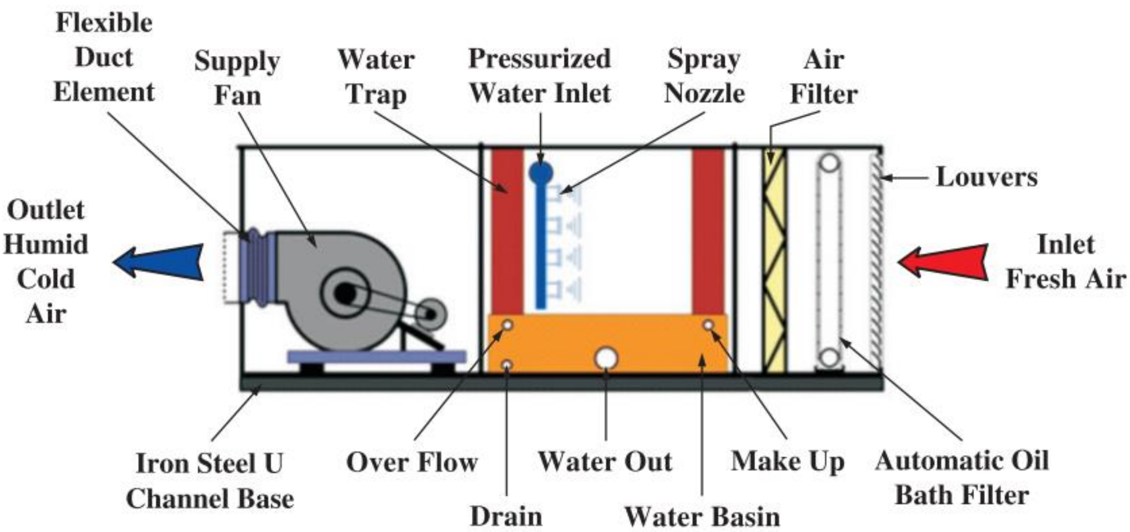


Figure 22.10 Air Washer Unit

Humidifying Air by adding Water

If water is added to air without any heat supply the state of air change **adiabatic** along a constant enthalpy line in the *psychrometric chart.* The dry bulb temperature of the air decreases.

The amount of added water can be expressed as

$m_w \quad = v\,\rho\,(\acute{\omega}_{out} - w_{in})$

Where,

m_w = mass of added water (kg/hr)

v = volume flow of air (m^3/hr)

ρ = density of air - vary with temperature, 1.293 kg/m^3 at 20°C (kg/m^3)

$\acute{\omega}$ = specific humidity of air (kg/kg)

Example 22.3

Humidifying Air by adding Water

In an air washer of textile humidification system airflow of 3000 m^3/h at 25°C and 10% relative humidity is humidified to 60% relative humidity by adding water through spray nozzles. Calculate the amount of water required. The specific humidity of air at inlet and outlet are 0.002 kg/kg and 0.0062 kg/kg respectively.

Solution

The amount of water added can be calculated as:

m_w = 3000 X 1.184 X (0.0062 - 0.002) 14.9 kg/h

22.12 Energy Saving Opportunities

a) Cold Insulation

Insulate all cold lines / vessels using economic insulation thickness to minimize heat gains; and choose appropriate (correct) insulation.

b) Building Envelope

Optimise air conditioning volumes by measures such as use of false ceiling and segregation of critical areas for air conditioning by air curtains.

c) Building Heat Loads Minimisation

Minimise the air conditioning loads by measures such as roof cooling, roof painting, efficient lighting, pre-cooling of fresh air by air- to-air heat exchangers, variable volume air system, optimal thermo-static setting of temperature of air conditioned spaces, sun film applications, etc.

d) Process Heat Loads Minimisation

Minimize process heat loads in terms of TR capacity as well as refrigeration level, i.e., temperature required, by way of:

Flow optimization

Heat transfer area increase to accept higher temperature coolant
Avoiding wastages like heat gains, loss of chilled water, idle flows.
Frequent cleaning / de-scaling of all heat exchangers

e) At the Refrigeration A/C Plant Area

- Ensure regular maintenance of all A/C plant components as per manufacturer guidelines.
- Ensure adequate quantity of chilled water and cooling water flows, avoid bypass flows by closing valves of idle equipment.
- Minimize part load operations by matching loads and plant capacity on line; adopt variable speed drives for varying process load.
- Make efforts to continuously optimize condenser and evaporator parameters for minimizing specific energy consumption and maximizing capacity.
- Adopt VAR system where economics permit as a non-CFC solution.

22.13 Case Study: Screw Compressor Application

Background

Rotary Screw Compressors are widely used for refrigeration applications to compress ammonia & other refrigerating gases. A typical sectional view of the compressor is shown below in Figure 22.11.

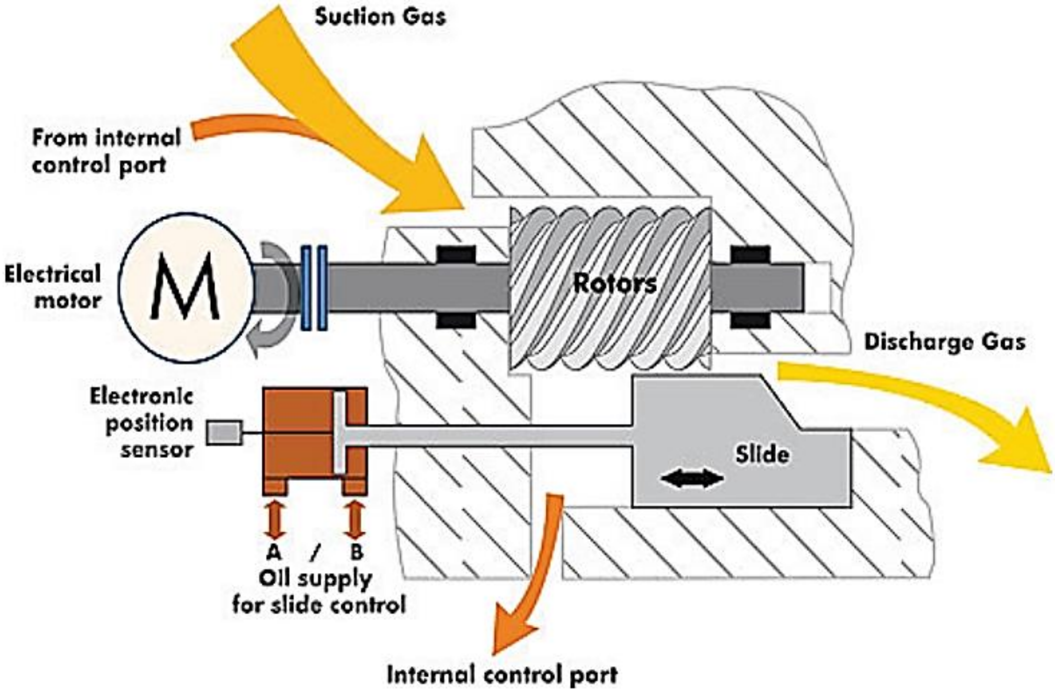


Figure 22.11 Section of Screw Compressor showing the meshing screws & slide valve

The table 22.5 below gives the measured system data during compressor running at part load condition.

Table 22.5 Performance parameters for partial load conditions

Volumetric refrigerant flow (m^3)	Suction Pressure (kg/cm^2)	Discharge Pressure (kg/cm^2)	Inlet Temp. (°C)	Outlet Temp. (°C)	Total refrigeration load (Calories)	Total refrigeration load (TR)
21.03	3.19	11.89	28.08	1.49	558964	184.73
26.62	3.16	11.65	26.85	2.12	658336	217.57
26	3.17	11.63	27.75	1.68	678000	224.07
28	3.22	11.7	27.91	1.92	727650	240.47
32	3.22	11.78	27.98	2.28	822400	271.79
20.13	3.25	12.22	27.28	1.5	518947	171.5
21.71	3.25	12.38	27.77	1.6	568197	187.78
23.36	3.25	12.52	28.4	1.64	625306	206.65
28.15	3.25	11.99	28.58	1.27	714310	236.07
28.51	3.25	12.31	28.7	1.54	774362	255.91

The table 22.6 below gives the power consumption data for partial load operation with and without VFD.

Table 22.6 Power consumption for partial load operation (with & without VFD)

Power consumed without VFD (kW)	Power consumed with VFD (kW)	Measured Power consumed per ton of refrigeration load without VFD (kW/TR)	Measured Power consumed per ton of refrigeration load with VFD (kW/TR)	Hourly savings due to VFD operation (kW)
173.14	127.25	0.94	0.69	45.89
203.93	149.87	0.94	0.69	54.06
210.02	154.35	0.94	0.69	55.67
225.4	165.65	0.94	0.69	59.75
254.75	187.22	0.94	0.69	67.53
160.75	118.14	0.94	0.69	42.61
176	129.35	0.94	0.69	46.65
193.69	142.35	0.94	0.69	51.34
221.26	162.61	0.94	0.69	58.65
239.87	176.28	0.94	0.69	63.59

Average hourly power savings = 57.6 kW
Average yearly energy savings (250 days x 10 hours) = 136435 kWh Average yearly monetary savings (BDT. 6.00/kWh) = BDT. 8, 18,610 /-

Example 22.4

The measured values of a 20 TR package air conditioning plant are given below: Average air velocity across suction side filter: 2.5 m/s
Cross Sectional area of suction: 1.2 m^2
Inlet air = Dry Bulb: 20°C, Wet Bulb: 14 °C, Enthalpy: 9.37 kcal/kg
Outlet air = Dry Bulb: 12.7 °C, Wet Bulb: 11.3 °C; Enthalpy: 7.45 kcal/kg
Specific volume of air: 0.85 m^3/kg
Power drawn: by compressor: 10.69 kW
by Pump: 4.86 kW
by Cooling tower fan: 0.87 kW

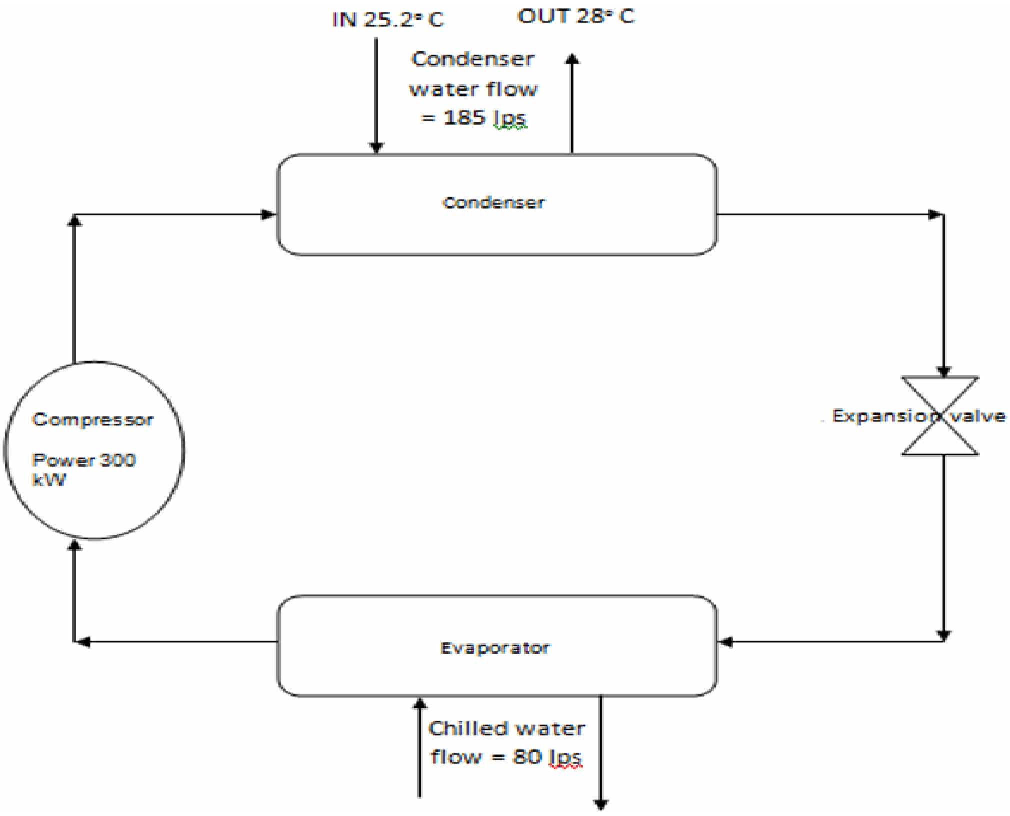
Calculate:

a) Air Flow rate in m^3/hr
b) Cooling effect delivered in kW
c) Specific power consumption of compressor in kW/TR
d) Overall kW/TR
e) Energy Efficiency Ratio in kW/kW

Solution

Air flow rate = 2.5*1.2	=	3 m^3/sec = 10800 m^3/hr
Cooling Effect delivered	=	[(9.37-7.45)*10800]/(0.85*3024)
	=	8.07 TR = 28.32 kW
Compressor kW/TR = 10.69/8.07	=	1.32
Overall kW/TR = (10.69+4.86+0.87)/8.07	=	2.04
Energy Efficiency Ratio (EER) in kW/kW	=	28.32/10.69 = 2.65

Example 22.5



Evaluate the CoP of centrifugal chiller.

Find the ratio of evaporator refrigeration load (TR) to condenser heat rejection load (TR)

Solution:

Refrigeration load (TR)	:	(m x C_p x ΔT)/3024
	:	80 x 3600 x 1 x (13-8)/3024
	:	476 TR
Coefficient of performance (COP)	:	Cooling effect (kW)
Power input to compressor (kW)		
	:	(476TRx3024/860) / 300= 5.579
Evaporator cooling load (TR)	:	476 TR
Condenser heat rejection load (TR)	:	185 x 3600 x (28 – 25.2)/3024
	:	616 TR
Ratio	:	$\frac{Evaporator}{Condenser} = \frac{476}{616} = 0.77$

CHAPTER 23: COOLING TOWER

23.1 Introduction

Cooling towers are a very important part of many chemical plants. The primary task of a cooling tower is to reject heat into the atmosphere. They represent a relatively inexpensive and dependable means of removing low-grade heat from cooling water. The make-up water source is used to replenish water lost to evaporation. Hot water from heat exchangers is sent to the cooling tower. The water exits the cooling tower and is sent back to the exchangers or to other units for further cooling. Typical closed loop cooling tower system is shown in Figure 23.1.

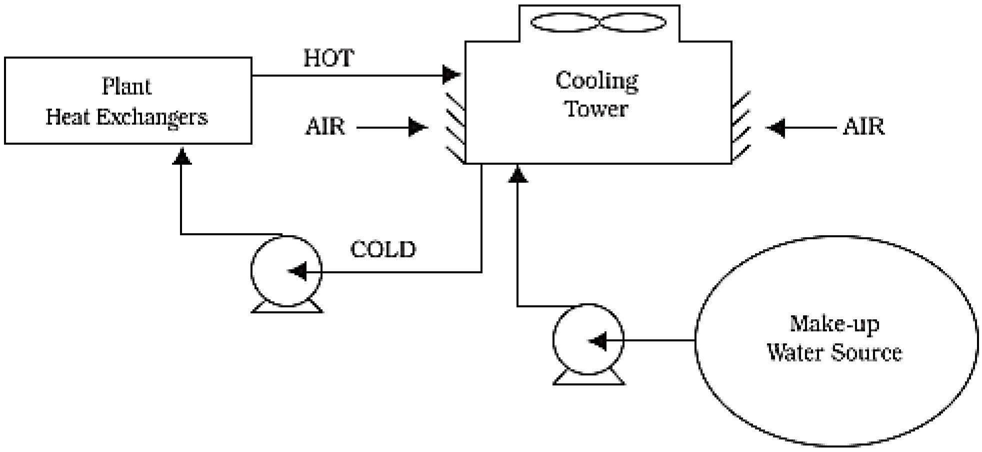


Figure 23.1 Cooling Water System

23.2 Cooling Tower Types

Cooling towers fall into two main categories: Natural draft and Mechanical draft.

Natural draft towers use very large concrete chimneys to introduce air through the media. Due to the large size of these towers, they are generally used for water flow rates above 45,000 m3/hr. These types of towers are used only by utility power stations.

Mechanical draft towers utilize large fans to force or suck air through circulated water. The water falls downward over fill surfaces, which help increase the contact time between the water and the air – this helps maximise heat transfer between the two. Cooling rates of Mechanical draft towers depend upon their fan diameter and speed of operation. Since, the mechanical draft cooling towers are much more widely used; the focus is on them in this chapter.

Mechanical draft towers are available in the following airflow arrangements:

1. Counter flows induced draft.
2. Counter flow forced draft.
3. Cross flow induced draft.

The Figure 23.2 illustrates various cooling tower types.

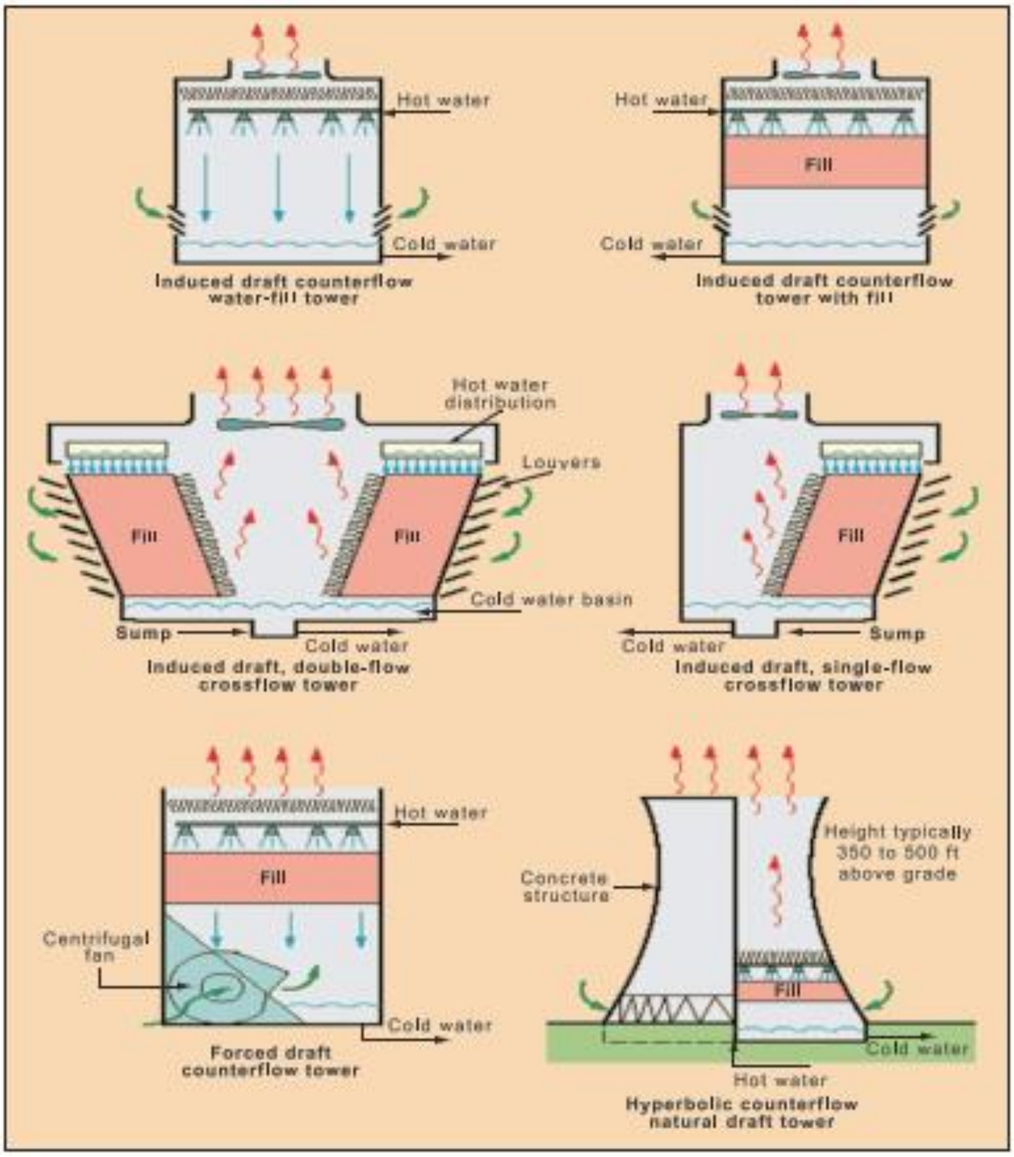


Figure 23.2 Cooling Tower Types

23.3 Components of Cooling Tower

The basic components of an evaporative tower are: Frame and casing, fill, cold water basin, drift eliminators, air inlet, louvers, nozzles and fans.

Frame and easing: Most towers have structural frames that support the exterior enclosures (casings), motors, fans, and other components. With some smaller designs, such as some glass fiber units, the casing may essentially be the frame.

Fill: Most towers employ fills (made of plastic or wood) to facilitate heat transfer by maximising water and air contact. Fill can either be splash or film type.

With splash fill, water falls over successive layers of horizontal splash bars, continuously breaking into smaller droplets, while also wetting the fill surface. Plastic splash fill promotes better heat transfer than the wood splash fill.

Film fill consists of thin, closely spaced plastic surfaces over which the water spreads, forming a thin film in contact with the air. These surfaces may be flat, corrugated, honeycombed, or other patterns. The film type of fill is the more efficient and provides same heat transfer in a smaller volume than the splash fill.

Cold water basin: The cold-water basin, located at or near the bottom of the tower, receives the cooled water that flows down through the tower and fill. The basin usually has a sump or low point for the cold-water discharge connection. In many tower designs, the cold-water basin is beneath the entire fill.

In some forced draft counter flow design, however, the water at the bottom of the fill is channelled to a perimeter trough that functions as the cold-water basin. Propeller fans are mounted beneath the fill to blow the air up through the tower. With this design, the tower is mounted on legs, providing easy access to the fans and their motors.

Drift eliminators:

These capture water droplets entrapped in the air stream that otherwise would be lost to the atmosphere.

Air inlet: This is the point of entry for the air entering a tower. The inlet may take up an entire side of a tower-cross flow design-or be located low on the side or the bottom of counter flow designs.

Louvers: Generally, cross-flow towers have inlet louvers. The purpose of louvers is to equalize air flow into the fill and retain the water within the tower. Many counter flow tower designs do not require louvers.

Nozzles: These provide the water sprays to wet the fill. Uniform water distribution at the top of the fill is essential to achieve proper wetting of the entire fill surface. Nozzles can either be fixed in place and have either round or square spray patterns or can be part of a rotating assembly as found in some circular cross-section towers.

Fans: Both axial (propeller type) and centrifugal fans are used in towers. Generally, propeller fans are used in induced draft towers and both propeller and centrifugal fans are found in forced draft towers. Depending upon their size, propeller fans can either be fixed or variable pitch. A fan having non-automatic adjustable pitch blades permits the same fan to be used over a wide range of kW with the fan adjusted to deliver the desired air flow at the lowest power consumption.

Automatic variable pitch blades can vary air flow in response to changing load conditions.

23.4 Tower Materials

In the early days of cooling tower manufacture, towers were constructed primarily of wood. Wooden components included the frame, casing, louvers, fill, and often the cold-water basin. If the basin was not of wood, it likely was of concrete.

Today, tower manufacturers fabricate towers and tower components from a variety of materials. Often several materials are used to enhance corrosion resistance, reduce maintenance, and promote reliability and long service life. Galvanized steel, various grades of stainless steel, glass fiber, and concrete are widely used in tower construction as well as aluminium and various types of plastics for some components.

Wood towers are still available, but they have glass fiber rather than wood panels (casing) over the wood framework. The inlet air louvers may be glass fiber, the fill may be plastic, and the cold-water basin may be steel.

Larger towers sometimes are made of concrete. Many towers—casings and basins—are constructed of galvanized steel or, where a corrosive atmosphere is a problem, stainless steel. Sometimes a galvanized tower has a stainless-steel basin. Glass fiber is also widely used for cooling tower casings and basins, giving long life and protection from the harmful effects of many chemicals.

Plastics are widely used for fill, including PVC, polypropylene, and other polymers. Treated wood splash fill is still specified for wood towers, but plastic splash fill is also widely used when water conditions mandate the use of splash fill. Film fill, because it offers greater heat transfer efficiency, is the fill of choice for applications where the circulating water is generally free of debris that could plug the fill passageways.

Plastics also find wide use as nozzle materials. Many nozzles are being made of PVC, ABS, polypropylene, and glass-filled nylon. Aluminium, glass fiber, and hot-dipped galvanized steel are commonly used fan materials. Centrifugal fans are often fabricated from galvanized steel. Propeller fans are fabricated from galvanized, aluminium, or moulded glass fiber reinforced plastic.

23.5 Fan-less Cooling Towers

Basis of Theory

Fan-less cooling tower (Figure 23.3) takes advantage of the water pressure of the existing water circulation pump forming a water screen with specially designed ejection headers. As the water flows through the nozzles at high velocity, based on an ejector principle, low pressure is created which sucks the ambient cold air into the tower. The kinetic energy of Water entering the cooling tower is converted into kinetic energy of the air by the use of specially designed ejector nozzles. Water Pressure required in the Jet Ejector Nozzles is min. 0.5 Bar.

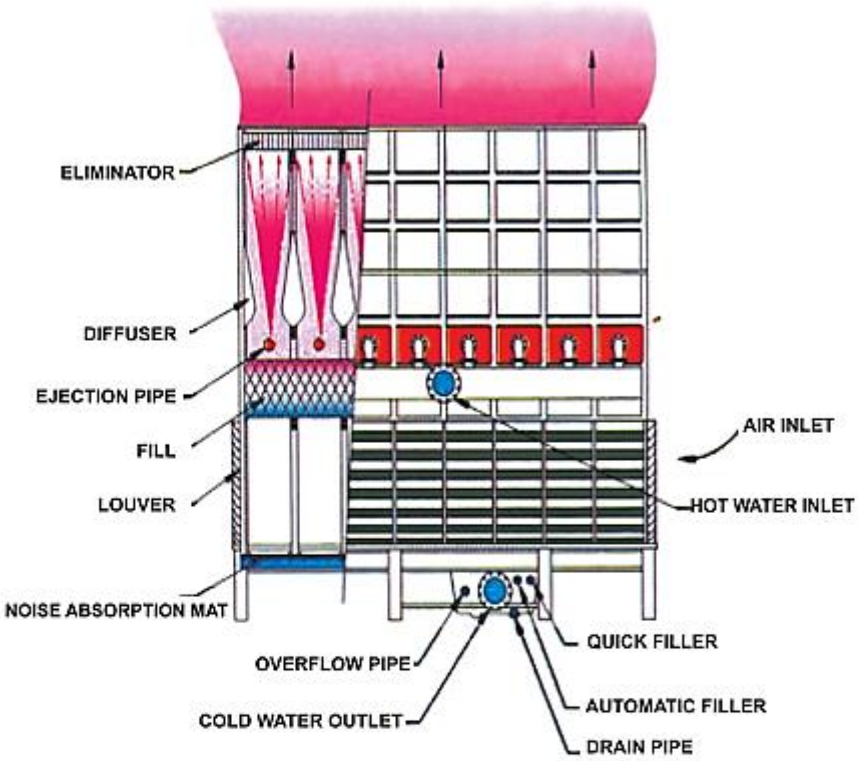


Figure 23.3 Fanless Cooling Tower

The incoming air passes through the fills at the bottom while the ejected water falls on the fills thus enabling a counter current heat exchange between water and air. Drift eliminators are provided to contain the drift losses.

Features of Fanless Cooling Tower

Energy saving

Since fans are not used in this type of cooling there is a considerable saving of power even though marginally higher power consumption is required for the pump.

Low noise

The noises of traditional cooling tower originate from the operating fans and motors. Further the vibration caused by these transmission units reinforces the noise resonance. This problem is eliminated in fanless cooling tower since no fan/motor is used.

Water saving

The velocity of water is less than that in conventional cooling tower. In combination with high efficiency drift eliminators this can reduce the drift loss to 0.001% which is much less than that for a conventional tower. Since the water droplets will be less than 50 micron it evaporates immediately without causing any pollution nearby.

Low maintenance cost

Since the fanless cooling tower has no mechanical equipment such as fan, motor, gearbox etc. there is hardly any maintenance required, provided the quality of circulation water is kept clean and well maintained.

23.6 Cooling Tower Performance

The important parameters, from the point of determining the performance of cooling towers, are:

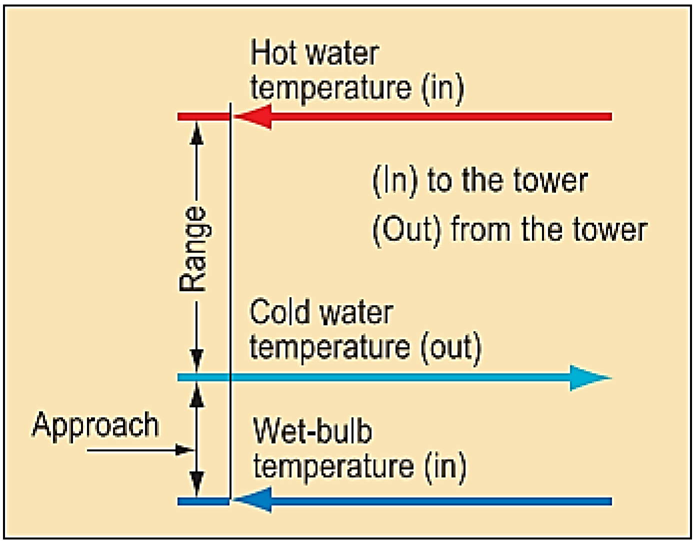


Figure 23.4 Range and Approach

i. "Range" is the difference between the cooling tower water inlet and outlet temperature. (see Figure 23.4).

ii. "Approach" is the difference between the cooling tower outlet cold water temperature and ambient wet bulb temperature. Although, both range and approach should be monitored, the

'Approach' is a better indicator of cooling tower performance. (see Figure 23.4).

iii. Cooling tower effectiveness (in percentage) is the ratio of range, to the ideal range, i.e., difference between cooling water inlet temperature and ambient wet bulb temperature, or in other words it is **= Range / (Range + Approach).**

iv. Cooling capacity is the heat rejected in kcal/hr or TR, given as product of mass flow rate of water, specific heat and temperature difference

v. Evaporation loss is the water quantity evaporated for cooling duty and, theoretically, for every 10, 00,000 kcal heat rejected, evaporation quantity works out to 1.8 m3. An empirical relation used often is:

*Evaporation Loss (m3/hr) = 0.00085 x 1.8 x circulation rate (m3/hr) x (T_1-T_2)

T_1 -T_2 = Temperature difference between inlet and outlet water.

*Source: Perry's Chemical Engineers Handbook (Page: 12-17)

vi. Cycles of concentration (CDC) is the ratio of dissolved solids in circulating water to the dissolved solids in makeup water.

Blow Down = Evaporation Loss / (C.O.C. - 1)

vii. Liquid/Gas (L/G) ratio, of a cooling tower is the ratio between the water and the air mass flow rates. Against design values, seasonal variations require adjustment and tuning of water and air flow rates to get the best cooling tower effectiveness through measures like water box loading changes, blade angle adjustments.

Thermodynamics also dictate that the heat removed from the water must be equal to the heat absorbed by the surrounding air:

$L (T_1 - T_2) = G (h_2 - h_1)$

$$\frac{L}{G} = \frac{h_2 - h_1}{T_1 - T_2}$$

Where,

L/G	=	liquid to gas mass flow ratio (kg/kg)
T_1	=	hot water temperature (0C)
T_2	=	cold water temperature (0C)
h_2	=	enthalpy of air-water vapor mixture at exhaust wet-bulb temperature (same units as above)
h_1	=	enthalpy of air-water vapor mixture at inlet wet-bulb temperature (same units as above)

23.6.1 Factors Affecting Cooling Tower Performance

Capacity

Heat dissipation (in kcal/hour) and circulated flow rate (m3/hr) are not sufficient to understand cooling tower performance. Other factors, which we will see, must be stated along with flow rate m3/hr. For example, a cooling tower sized to cool 4540 m3/hr through a 13.9°C range might be larger than a cooling tower to cool 4540 m3/hr through 19.5°C range.

Range

Range is determined not by the cooling tower, but by the process it is serving. The range at the exchanger is determined entirely by the heat load and the water circulation rate through the exchanger and on to the cooling water.

Range ^{O}C = Heat Load in kcaUhour / Water Circulation Rate in LPH

As a generalization, the closer the approach to the wet bulb, the more expensive the cooling tower due to increased size. Usually, a 2.8°C approach to the design wet bulb is the coldest water temperature that cooling tower manufacturers will guarantee. If flow rate, range, approach and wet bulb had to be ranked in the order of their importance in sizing a tower, approach would be first with flow rate closely following the range and wet bulb would be of lesser importance.

Factors that affect cooling tower size

Cooling tower size is affected by the heat load, range, approach, and WBT. When three of these four quantities are held constant, tower size varies in the following manner:

- Directly with the heat load
- Inversely with the range
- Inversely with the approach
- Inversely with the entering WBT

Heat Load

The heat load imposed on a cooling tower is determined by the process being served. The degree of cooling required is controlled by the desired operating temperature level of the process. In most cases, a low operating temperature is desirable to increase process efficiency or to improve the quality or quantity of the product. In some applications (e. g. internal combustion engines), however, high operating temperatures are desirable. The size and cost of the cooling tower is proportional to the heat load. If heat load calculations are low undersized equipment will be purchased. If the calculated load is high, oversize and more costly, equipment will result.

Process heat loads may vary considerably depending upon the process involved. Determination of accurate process heat loads can become very complex but proper consideration can produce satisfactory results. On the other hand, air conditioning and refrigeration heat loads can be determined with greater accuracy.

Information is available for the heat rejection requirements of various types of power equipment. A sample list is as follows:

Air Compressor

- Single-stage	- 129 kcal/kW/hr
- Single-stage with after cooler	- 862 kcal/kW/hr
- Two-stage with intercooler	- 518 kcal/kW/hr
- Two-stage with intercooler and after cooler	- 862 kcal/kW/hr

Refrigeration, Compression - 63 kcal/min/TR

Refrigeration, Absorption	- 127 kcal/min/TR
Steam Turbine Condenser	- 555 kcal/kg of steam
Diesel Engine, Four-Cycle, Supercharged	- 880 kcal/kW/hr
Natural Gas Engine, Four-cycle (l8 kg/cm^2 compression)	- 1523 kcal/kW/hr

Wet Bulb Temperature

Wet bulb temperature is an important factor in performance of evaporative water-cooling equipment. It is a controlling factor from the aspect of minimum cold-water temperature to which water can be cooled by the evaporative method. Thus, the wet bulb temperature of the air entering the cooling tower determines operating temperature levels throughout the plant, process, or system. Theoretically, a cooling tower will cool water to the entering wet bulb temperature, when operating without a heat load. However, a thermal potential is required to reject heat, so it is not possible to cool water to the entering air wet bulb temperature, when a heat load is applied. The approach obtained is a function of thermal conditions and tower capability.

Initial selection of towers with respect to design wet bulb temperature must be made on the basis of conditions existing at the tower site. The temperature selected is generally close to the average maximum wet bulb for the summer months. An important aspect of wet bulb selection is, whether it is specified as ambient or inlet. The ambient wet bulb is the temperature, which exists generally in the cooling tower area, whereas inlet wet bulb is the wet bulb temperature of the air entering the tower. The later can be, and often is, affected by discharge vapours being recalculated into the tower. Recirculation raises the effective wet bulb temperature of the air entering the tower with corresponding increase in the cold-water temperature. Since there is no initial knowledge or control over the recirculation factor, the ambient wet bulb should be specified. The cooling tower supplier is required to furnish a tower of sufficient capability to absorb the effects of the increased wet bulb temperature peculiar to his own equipment.

It is very important to have the cold-water temperature low enough to exchange heat or to condense vapours at the optimum temperature level. By evaluating the cost and size of heat exchangers versus the cost and size of the cooling tower, the quantity and temperature of the cooling tower water can be selected to get the maximum economy for the particular process.

The Table 23.1 illustrates the effect of approach on the size and cost of a cooling tower. The towers included were sized to cool 4540 m^3/hr through a 16.67°C range at a 267°C design wet bulb. The overall width of all towers is 21.65 meters; the overall height, 15 .25 meters, and the pump head, 10.6 m approximately.

Table- 23.1: Approach VS Cooling Tower Size (4540 m^3 /hr; 16.67^{o}C Range; 26.7 ^{o}C Wet bulb; 10. 7 Pump Head)

Approach °C	2.77	3.33	3.88	4.44	5.0	5.55
Hot Water °C	46.11	46.66	47.22	47.77	48.3	48.88
Cold Water °C	29.44	30	30.55	31.11	31.66	32.22
No. of Cells	4	4	3	3	3	3
Length of Cells Mts.	10.98	8.54	10.98	9.76	8.54	8.54
Overall Length Mts.	43.9	34.15	32.93	29.27	25.61	25.61
No. of Fans	4	4	3	3	3	3
Fan Diameter Mts.	7.32	7.32	7.32	7.32	7.32	6.71
Total Fan kW	270	255	240	202.5	183.8	183.8

Approach and Flow

Suppose a cooling tower is installed that is 21.65 m wide x 36.9 m long x 15.24 m high, has three 7.32m diameter fans and each powered by 25 kW motors. The cooling tower cools from 3632 m3/hr water from 461°C to 294°C at 26.7°C WBT dissipating 60.69 million kcal/hr. The Table 23.2 shows what would happen with additional flow but with the range remaining constant at 16.67°C. The heat dissipated varies from 60.69 million kcal/hr to 271.3 million kcal/hr.

Table 23.2: Flow vs. Approach for a Given Tower (Tower is 21.65 m x 36.9 M; Three 7.32 M Fans; Three 25 kw Motor; 16.7°C Range with 26.7°C Wet Bulb

Flow m³/hr	Approach °C	Cold Water °C	Hot Water °C	Million kcal/hr
3632	2.78	29.40	46.11	60.691
4086	3.33	29.95	46.67	68.318
4563	3.89	30.51	47.22	76.25
5039	4.45	31.07	47.78	84.05
5516	5.00	31.62	48.33	92.17
6060.9	5.56	32.18	48.89	101.28
7150.5	6.67	33.29	50.00	119.48
8736	8.33	35.00	51.67	145.63
11590	11.1	37.80	54.45	191.64
13620	13.9	40.56	57.22	226.91
16276	16.7	43.33	60.00	271.32

For meeting the increased heat load, few modifications would be needed to increase the water flow through the tower. However, at higher capacities, the approach would increase.

Range, Flow and Heat Load

Range is a direct function of the quantity of water circulated and the heat load. Increasing the range as a result of added heat load does require an increase in the tower size. If the cold water temperature is not changed and the range is increased with higher hot water temperature, the driving force between the wet bulb temperature of the air entering the tower and the hot water temperature is increased, the higher level heat is economical to dissipate.
If the hot water temperature is left constant and the range is increased by specifying a lower cold water temperature, the tower size would have to be increased considerably. Not only would the range be increased, but the lower cold-water temperature would lower the approach. The resulting change in both range and approach would require a much larger cooling tower.

Approach & Wet Bulb Temperature

The design wet bulb temperature is determined by the geographical location. Usually the design wet bulb temperature selected is not exceeded over 5 percent of the time in that area. Wet bulb temperature is a factor in cooling tower selection; the higher the wet bulb temperature, the smaller the tower required to give a specified approach to the wet bulb at a constant range and flow rate.

A 4540 m3/hr cooling tower selected for a 16.67°C range and a 4.45°C approach to 21.11°C wet bulb would be larger than a 4540 m3/hr tower selected for a 16.67°C range and a 4.45°C approach to a 26.67°C wet bulb. Air at the higher wet bulb temperature is capable of picking up more heat. Assume that the wet bulb temperature of the air is increased by approximately 11.1°C. As air removes heat from the water in the tower, each kg of air entering the tower at 21.1°C wet bulb would contain 18.86 kcals and if it were to leave the tower at 322°C wet bulb it would contain 24.17 kcal per kg of air.

In the second case, each kg of air entering the tower at 26.67°C wet bulb would contain 24.17 kcal and were to leave at 378°C wet bulb it would contain 39.67 kcal per kg of air.

In going from 21.1^{0}C to 32.2^{o}C, 12.1 kcal per kg of air is picked up, while 15.5 kcal/kg of air is picked up in going from 26.67°C to 37.8°C.

Fill Media Effects

In a cooling tower, hot water is distributed above fill media which flows down and is cooled due to evaporation with the intermixing air. Air draft is achieved with use of fans. Thus some power is consumed in pumping the water to a height above the fill and also by fans creating the draft.

An energy efficient or low power consuming cooling tower is to have efficient designs of fill media with appropriate water distribution, drift eliminator, fan, gearbox and motor. Power savings in a cooling tower, with use of efficient fill design, is directly reflected as savings in fan power consumption and pumping head requirement.

Function of Fill media in a Cooling Tower

Heat exchange between air and water is influenced by surface area of heat exchange, time of heat exchange (interaction) and turbulence in water effecting thoroughness of intermixing. Fill media in a cooling tower is responsible to achieve all of above.

Splash and Film Fill Media: As the name indicates, splash fill media generates the required heat exchange area by splashing action of water over fill media and hence breaking into smaller water droplets. Thus, surface of heat exchange is the surface area of the water droplets, which is in contact with air.

Film Fill and its Advantages

In a film fill, water forms a thin film on either side of the fill sheets. Thus area of heat exchange is the surface area of the fill sheets, which is in contact with air. Typical comparison between various fill media is shown in Table 23.3.

Table 23.3. Comparisons between various fill media

	Splash Fill	Film Fill	Low Clog Film Fill
Possible L/G Ratio	1.1 – 1.5	1.5 – 2.0	1.4 – 1.8
Effective Heat Exchange Area	30 – 45 m^2/m^3	150 m2/m^3	85 – 100 m^2/m^3
Fill Height Required	5 – 10 m	1.2 – 1.5 m	1.5 – 1.8 m
Pumping Head Requirement	9 – 12 m	5 – 8 m	6 – 9 m
Quantity of Air Required	High	Much low	Low

Due to fewer requirements of air and pumping head, there is a tremendous saving in power with the invention of film fill. Recently, low-clog film fills with higher flute sizes have been developed to handle high turbid waters. For sea water, low clog film fills are considered as the best choice in terms of power saving and performance compared to conventional splash type fills.

Choosing a Cooling Tower

The counter-flow and cross flows are two basic designs of cooling towers based on the fundamentals of heat exchange. It is well known that counter flow heat exchange is more effective as compared to cross flow or parallel flow heat exchange.

Cross-flow cooling towers are provided with splash fill of concrete, wood or perforated PVC. Counter-flow cooling towers are provided with both film fill and splash fill.

Typical comparison of Cross flow Splash Fill, Counter Flow Tower with Film Fill and Splash fill is shown in Table 23.4. The power consumption is least in Counter Flow Film Fill followed by Counter Flow Splash Fill and Cross-Flow Splash Fill.

Table 23.4: Typical Comparison of Cross flow splash fill, Counter Flow Tower with Film Fill and Splash Fill

Number of Towers : 2			
Water Flow : 16000 m^3/hr.			
Hot Water Temperature : 41.5°C			
Cold Water Temperature : 32.5°C			
Design Wet Bulb Temperature : 27.6°C			
	Counter Flow Film Fill	**Counter Flow Splash Fill**	**Cross-Flow Splash Fill**
Fill Height, Meter	1.5	5.2	11.0
Plant Area per Cell	14.4 × 14.4	14.4 × 14.4	12.64 × 5.49
Number of Cells per Tower	6	6	5
Power at Motor Terminal/Tower, kW	253	310	330
Static Pumping Head, Meter	7.2	10.9	12.05

23.7 Efficient System Operation

i. Cooling Water Treatment

Cooling water systems is one of the Critical utility in Power plants, process industries and in Air-conditioning systems. The power plant performance, Chiller performance have direct effect on energy consumption, based on Cooling water temperatures which in turn is maintained by good cooling water treatment.

The various problems in Cooling water system and the corrective measures required are discussed below.

a) Water Side Problems

Usually the typical problems that any (Open) cooling system meets with are:

- Corrosion and/or Scale formation
- Biological/Micro-biological fouling

Corrosion:

Corrosion, being not a precisely understood phenomenon, is a function of various factors of which the following are the main factors responsible for promoting corrosion in the system; high salinity of the water, low PH, low Alkalinity, presence of corrosive gases (mainly oxygen and C02), dissimilarity of the metals etc.

Corrosion can either lead to failure of the metallurgy (leakages in the heat exchangers) and/or deposit formation of corrosion products.

Scale Formation:

The main sources for the scale formation in the Open Evaporative Condenser circuit are:

Hard water containing, high levels of Calcium and Magnesium, high level of PH and Alkalinity. An open evaporative cooling systems (condenser water systems) operated on softened water can meet with severe scaling problems when

- PH of the circulating water is above 9.0
- The total Alkalinity as $CaCO_3$ is above 550 ppm
- Temporary hardness in the sources of make-up is above 200 ppm

Biological/Micro—Biological Fouling

Systems exposed to sunlight (mainly cooling tower) often meet with severe problem of algae formation. Other problems associated with algae are slime mass, fungi and various species of bacteria.

Bacteria being miniature bodies, of which growth is not controlled, can lead to the formation of fine masses of suspended particles that lead to fouling and deposit formation. Algae obviously block the nozzles of the cooling tower and thus reduce temperature drop across the tower. Slime masses again are responsible for fouling and deposit formation.

Deposit Formation:

Foreign matter such as; turbidity, sand, silt, mud, air borne debris and other suspended impurities are the sources of deposits formation. Corrosion products that are formed also add to the deposit formation.

b) Energy Losses:

Regardless of the type of system, be it open or closed, if it meets with any of the above problems, either the cooling tower nozzles are blocked resulting in reduced Delta 'T' and/or the deposits/scales are formed on the heat transfer surfaces.

For example, the energy losses due to scale and deposit formation in a cooling water circuit of a refrigeration system are significant as shown in Table 23.5. The scale and deposit on the heat transfer area in process equipment can also cause production loss.

Table 23.5 Effect of Fouling on Efficiency and Power Consumption

Fouling Factor	Thickness of scale/deposit (mm)	% Reduction in efficiency in terms of heat transfer (Condenser)	% Increase in power consumption due to drop in condenser efficiency
Clean	0.00	0	-
0.0005	0.15	30	5
0.001	0.30	44	10
0.002	0.60	63	20
0.003	0.90	72	30

c) Solution to the Problems

ON line / OFF Line Chemical Cleaning

Depending on the criticality the plant management may adopt ON line/ OFF line cleaning systems.

Preventive Treatment

For preventive treatment, a wide range of chemicals are available in the market and formulations manufactured by reputed companies are generally very safe to use in the system.

Corrosion/Scale Inhibitors

To control corrosion and scale formation depending upon the severity of each of the problem, either or both chemicals should be used and the selection of the chemicals should be made in accordance with the quality of the make-up water available for plant operation.

Dispersants (For Deposit Formation)

Suitable dispersants help in controlling the deposit formation and selection of the dispersants is made in accordance with the nature of suspended solids/deposits forming particulate present in the water.

Side Stream Filter

Circulating water having very high levels of turbidity and/or suspended impurities should be facilitated with side stream filters. Side stream filters are generally selected to handle 2% to 5% of the total rate of circulation, but to ensure that the total water content in the system (hold-up volume) is filtered approximately once in 12 hours.

Bio Dispersants and Biocides

To combat problems arising due to the growth of biological and micro biological species, such as algae, fungi, slime, bacteria etc. It is very essential to select a combination of oxidizing and non- oxidizing biocides. Bio-dispersants are used to remove the upper layer of the biological masses and allow better penetration of biocides in the lower layers of bio-masses.

Chlorination

Chlorination is the most effective and most economical oxidizing biocide. Chlorination for the smaller systems may be done with hypo chlorite-based products and for the larger systems having hold-up volume in excess of 100 m3 be done with suitable gas chlorinators. The safest gas chlorination equipment is vacuum gravity feed type which can be easily installed on either 50 kg or 100 kg chlorine cylinders.

ii. Drift Loss in the Cooling Towers

It is very difficult to ignore drift problem in cooling towers. Now-a—days most of the end user specification calls for 0.02% drift loss. With technological development and processing of PVC, manufacturers have brought large change in the drift eliminator shapes and the possibility of making efficient designs of drift eliminators that enable end user to specify the drift loss requirement to as low as 0.003 — 0.001%.

iii. Cooling Tower Fans

The purpose of a cooling tower fan is to move a specified quantity of air through the system, overcoming the system resistance which is defined as the pressure loss. The product of air flow and the pressure loss is air power developed/work done by the fan; this may be also termed as fan output and input kW depends on fan efficiency.

The fan efficiency in turn is greatly dependent on the profile of the blade. An aerodynamic profile with optimum twist, taper and higher coefficient of lift to coefficient of drop ratio can provide the fan total efficiency as high as 85-92 %. However, this efficiency is drastically affected by the factors such as tip clearance, obstacles to airflow and inlet shape, etc.

As the metallic fans are manufactured by adopting either extrusion or casting process it is always difficult to generate the ideal aerodynamic profiles. The FRP blades are normally hand moulded which facilitates the generation of optimum aerodynamic profile to meet specific duty condition more efficiently. Cases reported where replacement of metallic or Glass fibre reinforced plastic fan blades have been replaced by efficient hollow FRP blades, with resultant fan energy savings of the order of 20-30% and with simple payback period of 6 to 7 months.

Also, due to lightweight, FRP fans need low starting torque resulting in use of lower HP motors. The Light weight of the fans also increases the life of the gear box, motor and bearing is and allows for easy handling and maintenance.

iv. Performance Assessment of Cooling Towers

In operational performance assessment, the typical measurements and observations involved are:

- Cooling tower design data and curves to be referred to as the basis.
- Intake air WBT and DBT at each cell at ground level using a whirling psychrometer.
- Exhaust air WBT and DBT at each cell using a whirling psychrometer.
- CW inlet temperature at risers or top of tower, using accurate mercury in glass or a digital thermometer.
- CW outlet temperature at full bottom, using accurate mercury in glass or a digital thermometer.
- Process data on heat exchangers, loads on line or power plant control room readings, as relevant.
- CW flow measurements, either direct or inferred from pump motor kW and pump head and flow characteristics.
- CT fan motor amps, volts, kW and blade angle settings
- TDS of cooling water.
- Rated cycles of concentration at the site conditions.
- Observations on nozzle flows, drift eliminators, condition of fills, splash bars, etc.

The findings of one typical trial pertaining to the Cooling Towers of a Thermal Power Plant 3 x 200 MW is given below:

Observations

Unit Load 1 & 3 of the Station	=	398 MW
Mains Frequency	=	49.3
Inlet Cooling Water Temperature °C	=	44 (Rated 43°C)
Outlet Cooling Water Temperature °C	=	37.6 (Rated 33°C)
Air Wet Bulb Temperature near Cell °C	=	29.3 (Rated 27.5°C)
Air Dry Bulb Temperature near Cell °C	=	40.8°C
Number of CT Cells on line with water flow	=	45 (Total 48)
Total Measured Cooling Water Flow m^3/hr	=	70426.76
Measured CT Fan Flow m^3/hr	=	989544

Analysis

CT water Flow/Cell, m^3/hr	=	1565 m^3/hr (1565000 kg/hr) (Rated 1875 m^3/hr)
CT Fan air Flow, m^3/hr (Avg.)	=	989544 m^3/hr (Rated 997200 m^3/hr)
CT Fan air Flow kg/hr (Avg.) @ Density of 1.08 kg/m^3	=	1068708 kg/hr
L/G Ratio of C.T. kg/kg	=	1.46 (Rated 1.74 kg/kg)

CT Range = (44 – 37.6) = 6.4°C

CT Approach = (37.6 – 29.3) = 8.3°C

% CT Effectiveness

$$= \frac{Range}{(Range + Approach)} \, x \, 100$$

$$= \frac{6.4}{(6.4 + 8.3)} \, x \, 100$$

$$= 43.53$$

Rated % CT Effectiveness = 100 * (43 – 33) / (43 – 27.5)

= 64.5%

Cooling Duty Handled/Cell in kcal	= $1565 * 6.4 * 10^3$
(i.e., Flow * Temperature Difference in kcal/hr)	= $10016 * 10^3$ kcal/hr (Rated $18750 * 10^3$ kcal/hr)
Evaporation Losses in m^3/hr	= 0.00085 x 1.8 x circulation rate (m^3/hr) x (T_1-T_2)
	= 0.00085 x 1.8 x 1565 x (44-37.6)
	= 15.32 m^3/hr per cell
Percentage Evaporation Loss	= [15.32/1565]*100
	= 0.97%
Blow down requirement for site COC of 2.7	= Evaporation losses / (COC–1)
	= 15.32/(2.7–1) per cell i.e., 9.01 m^3/hr
Make up water requirement/cell in m^3/hr	= Evaporation Loss + Blow down Loss
	= 15.32 + 9.01 = 2433

Comments

- Cooling water flow per cell is much lower, almost by 16.5%, need to investigate CW pump and system performance for improvements. Increasing CW flow through cell was identified as a key result area for improving performance of cooling towers.
- Flow stratification in 3 cooling tower cells identified.
- Algae growth identified in 6 cooling tower cells.
- Cooling tower fans are of GRP type drawing 36.2 kW average. Replacement by efficient hollow FRP fan blades is recommended.

23.8 Flow Control Strategies

Control of tower air flow can be done by varying methods: starting and stopping (ON-OFF) of fans, use of two- or three-speed fan motors, use of automatically adjustable pitch fans, and use of variable speed fans.

ON-OFF fan operation of single speed fans provides the least effective control. Two-speed fans provide better control with further improvement shown with three speed fans. Automatic adjustable pitch fans and variable-speed fans can provide even closer control of tower cold-water temperature. In multi-cell towers, fans in adjacent cells may be running at different speeds or some may be on and others off depending upon the tower load and required water temperature. Depending upon the method of air volume control selected, control strategies can be determined to minimize fan energy while achieving the desired control of the Cold water temperature.

23.9 Energy Saving Opportunities in Cooling Towers

- Follow manufacturer's recommended clearances around cooling towers and relocate or modify structures that interfere with the air intake or exhaust.
- Optimize cooling tower fan blade angle on a seasonal and/or load basis.
- Correct excessive and/or uneven fan blade tip clearance and poor fan balance.
- On old counter-flow cooling towers, replace old spray type nozzles with new square spray
- ABS practically non-clogging nozzles.
- Replace splash bars with self-extinguishing PVC cellular film fill.

- Install new nozzles to obtain a more uniform water pattern
- Periodically clean plugged cooling tower distribution nozzles.
- Balance flow to cooling tower hot water basins.
- Cover hot water basins to minimize algae growth that contributes to fouling.
- Optimize blow down flow rate, as per COC limit.
- Replace slat type drift eliminators with low pressure drop, self-extinguishing, PVC cellular units.
- Restrict flows through large loads to design values.
- Segregate high heat loads like furnaces, air compressors, DG sets, and isolate cooling towers for sensitive applications like A/C plants, condensers of captive power plant etc. A 1°C cooling water temperature increase may increase A/C compressor kW by 2.7%. A 1°C drop in cooling water temperature can give a heat rate savings of 5 kcal/kWh in a thermal power plant.
- Monitor L/G ratio, CW flow rates w.r.t. design as well as seasonal variations. It would help to increase water load during summer and times when approach is high and increase air flow during monsoon times and when approach is narrow.
- Monitor approach, effectiveness and cooling capacity for continuous optimization efforts, as per seasonal variations as well as load side variations. — Consider COC improvement measures for water savings.
- Consider energy efficient FRP blade adoption for fan energy savings.
- Consider possible improvements on CW pumps w.r.t. efficiency improvement.
- Control cooling tower fans based on leaving water temperatures especially in case of small units.
- Optimize process CW flow requirements, to save on pumping energy, cooling load, evaporation losses (directly proportional to circulation rate) and blow down losses.

23.10 Case Study: Application of VFD for Cooling Tower (CT) Fan

The rating (KW) of the CT fan is selected for the worst case wet and dry bulb temperatures. In areas where such temperature conditions occur for a small portion of the year & which require maximum air flow for this condition, it is possible to improve energy efficiency by reducing the speed of the fan (to obtain reduced air flow), using a VFD.

It is therefore necessary to obtain data for the variations in wet and dry bulb temperatures on an annual basis to arrive at estimates for the energy saved through use of VFD. Alternatively, it is also possible to install a VFD on a trial basis on the CT fans and measure the electrical power consumed with and Without VFD.
The relationship between the power consumed by the CT fan and the airflow delivered by it follows a cube law. The potential for energy savings exists if a proper analysis of the cooling system is made.

Implementation with VFD

An energy efficient system with VFD can be realized through the use of closed loop control. In this control method, the return or cold water temperature is used as the feedback signal to the PID controller which is a standard control block in the drive.

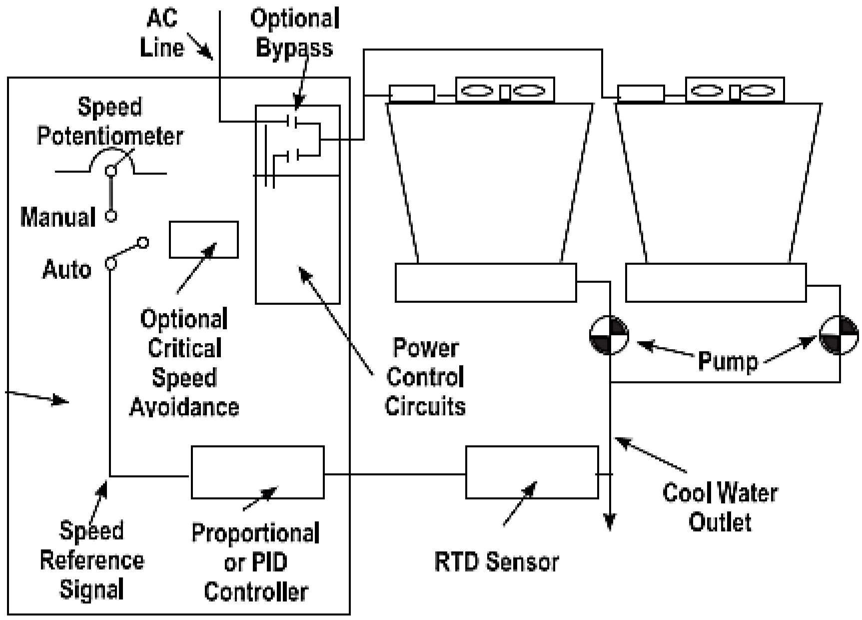


Figure 23.5 Schematic of CT fan control with VFD & closed loop feedback

The highlights of control with temperature feedback and drive can be summarized below:

An RTD sensor, installed at the CT outlet generates a 4 -20 mA current signal as the feedback to the integrated Process PID Controller in the drive.

The set point for the cooled water temperature is entered in engineering units (°C or 0F) in the drive controller.

Any error between the set point and the feedback signal (temperature in this case) will be integrated by the PID controller so that the same, after correction, is zero. For example, if there is an increase in the outlet temperature (due to wet bulb temperature increase or due to an increase in plant load), the feedback exceeds the set point & the error A becomes negative. The PID controller output will now try to increase the drive frequency so that the fans deliver more cooling air for evaporation. This has the effect of bringing down the outlet temperature. The correction continues till the feedback signal matches the set point. A similar correction takes place when the outlet temperature reduces. In that case, the CT fan motor speed is reduced to bring the A value to zero.

This design therefore permits precise control of outlet temperature and conserves energy.

In the event of drive failure, the CT fans can still be operated through an optional built-in bypass circuit which will transfer the power source to the mains supply, thereby ensuring uninterrupted operation.

Use of VFD for CT fan motors in Ingot manufacturing plant

An aluminium ingot manufacturing plant requires large amounts of water for cooling of the ingots. Hence cooling tower fans are required to cool the water from the ingot plant. The salient features of the application are as given below:

- Drives have been installed on two Cooling Towers.
- Details of drives supplied as follows:

Cooling Tower (CT)	No of CT Fans	CT Fan Motor, KW	Drive, KW
1	3	11	37
2	3	15	45

Details of control and power consumption

The previous method of control employed a digital temperature controller to switch ON & OFF the CT Fans depending upon the basin temperature. A typical daily regimen employed for CT#l was as follows:

(a) 3 Nos. CT Fans running for 8 Hours.
(b) 2 Nos. CT Fans running for 8 Hours.
(C) 1 No CT Fan running for 5 hours.

Trials were taken with the VFD (common to 3 nos. drive motors as shown in Figure 7.6 below) installed in CT 1 and run for a period of one month to ascertain the power consumption with and without the drive.

Note:

- The applicable power supply voltage in this case would be 415V, 50Hz.
- There is a bypass line which will enable the motors to operate from mains supply in case of VFD failure.

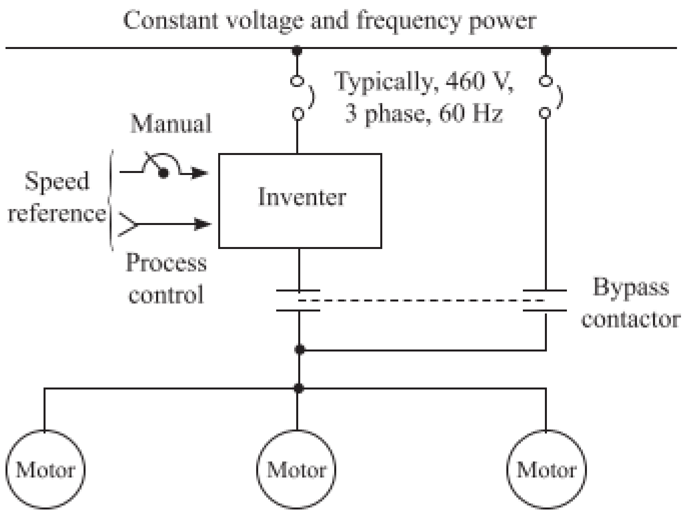


Figure 23.6 Typical Power Schematic of VFD and CT fan motors

It was compared with the power consumed with manual operation (as described above) on a daily basis. It yielded a significant result in terms of power saved daily.

Savings calculation with VFD operation:

Energy consumed daily with manual control (kWh)	= 392
Energy consumed daily with VFD control (kWh)	= 254
Energy saved on daily basis with VFD control (kWh)	= 138
Energy saved on daily basis with VFD control (%)	= 35.2
Unit energy cost (BDT)	= 5
Number of days of running of fans in a month	= 26

Number of months in a year	= 12
Annual savings due to VFD operation (BDT)	= 215280
Average price of drive panel (BDT)	= 250000
Payback period (Year)	= 1.16

*Data for savings extrapolated for annual estimates

In practice, the power saved with VFD operation would also depend upon the wet bulb temperature which would vary on a seasonal basis. In case of higher temperatures, the VFD would be required to run at maximum speed during which period, the savings would be negligible. Hence the average annual savings would reduce depending upon the site environmental conditions. The quantum of savings can be optimized by having a closed loop system as shown above which will track the outlet water temperature and determine the drive motor speed accurately.

Example 23.2

The energy audit observations at a cooling tower (CT) in a process industry are given below:
Cooling Water (CW) Flow: 3000 m3/hr
CW in Temperature: 4 1 deg. C
CW Out Temperature: 31 deg C
Wet Bulb Temperature: 24 deg. C

Find out Range, Approach, Effectiveness and cooling tower capacity in kcal per hour of the CT?

Solution

Range = (Inlet -Outlet) Cooling Water Temperature deg. C
Range = (41 - 31) =10 deg. C
Approach = (Outlet Cooling Water - Air Wet Bulb) Temperature deg. C
Approach = (31 - 24) = 7 deg C
% CT Effectiveness = Range / (Range + Approach) x 100
% Effectiveness = 100 x [Range / (Approach + Range)]
10/ [10+7] x 100 = 58.8 %
Cooling capacity, kcal/hr = heat rejected = CW flow rate in kg per hour x (CW inlet hot water temp. to CT, deg. C - CW outlet cold well temp, deg. C)
Cooling capacity = 3000X1000X (41 - 31) = 30,000,000 kCal per ho

CHAPTER 24: ALTERNATE POWER GENERATION SYSTEM

24.1 Diesel / Natural Gas Power Generating System

24.1.1 Introduction

Reciprocating engines produce electricity using a combustible fuel and generator. In addition to producing electricity, useful heat can be recovered from the exhaust gas using a heat recovery steam generator (HRSG), or heat recovery system for hot water (Figure 24.1). Heat can also be recovered from the lubricating oil cooler, the jacket water cooler and/or the charge air cooler, and this recovered "waste" heat can be provided to a heating load. In this case, the reciprocating engine power plant would be operating in a Combined Heat & Power (CHP) or cogeneration mode. The energy performance of a reciprocating engine is influenced by a number of factors such as the type of fuel, the reciprocating engine power capacity, minimum capacity, availability, heat rate and heat recovery efficiency.

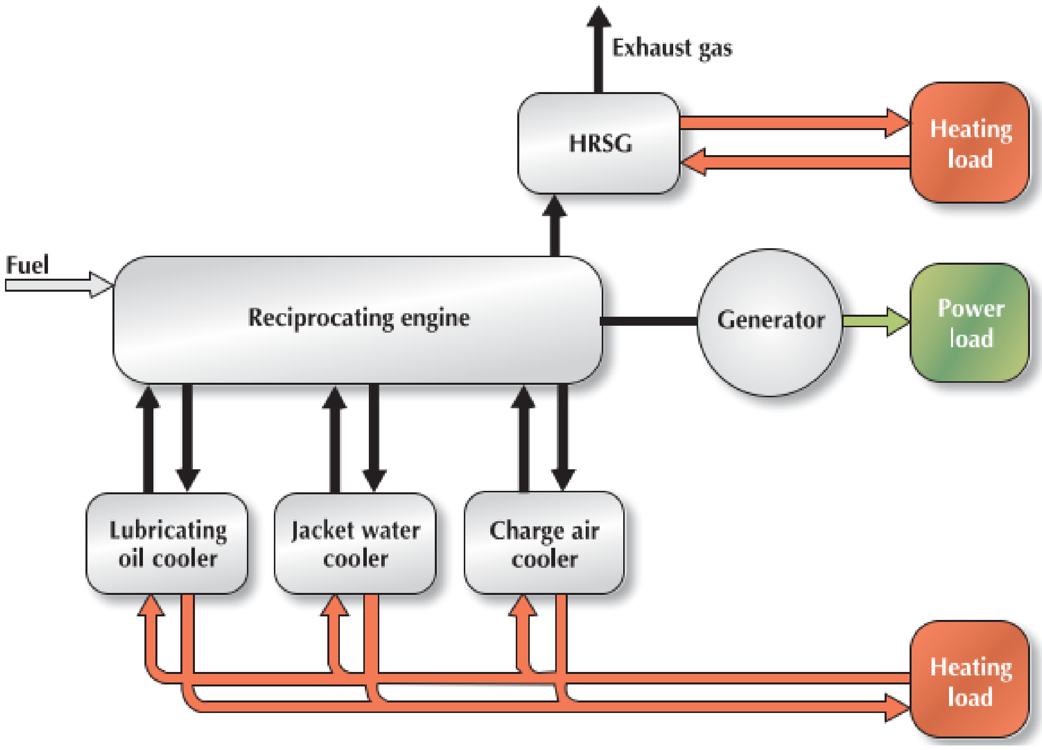


Figure 24.1 Reciprocating Engine Cogeneration

There are two basic types of reciprocating engines - spark ignition and compression ignition. Spark ignition engines use a spark (across a spark plug) to ignite a compressed fuel-air mixture. Typical fuels for such engines are gasoline, natural gas and sewage and landfill gas. Compression ignition engines compress air to a high pressure, heating the air to the ignition temperature of the fuel, which then is injected. The high compression ratio used for compression ignition engines results in a higher efficiency than is possible with spark ignition engines. Diesel/heavy fuel oil is normally used in compression ignition engines, although some are dual-fuelled (natural gas is compressed with the combustion air and diesel oil is injected at the top of the compression stroke to initiate combustion).

Diesel Engine Cycle

Diesel engine is the prime mover, which drives an alternator to produce electrical energy. In the Diesel engine, air is drawn into the cylinder and is compressed to a high ratio (14:1 to 25:1). During this compression, the air is heated to a temperature of700—90000 A metered quantity of diesel fuel is then injected into the cylinder, which ignites spontaneously because of the high temperature. Hence, the diesel engine is also known as compression ignition (CI) engine. DG set can be classified according to cycle type as: two stroke and four stroke. However, the bulk of IC engines use the four stroke cycle. Let us look at the principle of operation of the four-stroke diesel engine. The 4 stroke operations in a diesel engine (Figure 24.2) are: induction stroke, compression stroke, ignition and power stroke and exhaust stroke.

1st : Induction stroke - while the inlet valve is open, the descending piston draws in fresh air.
2nd : Compression stroke - while the valves are closed, the air is compressed to a pressure of up to 25 bar.
3rd : Ignition and power stroke - fuel is injected, while the valves are closed (fuel injection actually starts at the end of the previous stroke), the fuel ignites spontaneously and the piston is forced downwards by the combustion gases.
4th : Exhaust stroke - the exhaust valve is open and the rising piston discharges the spent gases from the cylinder

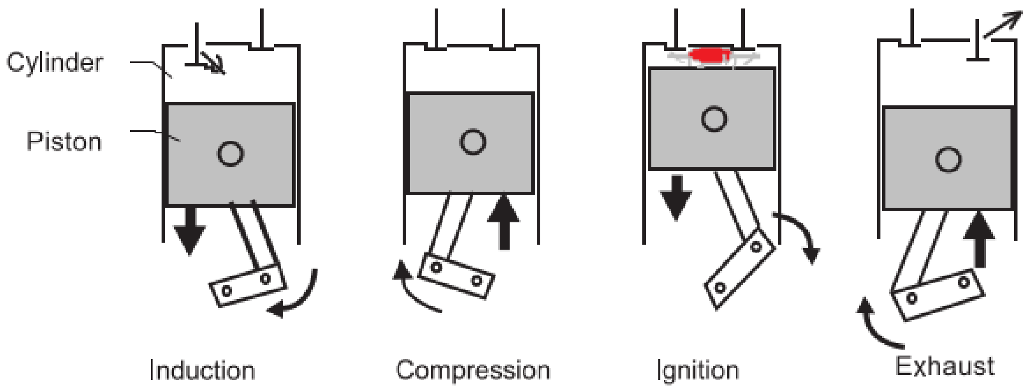


Figure 24.2 Schematic Diagram of Four-Stroke Diesel Engine

Since power is developed during only one stroke, the single cylinder four-stroke engine has a low degree of uniformity. Smoother running is obtained with multi cylinder engines because the cranks are staggered in relation to one another on the crankshaft. There are many variations of engine configuration, for example. 4 or 6 cylinders, in-line, horizontally opposed, vee or radial configurations.

Gas Engines

A typical spark-ignited lean-burn engine is depicted in Figure 9.3. In this process, the gas is mixed with air before the inlet valves. During the intake period, gas is also fed into a small pre chamber, where the gas mixture is rich compared to the gas in the cylinder. At the end of the compression phase the gas/air mixture in the pre chamber is ignited by a spark plug. The flames from the nozzle of the pre chamber ignite the gas/air mixture in the whole cylinder. Combustion is fast. After the working phase the cylinder is emptied of exhaust and the process starts again. Reciprocating engines with modern lean-bum technology reach close to 45% electrical efficiency.

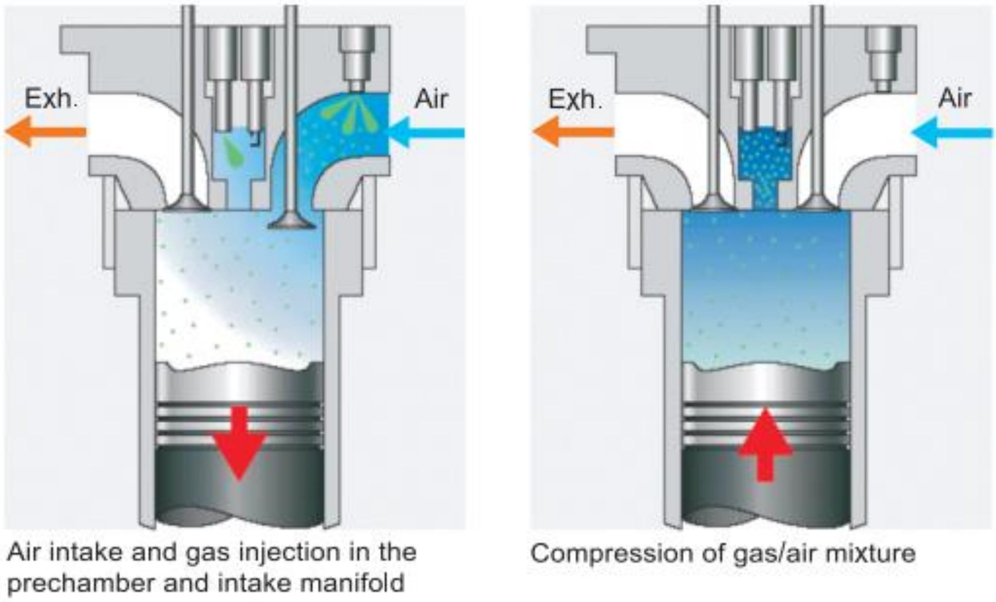


Figure 24.3 Natural Gas Engine

DG Set as a System

A diesel generating set (Figure 24.4) should be considered as a system since its successful operation depends on the well-matched performance of the components, namely:

a) The diesel engine and its accessories.

b) The AC Generator.

c) The control systems and switchgear.

d) The foundation and power house civil works.

e) The connected load with its own components like heating, motor drives, lighting etc.

It is necessary to select the components with highest efficiency and operate them at their optimum efficiency levels to conserve energy in this system.

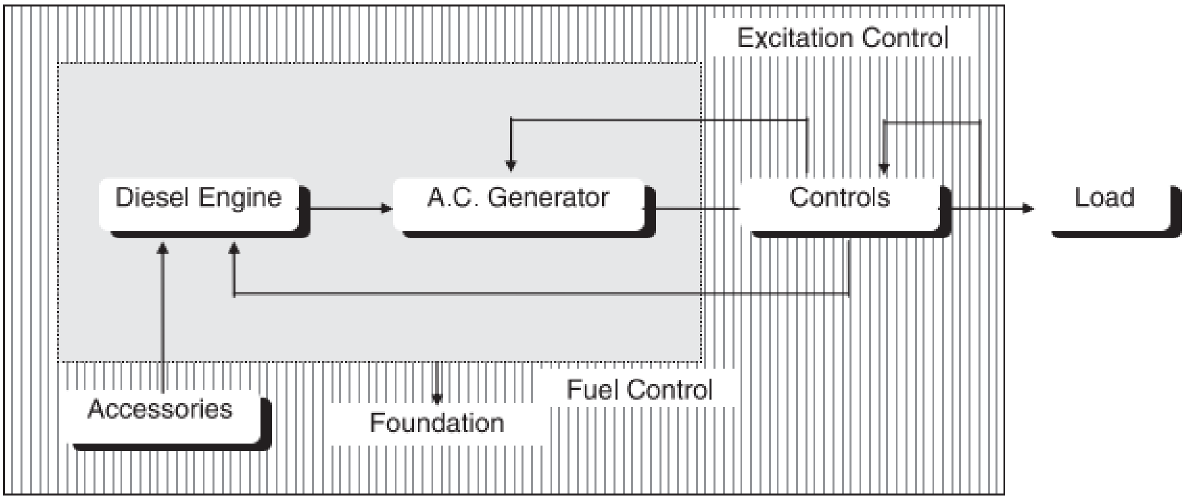


Figure 24.4 DG Set System

Selection Considerations

To make a decision on the type of engine, which is most suitable for a specific application, several factors need to be considered. The two most important factors are: power and speed of the engine. The power requirement is determined by the maximum load. The engine power rating should be 10-20 % more than the power demand by the end use. This prevents overloading the machine by absorbing extra load during starting of motors or switching of some types of lighting systems or when wear and tear on the equipment pushes up its power consumption. Speed is measured at the output shaft and given in revolutions per minute (RPM). An engine will operate over a range of speeds, with diesel engines typically running at lower speeds (1300 - 3000 RPM). There will be an optimum speed at which fuel efficiency will be greatest. Engines should be run as closely as possible to their rated speed to avoid poor efficiency and to prevent build-up of engine deposits due to incomplete combustion - which will lead to higher maintenance and running costs. To determine the speed requirement of an engine, one has to again look at the requirement of the load. For some applications, the speed of the engine is not critical, but for other applications such as a generator, it is important to get a good speed match. If a good match can be obtained, direct coupling of engine and generator is possible; if not, then some form of gearing will be necessary - a gearbox or belt system, which will add to the cost and reduce the efficiency. There are various other factors that have to be considered, when choosing an engine for a given application. These include the following: cooling system, abnormal environmental conditions (dust, dirt, etc.), fuel quality, speed governing (fixed or variable speed), poor maintenance, control system, starting equipment, drive type, ambient temperature, altitude, humidity, etc. Suppliers or manufacturers literature will specify the required information when purchasing an engine. The efficiency of an engine depends on various factors, for example, load factor (percentage of full load), engine size, and engine type.

Diesel Generator Captive Power Plants

Diesel engine power plants are most frequently used in small power (captive non-utility) systems. The main reason for their extensive use is the higher efficiency of the diesel engines compared with gas turbines and small steam turbines in the output range considered. In applications requiring low captive power, without much requirement of process steam, the ideal method of power generation would be by installing diesel generator plants. The fuels burnt in diesel engines range from light distillates to residual fuel oils. Most frequently used diesel engine sizes are between the range 4 to 15 MW. For continuous operation, low speed diesel engine is more cost-effective than high speed diesel engine.

Advantages of adopting Diesel Power Plants are:

- Low installation cost
- Short delivery periods and installation period
- Higher efficiency (as high as 43 -45 %)
- More efficient plant performance under part loads
- Suitable for different type of fuels such as low sulphur heavy stock and heavy fuel oil in case of large capacities.
- Minimum cooling water requirements,
- Adopted with air cooled heat exchanger in areas where water is not available
- Short start up time

A brief comparison of different types of captive power plants (combined gas turbine and steam turbine, conventional steam plant and diesel engine power plant) is given in Table 24.1. It can be seen from the Table that captive diesel plant wins over the other two in terms of thermal efficiency, capital cost, space requirements, auxiliary power consumption, plant load factor etc.

Table 24.1: Comparison of Different type of Captive Power Plant

Description	Units	Combined GT & ST	Conventional Steam Plant	Diesel Engine Power Plant
Thermal Efficiency	%	40 - 46	33 - 36	43 - 45
Initial Investment of Installed Capacity	BDT/KW	8,500- 10,000	15,000-18,000	7,500 - 9,000
Space requirement		125% (approx.)	250% (approx.)	100% (approx.)
Construction time	Months	24 - 30	42 - 48	12 - 15
Project period	Months	30 - 36	52 - 60	12
Auxiliary Power Consumption	%	2 - 4	8 - 10	1.3 - 2.1
Plant Load Factor	kWh/kW	6000 - 7000	5000 - 6000	7200 - 7500
Start Up Time from Cold	Minutes	About 10	120 - 180	15 - 20

Diesel Engine Power Plant Developments

The diesel engine developments have been steady and impressive. The specific fuel consumption has come down from a value of 220 g/kWh in the 1970's to a value of around 160 g/kWh in present times. Slow speed diesel engine, with its flat fuel consumption curve over a wide load range (50%-100%), compares very favourably over other prime movers such as medium speed diesel engine, steam turbines and gas turbines. With the arrival of modern, high efficiency turbochargers, it is possible to use an exhaust gas driven turbine generator (Figure 9.5) to further increase the engine rated output. The net result would be lower fuel consumption per kWh and further increase in overall thermal efficiency.

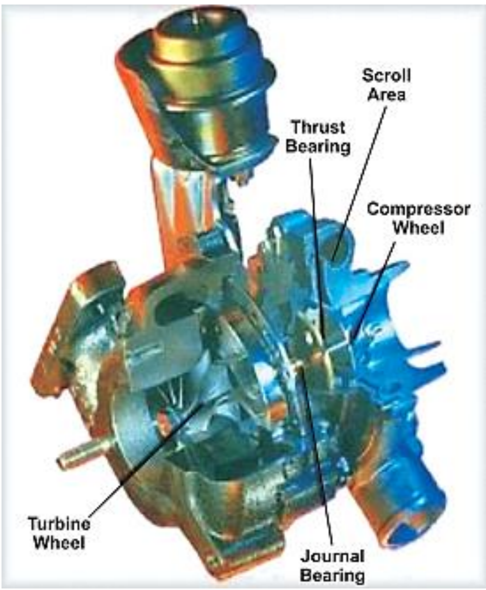


Figure 24.5: Turbocharger

The diesel engine is able to burn the poorest quality fuel oils, unlike gas turbine, which is able to do so with only costly fuel treatment equipment. Slow speed dual fuel engines are now available using high-pressure gas injection, which gives the same thermal efficiency and power output as a regular fuel oil engine.

24.1.2 Selection and Installation Factors

Sizing of a Genset:

a) If the DG set is required for 100% standby, then the entire connected load in HP / kVA should be added. After finding out the diversity factor, the correct capacity of a DG set can be found out.

Example 9.1

Connected Load	= 650 kW
Diversity Factor	= 0.54
(Demand / Connected load)	
Max. Demand	= 650 x 0.54 = 350 kW
% Loading	= 70
Set rating	= 350/0.7 = 500 kW
At 0.8 PF, rating	= 625 kVA

b) For an existing installation, record the current, voltage and power factors (kWh / kVAh) reading at the main bus-bar of the system at every half-an—hour interval for a period of 2-3 days and during this period the factory should be having its normal operations. The non-essential loads should be switched off to find the realistic current taken for running essential equipment. This will give a fair idea about the current taken from which the rating of the set can be calculated.

For existing installation:

kVA = √3 VI
kVA Rating = kVA/ Load Factor
where Load factor = Average kVA/ Maximum kVA

c) For a new installation, an approximate method of estimating the capacity of a DG set is to add full load currents of all the proposed loads to be run in DG set. Then, applying a diversity factor depending on the industry, process involved and guidelines obtained from other similar units correct capacity can be arrived at.

High Speed Engine or Slow/Medium Speed Engine

The normal accepted definition of high speed engine is 1500 rpm. The high speed sets have been developed in India, whereas the slow speed engines of higher capacities are often imported. The other features and comparison between high and medium / slow speed engines are mentioned in Table 24.2 below:

Table 24.2 Comparison of High and Slow Speed Engine

Factor	Slow speed engine	High speed engine
Break mean effective pressure - therefore wear and tear and consumption of spares	Low	High
Weight to power ratio- therefore sturdiness and life	More	Less
Space	High	Less
Type of use	Continuous use	Intermittent use
Period between overhauls*	8000 hours	3200
Direct operating cost (Include Lubricating Oils, filters etc.	Less	High

* Typical recommendations from manufacturers

Keeping the above factors and available capacities of DG set in mind, the cost of economics for both the engines should be worked out before arriving at a decision.

Capacity Combinations

From the point of View of space, operation, maintenance and initial capital investment, it is certainly economical to go in for one large DG set than two or more DG sets in parallel.

Two or more DG sets running in parallel can be an advantage as only the short-fall in power — depending upon the extent of power cut prevailing - needs to filled up. Also, flexibility of operation is increased since one DG set can be stopped, while the other DG set is generating at least 50% of the power requirement. Another advantage is that one DG set can become 100% standby during lean and low power-cut periods.

Air Cooling Vs. Water Cooling

The general feeling has been that a water-cooled DG set is better than an air-cooled set, as most users

are worried about the overheating of engines during summer months. This is to some extent is true and precautions have to be taken to ensure that the cooling water temperature does not exceed the prescribed limits.
However, from performance and maintenance point of view, water and air-cooled sets are equally good except that proper care should be taken to ensure cross ventilation so that as much cool air as possible is circulated through the radiator to keep its cooling water temperature within limits. While, it may be possible to have air cooled engines in the lower capacities, it will be necessary to go in for water cooled engines in larger capacities to ensure that the engine does not get over-heated during summer months.

Safety Features

It is advisable to have short circuit, over load and earth fault protection on all the DG sets. However, in case of smaller capacity DG sets, this may become uneconomical. Hence, it is strongly recommended to install a circuit protection. Other safety equipment like high temperature, low lube oil pressure cut-outs should be provided, so that in the event of any of these abnormalities, the engine would stop and prevent damage. It is also essential to provide reverse power relay when DG sets are to run in parallel to avoid back feeding from one alternator to another.

Parallel Operation with Grid

Running the DG set in parallel with the mains from the supply undertakings can be done in consultation with concerned electricity authorities. However, some supply undertakings ask the consumer to give an undertaking that the DG set will not be run in parallel with their supply. The reasons stated are that the grid is an infinite bus and paralleling a small capacity DG set would involve operational risks despite normal protections like reverse power relay, voltage and frequency relays.

Maximum Single Load on DG Set

The starting current of squirrel cage induction motors is as much as six times the rated current for a few seconds with direct-on-line starters. In practice, it has been found that the starting current value should not exceed 200 % of the full load capacity of the alternator. The voltage and frequency throughout the motor starting interval recovers and reaches rated values usually much before the motor has picked up full speed.

In general, the HP of the largest motor that can be started with direct on line starting is about 50 % of the kVA rating of the generating set. On the other hand, the capacity of the induction motor can be increased, if the type of starting is changed over to star delta or to auto transformer starter, and with this starting the HP of the largest motor can be up to 75 % of the kVA of Gen set.

Unbalanced Load Effects

It is always recommended to have the load as much balanced as possible, since unbalanced loads cause heating of the alternator, which may result in unbalanced output voltages. The maximum unbalanced load between phases should not exceed 10 % of the capacity of the generating sets.

Neutral Earthing

The electricity rules clearly specify that two independent earths to the body and neutral should be provided to give adequate protection to the equipment in case of an earth fault, and also to drain away any leakage of potential from the equipment to the earth for safe working.

Site Condition Effects on Performance Derating

Site condition with respect to altitude, intake temperature, cooling water temperature and de-rate diesel engine output as shown in following Tables: 24.3 and 24.4.

Table 24.3 Altitude and Intake Temperature Corrections

Correction Factors For Engine Output				
Altitude Correction			Temperature Correction	
Altitude Meters over MSL	Non Super Charged	Super Charged	Intake °C	Correction Factor
610	0.980	0.980	32	1.000
915	0.935	0.950	35	0.986
1220	0.895	0.915	38	0.974
1525	0.855	0.882	41	0.962
1830	0.820	0.850	43	0.950
2130	0.780	0.820	46	0.937
2450	0.745	0.790	49	0.925
2750	0.712	0.765	52	0.913
3050	0.680	0.740	54	0.900
3660	0.612	0.685		
4270	0.550	0.630		
4880	0.494	0.580		

Table 24.4 Derating due to Air Inter Cooler Water Inlet

Water Temperature °C	Flow %	Derating %
25	100	0
30	125	3
35	166	5
40	166	8

24.1.3 Operational Factors

Load Pattern & DG Set Capacity

The average load can be easily assessed by logging the current drawn at the main switchboard on an average day. The 'over load' has a different meaning when referred to the D.G. set. Overloads, which appear insignificant and harmless on electricity board supply, may become detrimental to a D.G. set, and hence overload on D.G. set should be carefully analysed. Diesel engines are designed for 10% overload for 1 hour in every 12 hours of operation. The AC. generators are designed to meet 50% overload for 15 seconds as specified by standards. The D.G. set/s selection should be such that the overloads are within the above specified limits. It would be ideal to connect steady loads on DG set to ensure good performance. Alongside alternator loading, the engine loading in terms of kW or BHP, needs to be maintained above 50%. Ideally, the engine and alternator loading conditions are both to be achieved towards high efficiency.

Engine manufacturers offer curves indicating % Engine Loading vs fuel Consumption in grams/BHP. Optimal engine loading corresponding to best operating point is desirable for energy efficiency.

Alternators are sized for kVA rating with highest efficiency attainable at a loading of around 70% and more. Manufacturer's curves can be referred to for best efficiency point and corresponding kW and kVA loading values.

Sequencing of Loads

The captive diesel generating set has certain limits in handling the transient loads. This applies to both kW (as reflected on the engine) and kVA (as reflected on the generator). In this context, the base load that exists before the application of transient load brings down the transient load handling capability, and in case of AC. generators, it increases the transient voltage dip. Hence, great care is required in sequencing the load on D.G. set/s. It is advisable to start the load with highest transient kVA first followed by other loads in the descending order of the starting kVA. This will lead to optimum sizing and better utilization of transient load handling capacity of D.G. set.

Load Pattern

In many cases, the load will not be constant throughout the day. If there is substantial variation in load, then consideration should be given for parallel operation of D.G. sets. In such a situation, additional D.G. set(s) are to be switched on when load increases. The typical case may be an establishment demanding substantially different powers in first, second and third shifts. By parallel operation, D.G. sets can be run at optimum operating points or near about, for optimum fuel consumption and additionally, flexibility is built into the system. This scheme can be also be applied where loads can be segregated as critical and non-critical loads to provide standby power to critical load in the captive power system.

Load Characteristics

Some of the load characteristics influence efficient use of D.G. set. These characteristics are entirely load dependent and cannot be controlled by the D.G. set. The extent of detrimental influence of these characteristics can be reduced in several cases

Power Factor:

The load power factor is entirely dependent on the load. The AC. generator is designed for the power factor of0.8 lag as specified by standards. Lower power factor demands higher excitation currents and results in increased losses. Over sizing A.C. generators for operation at lower power factors results in lower operating efficiency and higher costs. The economical alternative is to provide power factor improvement capacitors.

Unbalanced Load:

Unbalanced loads on AC. generator leads to unbalanced set of voltages and additional heating in AC. generator. When other connected loads like motor loads are fed with unbalanced set of voltages additional losses occur in the motors as well. Hence, the load on the AC. generators should be balanced as far as possible. Where single phase loads are predominant, consideration should be given for procuring single phase A.C. generator.

Transient Loading:

On many occasions to contain transient voltage dip arising due to transient load application, a specially designed generator may have to be selected. Many times, a non-standard combination of engine and AC. generator may have to be procured. Such a combination ensures that the prime mover is not unnecessarily oversized which adds to capital cost and running cost.

Special Loads:

Special loads like rectifier/thyristor loads, welding loads, furnace loads need an application check. The manufacturer of diesel engine and AC generator should be consulted for proper recommendation so that desired utilization of DG set is achieved without any problem. In certain cases of loads, which are sensitive to voltage, frequency regulation, voltage wave form, consideration should be given to segregate the loads, and feed it by a dedicated power supply which usually assumes the form of DG motor driven generator set. Such an alternative ensures that special design of AC generator is restricted to that portion of the load which requires high purity rather than increasing the price of the D.G. set by specially designed AC generator for complete load.

Waste Heat Recovery in DG Sets

For combined heat and power applications, waste heat from reciprocating engines can be tapped mainly from exhaust gases and cooling water that circulates around cylinders in the engine jackets, with additional potential from oil and turbo coolers. While engine exhaust and cooling water each provide about half of the useful thermal energy, the exhaust is at much higher temperature (around 450 °C versus 100 °C) and hence is more versatile. Atypical energy balance in a reciprocating engine generator using Diesel and Natural gas is given in Table 24.5 below.

Table 24.5 Energy Balance for Reciprocating Engine

	Conventional cooling system		Cooling system with engine jacket and exhaust heat recovery		
500-kW natural gas engine generator*					
Electric power	**30%**			**30%**	
Jacket-water heat	**38%**	**70% wasted**		**38%**	**54% recoverable**
Exhaust heat	**24%**		**Exh recoverable**	**16%**	
			Exh lost	**8%**	**16% wasted**
Radiated heat lost to atmosphere	**8%**			**8%**	
	100%			**100%**	
500-kW diesel engine generator*					
Electric power	**35%**			**35%**	
Jacket water	**32%**	**65% wasted**		**32%**	**48% recoverable**
Exhaust heat	**24%**		**Exh recoverable**	**16%**	
			Exh lost	**8%**	**17% wasted**
Radiated heat lost to atmosphere	**9%**			**9%**	
	100%			**100%**	

The table reveals that for natural gas generator more thermal energy (54%) can be recovered from the reciprocating engine compared to an electrical energy conversion of 30%.

It would be realistic to assess the Waste Heat Recovery (WHR) potential in relation to quantity, temperature margin, in kcal/hr as:

$$\text{Potential WHR} = (\text{kWh Output/hour}) \times (8\ \text{kg Gases / kWh Output}) \times 0.25\ \text{kcal/kg}^\circ\text{C} \times (t_g - 180^\circ\text{C})$$

Where, t_g is the gas temperature after Turbocharger, (the criteria being that limiting exit gas temperature cannot be less than 180°C, to avoid acid dew point corrosion), 0.25 being the specific heat of flue gases and kWh output being the actual average unit generation from the set per hour. For a 1100 kVA set, at 800 kW loading, and with 480°C exhaust gas temperature, the waste heat potential works out to:

$$800 \text{ kWh} \times 8 \text{ kg gas generation / kWh output} \times 0.25 \text{ kcal/kg °C} \times (480 - 180), \text{ i.e., } 4{,}80{,}000 \text{ kcal/hr}$$

While the above method yields only the potential for heat recovery, the actual realizable potential depends upon various factors and if applied judiciously, a well configured waste heat recovery system can tremendously boost the economics of captive DG power generation.

The factors affecting Waste Heat Recovery from flue Gases are:

a) DG Set loading, temperature of exhaust gases
b) Hours of operation and
c) Back pressure on the DG set

Consistent DG set loading (to over 60% of rating) would ensure a reasonable exit flue gas quantity and temperature. Fluctuations and gross under loading of DG set results in erratic flue gas quantity and temperature profile at entry to heat recovery unit, thereby leading to possible cold end corrosion and other problems. Typical flue gas temperature and flow pattern in a 5 MW DG set at various loads are given in Table 24.6

Table 24.6 Typical Flue gas Temperature and Flow pattern in a 5-MW DG Set at Various Load

100% Load	11.84 kg/sec	370°C
90% Load	10.80 kg/sec	350°C
70% Load	9.08 kg/sec	330°C
60% Load	7.50 kg/sec	325°C

If the normal load is 60%, the flue gas parameters for waste heat recovery unit would be 325°Cinlet temperature, 180°C outlet temperature and 27180 kg/hour gas flow.

At 90% loading, however, values would be 350°C and 32,400 kgs/Hour, respectively.

* Number of hours of operation of the DG Set has an influence on the thermal performance of waste heat Recovery unit. With continuous DG Set operations, cost benefits are favourable.
* Back pressure in the gas path caused by additional pressure drop in waste heat recovery unit is another key factor. Generally, the maximum back pressure allowed is around 250-300 mmWC and the heat recovery unit should have a pressure drop lower than that. Choice of convective waste heat recovery systems with adequate heat transfer area are known to provide reliable serv1ce.

The configuration of heat recovery system and the choice of steam parameters can be judiciously selected with reference to the specific industry (site) requirements. Much good work has taken place in Indian Industry regarding waste heat recovery and one interesting configuration, deployed is installation of waste heat boiler in flue gas path along with a vapour absorption chiller, to produce 8°C chilled water working on steam from waste heat.

Trigeneration Technology

In order to further optimize fuel utilization Trigeneration systems are developed which involves the simultaneous production of electricity, heat and cooling. The prime mover used for power generation includes diesel engines/gas engines. The waste heat recovery system in captive power generation units consists of waste heat recovery boiler for generating steam and use of jacket cooling water for operating Vapor Absorption Machines (VAM) to meet Air conditioning requirements.

24.1.4 Energy Performance Assessment of DG Sets

Routine energy efficiency assessment of DG sets on shop floor involves following typical steps:

1) Ensure reliability of all instruments used for trial.
2) Collect technical literature, characteristics, and specifications of the plant.
3) Conduct a 2-hour trial on the DG set, ensuring a steady load, wherein the following measurements are logged at 15 minutes intervals.

a) Fuel consumption (by dip level or by flow meter)
b) Amps, volts, PF, kW, kWh
c) Intake air temperature, Relative Humidity (RH)
d) Intake cooling water temperature
6) Cylinder-wise exhaust temperature (as an indication of engine loading)
f) Turbocharger RPM (as an indication of loading on engine)
g) Charge air pressure (as an indication of engine loading)
h) Cooling water temperature before and after charge air cooler (as an indication of cooler performance)
i) Stack gas temperature before and after turbocharger (as an indication of turbocharger performance)

4) The fuel oil/diesel analysis is referred to from an oil company data.
5) Analysis: The trial data is to be analysed with respect to:

a) Average alternator loading.
b) Average engine loading.
c) Percentage loading on alternator.
d) Percentage loading on engine.
e) Specific power generation kWh/litre.
f) Comments on Turbocharger performance based on RPM and gas temperature difference.
g) Comments on charge air cooler performance.
h) Comments on load distribution among various cylinders (based on exhaust temperature, the temperature to be i 5% of mean and high/low values indicate disturbed condition).
i) Comments on housekeeping issues like drip leakages, insulation, vibrations, etc.

A format as shown in the Table 24.7 is useful for monitoring the performance

Table 24.7 Typical format for DG set monitoring

DG Set No.	Electricity Generating Capacity (Site), kW	Derated Electricity Generating Capacity, kW	Type of Fuel used	Average Load as % of Derated Capacity	Specific Fuel Cons. Lit/ kWh	Specific Lube Oil Cons. Lit/kWh
1.	480	300	LDO	89	0.335	0.007
2.	480	300	LDO	110	0.334	0.024
3.	292	230	LDO	84	0.356	0.006
4.	200	160	HSD	89	0.325	0.003
5.	200	160	HSD	106	0.338	0.003
6.	200	160	HSD			
7.	292	230	LDO	79	0.339	0.006
8.	292	230	LDO	81	0.362	0.005
9.	292	230	LDO	94	0.342	0.003
10.	292	230	LDO	88	0.335	0.006
11.	292	230	LDO	76	0.335	0.005
12.	292	230	LDO	69	0.353	0.006
13	400	320	HSD	75	0.334	0.004
14.	400	320	HSD	65	0.349	0.004
15.	880	750	LDO	85	0.318	0.007
16.	400	320	HSD	70	0.335	0.004
17.	400	320	HSD	80	0.337	0.004
18.	880	750	LDO	78	0.345	0.007
19.	800	640	HSD	74	0.324	0.002
20.	800	640	HSD	91	0.290	0.002
21.	880	750	LDO	96	0.307	0.002
22.	920	800	LDO	77	0.297	0.002

24.1.5 Energy Saving Measures for DC Sets

a) Ensure steady load conditions on the DG set, and provide cold, dust free air at intake (use of air washers for large sets, in case of dry, hot weather, can be considered).
b) Improve air filtration.
c) Ensure fuel oil storage, handling and preparation as per manufacturer's guidelines/oil company data.
d) Consider fuel oil additives in case they benefit fuel oil properties for DG set usage.
e) Calibrate fuel injection pumps frequently.
f) Ensure compliance with maintenance checklist.
g) Ensure steady load conditions, avoiding fluctuations, imbalance in phases, harmonic loads.
h) In case of a base load operation, consider waste heat recovery system adoption for steam generation or refrigeration chiller unit incorporation. Even the Jacket Cooling Water is amenable for heat recovery, vapour absorption system adoption.
i) In terms of fuel cost economy, consider partial use of biomass gas for generation. Ensure tar removal from the gas for improving availability of the engine in the long run.
j) Consider parallel operation among the DG sets for improved loading and fuel economy thereof.
k) Carryout regular field trials to monitor DG set performance, and maintenance planning as per requirements

Example 24.2

a) A 180 kVA, 0.80 PF rated DG set has diesel engine rating of 210 BHP. What is the maximum power factor which can be maintained at full load on the alternator without overloading the DG set? (Assume alternator losses and exciter power requirement as 5.66 kW and there is no derating of DG set)

Solution

Engine rated Power	= 210 X 0.746	= 156.66 kW
Rated power available for alternator	= 15 6.66-5.66	= 151 kW
Maximum power factor possible= 151 /180		= 0.84

b) ADG set is operating at 600 kW load with 450°C exhaust gas temperature. The DG set generates 8 kg of exhaust gas/ kWh generated. The specific heat of gas at 450°C is 0.25 kcal/ kg°C. A heat recovery boiler is installed after which the exhaust temperature drops to 230°C. How much steam will be generated at 3 kg/ cm^2 with enthalpy of 650.57 kcal/ kg. Assume boiler feed water temperature as 80°C.

Solution

Waste Heat Recovery = 600 kWh x 8 kg gas generated/ kWh output x 0.25 kcal/ kg °C x (450°C-230 °C) =2,64,000 kcal/hr

Steam generation = 2,64,000 kcal/hr/ (650.57 — 80) = 462.7 kg/ hr.

24.2 Renewable Energy

Bangladesh has a long legacy in the field of Renewable energy, which started back in 1957 with the start of construction of Country's first Hydroelectric project on Karnaphuli river at Kaptai, Chittagong. In October 1988 the fourth and fifth generating units, both 50 MW Kaplan-type turbines, were installed which raised the total generation capacity to 230 MW. In the mid of 80's initiative of private sector played an instrumental role to install the 1st Solar Home System (SHS) with the single installation of a home system at Sylhet. Since the introduction of SHS in 1996, it has become now the biggest renewable energy program in Bangladesh, so far installed 6 million units and ever increasing its number due to an integrated program undertaken by the government through its financial institution IDCOL.

This Solar Home System (SHS) is a robust and reliable system and it owes much of its success to a unique rural credit and 'cost buy down' system that it employs to improve access by rural households

Several fiscal incentives have been extended by the government to Renewable Energy project developers and investors. Dedicated funding support has also been extended through government financial institutions like Bangladesh Bank and IDCOL, as well as through private commercial banks. Moreover, government has extended fiscal incentives including duty exemption on certain renewable energy products, e.g. solar panel, solar panel manufacturing accessories, Charge Controller, Inverter, LED light, solar operated light and wind power plant.

Encouraged by the success of SHS, government has initiated number of programs like, Solar Irrigation, Solar Mini/Micro-grid, Solar Park, Solar Roof-top, Solar Boating and so on. The main focus of RE is to provide electricity to the rural areas and to reduce the dependency on diesel, so as to reduce the carbon emission.

24.2.1 Renewable Energy Potential

The exhaustive nature of fossil fuels and the way their costs have been increasing during the last few years rising costs escalations have heightened interests in renewable energy technologies. Like elsewhere, it is seen as one way to achieve energy security and to reduce CO2 emissions.

Among the different forms of RE potentials, at present solar energy seems to have the greatest potential with biomass and biogas having some limited applications. Bangladesh receives an average daily solar radiation in the range of 4.5 kWh/m²/day.

The potential for wind energy is still under study. Wind data are being collected from 13 locations and hopefully the data collection will be completed by 2017.

As is to be expected, households rely on renewable energy in places where there are no conventional energy supplies. Use of biomass for cooking and solar power and wind for drying grains and textile clothes are traditional ways in which renewable energy is being used in Bangladesh for thousands of years. At present, the different categories of renewable energy that are being used in limited ways in Bangladesh are as follows:

- Hydro-electricity
- Solar power using solar PV
- Wind power
- Electricity from municipal waste
- Bio-gas using cattle dung and poultry litter
- Electricity & Thermal energy generation from Biomass like rice husk bagasse, waste residues from industrial processes etc

24.2.2 Net metering guideline

Despite huge potential, grid-connected electricity consumers are yet to reap the benefits of solar energy. Every on- grid household and commercial or industrial consumers can utilize solar energy, which is the most dispersed form of energy, to generate electricity by installing solar photovoltaic (PV) panels on their own roofs and can become electricity producers meeting their electricity demand partly or fully by themselves and can even sell excess electricity produced to the distribution utilities if appropriate policies are in place.

Bangladesh enjoys good amount of sunshine and the use of solar energy continues to grow while the cost of solar technology continues to decline. Incentivizing grid-connected customers is of utmost importance to promote RE-based distributed generation. Net metering is one of the tools to popularize the RE based electricity generation in the country. Net metering is a policy approach designed to encourage distributed renewable energy development by allowing utility customers to generate their own electricity from solar or any other renewable sources and use the electricity produced to offset the amount of energy they draw from the utility grid (sometimes called the distribution grid) and any access generation can feed into the grid. Customers are only billed for their “net” energy use and receive credit usually in the form of kilowatt-hour (kWh) during a given period. A net balance in favour of the customer is carried forward to the next month, while a balance in favour of the utility is settled at the end of the month as usual. Net-metering can potentially drive widespread implementation of distributed generation by incentivizing end-users to adopt localized power generation through renewable energy technologies (RETs) such as solar, wind and biomass. As of 2017, 46 countries have some form of active net metering policy; local governments have adopted net metering policies in another nine countries in the absence of national-level actions.

Realizing its importance, the Government of Bangladesh published a net metering guideline in July, 2018 to establish a mechanism for distributed RE integration to the grid.

24.2.3 Wind Power Projects Installation Guideline

One of the prime challenges to the expanded use of wind and other renewable energy technologies globally is understanding regional renewable energy potential. The variable nature of the wind resource and its strict location dependency impose additional and often new challenges compared with conventional energy technologies.

Recently Sustainable and Renewable Energy Development Authority (SREDA) has started its venture to accomplish the responsibilities imposed by SREDA Act, 2012 (27. Power to make regulations. – The Authority may, with the prior approval of the Government, by notification in the official Gazette, make Regulations for carrying out the purposes of this Act). To harness wind energy in an orderly manner SREDA has consulted with stakeholders as well as global energy leaders to formulate a set of installation guidelines to implement land-based wind energy projects. This guideline will help project developers to implement the project according to the best practices of wind sector and get a risk-free business environment which will ensure availability of resources, proper land use, required transport logistics, quality power dispatch etc.

CHAPTER 25: ENERGY EFFICIENCY & CONSERVATION IN BUILDINGS

25.1 Introduction

There are several different uses of energy in buildings. The major uses are for lighting, heating, cooling, power delivery to equipment and appliances, and domestic water. The amount that each contributes to the total energy use varies according to the climate, type of building, number of working hours and time of year. Energy use for air-conditioning has the largest share at a national level. In areas where severe winters occur, heating load will be greater than cooling load in terms of the total energy use.
In some types of buildings in certain climatic zones, the lighting load might be greater than either the heating or cooling loads.

Industrial and commercial buildings are dissimilar in terms of energy use, as industries primarily use large quantities of energy for specialized processes whereas buildings use the major amount of energy for human comfort. It is difficult to generalize energy use by type of building because there are many variables that determine the energy use in a particular building.

25.2 EE&C Potential in Residential Sector

If all the existing home appliances in residences are to be replaced by higher efficiency products (as of today), huge energy reduction can be achieved. It is estimated that EE&C potential is 28.8% of the total energy consumption in the residential sector. Considering the fact that about 30% of national primary energy is consumed in the residential sector, the potential economic impact of EE&C measures is massive: almost 8.6% of the total energy consumption in the country can be reduced.

25.3 EE&C Potential in Commercial Sector (Buildings)

Electricity is the main mode of energy in commercial buildings. In detail, nearly 50% of the total energy is consumed by ACs and 10-30% by lighting systems. It is expected that a simple replacement of ACs and lighting systems with high energy efficiency ones can save about 50% of total electricity consumptions in the commercial sector. However, it is not easy to introduce EE&C measures for all the buildings. Thus, as a realistic value, EE&C potential for buildings was estimated about 10%.

25.4 Bangladesh National Building Code (BNBC):

In order to regulate tie technical details of building construction and to maintain the standard of construction the Bangladesh National Building Code (BNBC) was first published it 1993. Depletion of energy resources and environmental changes is a major concern worldwide. Bangladesh is no exception to it. Keeping these aspects in mind, changes and modifications have been suggested in BNBC 1993 for use of energy saving appliances, non-conventional fuels etc. in buildings. The updated BNBC contains chapters addressing the issues of energy conservation, rainwater harvesting and distribution mechanisms in buildings. The updated BNBC has 10 parts with a total of 49 chapters. In Part 3, "General Building Requirements, Control and Regulation" a new Chapter titled, "Energy Efficiency and Sustainability" has been included giving minimum code requirements for achieving the efficiency.

To reduce energy consumption in building provisions for use of variable refrigeration system in HVAC applications, Variable Voltage, Variable frequency drives in elevator applications has been included in Chapter-2 "Air Conditioning, Heating and Ventilation" of Part-8 "Building Services". Energy conservation in lighting using energy saving lamps, fluorescent lamps and GLS lamps has also been proposed in Chapter-1, "Electrical and Electronics Engineering Services for Buildings" of the same part. To augment water supply in Buildings, Chapter-8, "Rainwater Management" in Part-8 "Building Services" has been included in the Updated Code containing specific guidelines for harvesting, storage and distribution of rainwater.

For more details, please have a look of the Bangladesh National Building Code (BNBC).

The updated version of BNBC is proposed with addition of energy efficiency requirement of buildings in near future BNBC will be the core program for promoting EE&C in Buildings and contain the following requirement on building energy efficiency:

a. Heat insulation and/or ventilation performance of building envelope
b. Energy efficiency of building equipment (HVAC, lighting, fans, hot water supply, lift, escalator, renewable energy options)
c. Water efficiency and management and Sanitation
d. Roof gardening and vegetation

25.5 Building Energy Efficiency & Environment Rating (BEEER)

To ensure the energy efficiency in buildings, SREDA has developed the rating system for buildings and act as the implementation and execution body for the Building Energy & Environment Rating (BEER)

The objective to which the program aims to contribute is to:

- Promote green and sustainable building practices on the supply and demand side of Bangladesh's construction sector;
- Contribute to climate change mitigation by saving resources in the building sector while enhancing economic prosperity and competitiveness, as well as alleviating poverty by considering both green and social standards;
- Establish a building energy efficiency and environmental rating systems serving as a standard/reference for green building construction practices;
- Enhance sustainable consumption in the building sector through a rating system, providing consumer information and a distinctive grade for sustainable buildings;
- Mobilize and capacitate key stakeholders to get involved in green building design and construction.
- Promote green equipment and construction materials, fixtures and make the market ready.
- Develop the capacity of architects and Engineers, Energy Managers & Energy Auditors in Green Construction.
- Provide access to soft and subsidize loan facilities for green building developer and consumers.

Generally the Building should be Rated based on their typology. However, at the beginning stage of the Building Energy and Environment Rating cover all types of buildings by a single guideline. In next version, building typology (Existing Building, New Construction, Interior space, Township, Industries etc.) specific rating guideline will be developed.

The draft of BEER is available at SREDA website (www.sreda.gov.bd)

25.6 Energy Efficiency Measures in Buildings:

25.6.1 Air-Conditioning System:

Weather stripping of Windows and Doors

Minimize exfiltration of conditioned air and infiltration of external un-conditioned air through leaky windows and doors by incorporating effective means of weather stripping. Self-closing doors should also be provided where heavy traffic of people is anticipated.

Temperature and Humidity Setting

Ensure human comfort by setting the temperature to between 23°C and 25°C and the relative humidity between 55% and 65%.

Chilled Water Leaving Temperature

Ensure higher chiller energy efficiency by maintaining the chilled water leaving temperature at or above 7° C. As a rule of thumb, the efficiency of a centrifugal chiller increases by about 2% % for every 1° C rise in the chilled water leaving temperature.

Chilled Water Pipes and Air Ducts

Ensure that the insulation for the chilled water pipes and ducting system is maintained in good condition.
This helps to prevent heat gain from the surroundings.

Chiller Condenser Tubes

Ensure that mechanical cleaning of the tubes is carried out at least once every six months. Fouling in the condenser tubes in the form of slime and scales reduces the heat transfer of the condenser tubes and thereby reducing the energy efficiency of the chiller.

Cooling Towers

Ensure that the cooling towers are clean to allow for maximum heat transfer so that the temperature of the water returning to the condenser is less than or equal to the ambient temperature.

Air-handling Unit Fan Speed

Install devices such as frequency converters to vary the fan speed. This will reduce the energy consumption of the fan motor by as much as 15%.

Air Filter Condition

Maintain the filter in a clean condition. This will improve the heat transfer between air and chilled water and correspondingly reduce the energy consumption.

Lighting System:

All lighting systems generate heat that needs to be dissipated. By designing energy efficient lighting system that integrates day lighting and good controls, heat gains can be reduced significantly. This can reduce the size of the HVAC system resulting in first-cost savings.

Day lighting

Day lighting benefits go beyond energy savings and power reduction. Daylight spaces have been shown to improve people's ability to perform visual tasks, increase productivity and reduce illness. Building fenestration should be designed to optimize day lighting and reduce the need for electric lighting. Orient the building to minimize building exposure to the east and west and maximize glazing on the south and north exposures.

Daylight strategies do not save energy unless electric lights are turned off or dimmed appropriately.

ECBC requires controls in day lit areas that are capable of reducing the light output from luminaires by at least half.

- Install dimmers to take advantage of day lighting and where cost-effective.
- Replace rheostat dimmers with efficient electronic dimmers.
- Combine time switching with day lighting using astronomical time clocks.
- Control exterior lighting with photo controls where lighting can be turned off after a fixed interval.

Switch off Lights When Not in Use

Provision of Separate Switches for Peripheral Lighting

A flexible lighting system, which made use of natural lighting for the peripherals of the room, should be considered so that these peripheral lights can be switched off when not needed.

Install High Efficiency Lighting System

Replace incandescent and other inefficient lamps with lamps with higher lighting efficacy. For example, replacing incandescent bulbs with compact fluorescent lamps can reduce electricity consumption by 75% without any reduction in illumination levels.

Fluorescent Tube Ballasts

The ballast losses of conventional ballast and electronic ballast are 12W and 2W respectively. Hence, consider the use of electronic ballast for substantial energy savings in the lighting system.

Lamp Fixtures or Luminaries

Optical lamp luminaries made of aluminium, silver or multiple dielectric coatings have better light distribution characteristics. Use them to reduce electricity consumption by as much as 50% without compromising on illumination levels.

Integration of Lighting System with Air-Conditioning System

In open plan offices, the air-conditioning and lighting systems can be combined in such a way that the return air is extracted through the lighting luminaires. This measure ensures that lesser heat will be directed from the lights into the room.

Cleaning of Lights and Fixtures

Clean the lights and fixtures regularly. For best results, dust at least four times a year.

Use Light Colors for Walls, Floors and Ceilings

The higher surface reflectance values of light colours will help to make the most of any existing lighting system. Consider light coloured furniture and room partitions to optimize light reflectance. Avoid furniture colours and placement that will interfere with light distribution. Keep ceilings and walls as bright as possible.

Deal with each activity area and each fixture individually

Eliminate excessive lighting by reducing the total lamp wattage in each activity area

Task Lighting

Lighting layout should use task lighting principle. Install focusing lamps or flexible extensions wherever needed.

25.7 Building Water Pumping Systems

The pumps used in the buildings are for chilled water circulation, cooling water circulation, domestic water, hot water and sewage water. The water requirement for cooling, drinking and general-purpose requirements in buildings are meat by the local authorities and also from the independent bore wells.
The water received is stored and pumped to the overhead tanks provided on the building terrace are hydro pneumatic system is used. Normally the pumps used in the building are of centrifugal type with efficiencies of 60%. The following energy conservation measures are adopted to reduce energy consumption in water pumping in buildings:

- Installation of high efficiency pumps
- Operation of pumps in parallel
- Auto pump operation with low level/high level flow control systems.
- Installation of variable frequency drive for chiller water and cooling water pumps

25.8 Uninterruptible power supply

An Uninterruptible Power Supply (UPS) is a device that has an alternate source of energy, typically a battery backup that can provide power when the primary power source is temporarily disabled. The switchover time must be small enough to not cause a disruption in the operation of the loads (Figure 25.1). The components of a UPS are converter (AC to DC), battery, inverter (DC to AC), monitor and control hardware / software.

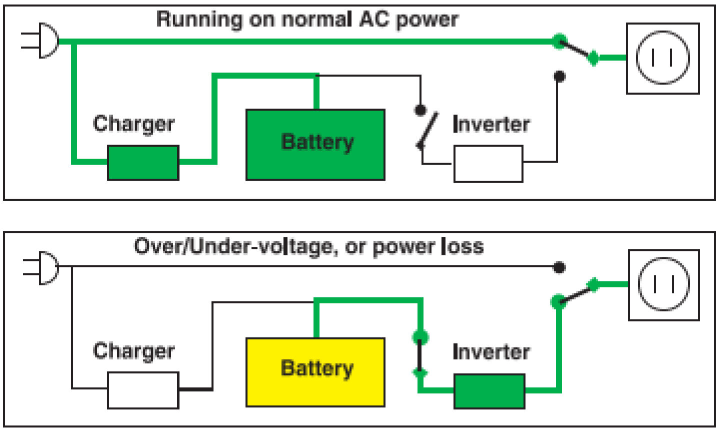


Figure 25.1: UPS Operation

There are two type of UPS architecture namely line interactive (OFF line) and ON line.

Simple OFF Line UPS systems, connect the load directly to the input AC line. Line Interactive systems have also the ability to correct UPS output if AC input voltage deviates beyond pre-set limits by means of an auto- transformer based Automatic Voltage Regulator. In case of significant utility voltage deeps or outages these systems transfer the UPS to battery operation.
Due to its direct connection to input AC power, OFF Line types, including Line Interactive systems offer higher efficiency when compared to an Online UPS. But, unstable grid environment, with frequent power interruptions or outages, might cause these systems to suffer from frequent transfers to battery operation. Thus, exposing the critical load to possible failures due to unsmooth or unsuccessful transfer, or to battery failure, because of numerous battery discharges, which decrease drastically battery life time.
An Online UPS system, frequently called Double conversion system, first converts the AC input voltage to stabilized DC, which is then converted back to AC, to feed continuously the critical load, with pure stabilized sinusoidal output, coming either from the input line via AC/DC converter, or from batteries in case of power failure.

Energy efficiency of a UPS is the difference between the amount of energy that goes into a UPS versus the amount of useful energy that comes out of the UPS and actually powers loads (Figure 10.7). In all UPS systems some energy is lost as heat when it passes through the internal components of the UPS (including transformers, rectifiers, and inverters).

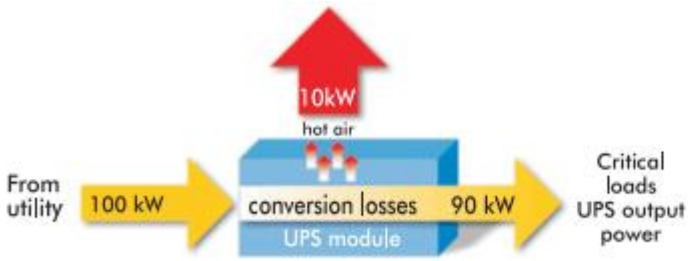


Figure 25.2 Energy Loss in UPS

Almost all UPS power 100% nonlinear loads +viz., computers, servers and electronic equipment, though the manufacturers test their UPS often using linear loads. UPS efficiency is often much higher when powering linear loads.
The second major factor to influence UPS efficiency is the power level at which the efficiency is measured. Most UPSs typically have their best efficiency operating at 50% to 100% load level. But in the real situation, most UPS systems operate at 25% to 60% of their nominal load- not fully loaded.

To determine accurate efficiency, the UPS should demonstrate efficiency at loads between 25—50%, where most UPS will likely to be operating.

25.9 Escalators and Elevators

The requirement of the maximum allowable electric power indicates ultimately the energy performance of the equipment. The power for lift equipment is to be measured when the lift is carrying its rated load and moving upward at its contract speed. For escalators and passenger conveyors, since the rated load is usually defined as number of person (not in kg weight), there is no theoretical rated load in kg for the equipment. Thus, the electric power is to be measured when the escalator/conveyor is carrying no load and moving at its rated speed either in the upward or downward direction.
In escalators and elevators, the dominating factors that determine the energy consumption are the efficiency of the motor, friction, the controller and the driving gear box. The proportion of frictional loss of the machine can also become significant in the power consumption in no load condition, as it is the fixed overhead to keep the equipment running.

25.9.1 Factors That Affect Energy Consumption in Elevators and Escalator System

Energy is consumed by lift and escalator equipment mainly on the following categories:

- ✓ Friction losses incurred while travelling.
- ✓ Dynamic losses while starting and stopping.
- ✓ Lifting (or lowering) work done, potential energy transfer.
- ✓ Regeneration into the supply system.

The general approach to energy efficiency in lift and escalator equipment is merely to minimize the friction losses and the dynamic losses of the system. There are many factors that will affect these losses for elevator and escalator system: -

(A) Characteristic of the equipment

The type of motor, drive and control system of the machine, the internal decoration, means to reduce friction in moving parts (e.g., guide shoes), type, speed and the pulley system of the equipment.

(B) Characteristic of the premises

The population distribution, the type of the premises, the height of the premises and the house keeping of the premises,

(C) The configuration of the lift/escalator system

The zoning of the lift system, the combination of lift and escalator equipment, the strategies for vertical transportation and the required grade of service of the system.

25.9.2 General Principles to Achieve Energy Efficiency

In general, the principles for achieving energy efficiency for lift/escalator installations are as follows:

- ✓ Specify energy efficiency equipment for the system.
- ✓ Do not over design the system.

- ✓ Suitable zoning arrangement.
- ✓ Suitable control and energy management of lift equipment
- ✓ Use lightweight materials for lift car decoration.
- ✓ Good housekeeping.

25.10 Building Energy Management System (BEMS)

Energy management systems can vary considerably in complexity and degree of sophistication. The simplest timing mechanism to switch systems ON and OFF at pre-determined intervals on a routine basis could be considered as an energy management system. These progresses to include additional features such as programmers, thermostatic controls, motorized valves, zoning, and optimum start controllers and compensated circuits.

The most complex of energy management systems have a computerized central controller linked to numerous sensors and information sources. These could include the basic internal and external range shown schematically in Figure 10.8, along with further processed data to include: the time, the day of the week, time of year, percentage occupancy of a building, meteorological data, system state feedback factors for plant efficiency at any one time and energy gain data from the sun, lighting, machinery and people.

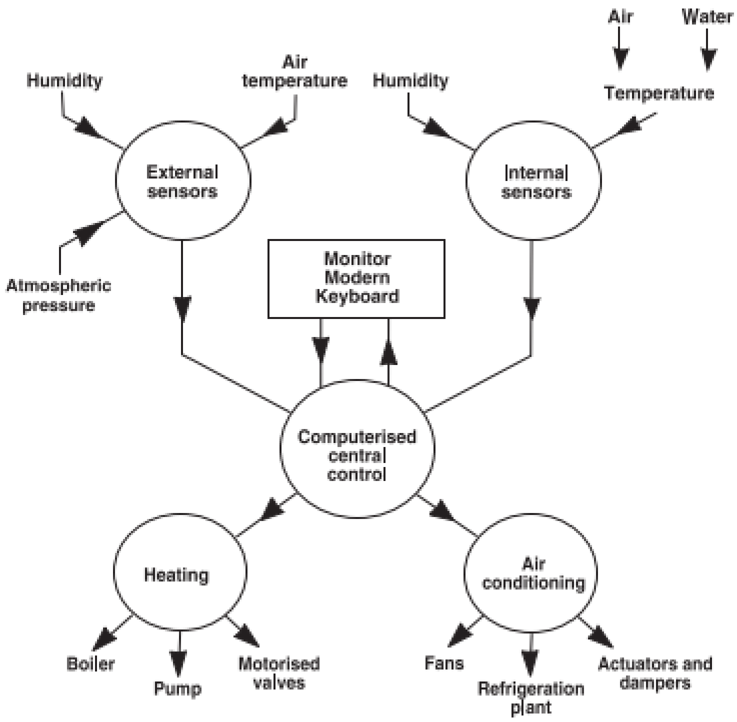


Figure 25.3 Building Energy Management

A microprocessor is then the main feature of the control system. Data on temperature, flow rates, pressures, etc., as appropriate, are collected from sensors 1n the system and the treated spaces and stored in the memory of the processor. Provided that equations defining the performance of the control elements, the items of plant and the behavioural characteristics of the systems controlled have been developed and fed into the micro-processor as algorithms, deviations from the desired performance can be dealt with by calculation, the plant output being varied accordingly. Mathematical functions replace control modes. For example, if room temperature rose in a space conditioned by a constant volume reheat system, the correct position of the valve in the low temperature hot water line feeding the heater battery could be calculated and corrected as necessary, to bring the room temperature back to the set point as rapidly as possible, without any offset. Data can be stored to establish trends and anticipation can be built into the program so that excessive swings in controlled conditions may be prevented. Furthermore, self-correction can be incorporated so that the control system learns from experience and the best possible system performance is obtained. This implies that commissioning inadequacies and possibly even design faults can be corrected but only to a certain extent. Optimum results are only obtainable, and the cost of the installation justified, from systems that have been properly designed, installed and commissioned. Under such circumstances it is then feasible to extend the scope of microprocessor control to include the management of all the building services with an economic use of its thermal and electrical energy needs.

The functions of a building management system (BMS) or building energy management system (BEMS) are monitoring and control of the services and functions of a building, in a way that is economical and efficient in the use of energy. Furthermore, it may be arranged that one system can control a group of buildings.

25.11 Energy performance Index: (EPI)

Energy Performance Index (EPI) in kWh / sq. m/ year will be considered for rating the building. Bandwidths for Energy Performance Index for different climatic zones have been developed based on percentage air-conditioned space. For example, a building in a composite climatic zone like Dhaka and having air-conditioned area greater than 50% of their built-up area, the bandwidths of EPI range between 190-90 kWh/sq. m/year. Thus, a building would get a 5-Star rating if its EPI falls below 90 kWh/sq. m/year and 1 Star if it is between 165-190 kWh/ sq. m/year.

CHAPTER 26: BENCHMARKING, ENERGY MONITORING, TARGETING AND REPORTING

26.1 Benchmarking:

Benchmarking can be a useful tool for understanding energy consumption patterns in an industrial sector and for taking measures to improve energy efficiency. Energy benchmarking for industry is a process in which the energy performance of an individual plant or an entire sector of similar plants is compared against a common metric that represents 'standard' or `optimal' performance. It may also entail comparing the energy performance of a number of plants against each other.

Since benchmark tool is used for comparison across a number of plants or sectors, there are two important features they should have. First, because they are applied to plants or sectors of different sizes and outputs, the metric used should be common irrespective of plant size. The most common metric used is energy intensity which measures 'energy use per unit of output'. Second, the tool should be used in a wide range of facilities so as to compensate for differences in production at similar facilities.

Benchmarking forms the basis for monitoring and target setting

Industrial Benchmarking Programs

There are three approaches for energy benchmarking. The first approach is to evaluate an entire industrial sector, such as iron and steel, aluminium, cement, etc. This evaluation is used to answer the following questions: How well is this sector performing compared to how it would perform using the best available technologies? How well is it performing compared to the same sector in other countries? Has the sector been improving over time?

The second approach is the comparison of individual plants within a sector. A benchmark-type indicator is calculated for all the facilities within a sector so that they can be compared on even terms. This evaluation can answer the following questions: What is the state-of-the-art performance in this given sector? How does my plant compare against the state-of-the-art? How does it compare against the majority of other plants in the sector? In developing benchmarks at the level of individual plants, the issue of proprietary data becomes important. Individual companies are very reluctant to disclose information about their production processes, particularly if it will be released to their competitors. It is important that the indicators developed are general enough not to reveal any proprietary information and that a credible system is established that encourages plants to trust the process.

The third approach for energy benchmarking that has been seen widely in recent years is for large companies to set themselves energy efficiency goals by using historical best performance as benchmark. Companies use this approach to set targets for reducing energy use by certain percentages over given time frames. Companies do not need to reveal any proprietary information, since the benchmarking is done internally.

Steps in energy conservation benchmarking are summarized below:

- Identify the best available technology for the individual process units.
- Collect information to thoroughly understand the process and identify key/controlling parameters.
- Determine the performance of the process unit.

- ➢ Analyze the gap between the existing and the benchmark for the key controlling parameters.
- ➢ Set targets or benchmarks, keeping constraints in view, and implement improvements based on the findings

The benchmark parameters for various sectors are given as follows:

- Gross Production Related

kWh/MT clinker or cement produced (Cement plant)
kWh/kg yarn produced (Textile unit)
kWh/MT, kcal/kg paper produced (Paper plant)
kcal/kWh Power produced (Heat rate of a power plant)
Million Calories/MT Urea or Ammonia (Fertilizer plant)
kWh/MT of liquid metal output (in a foundry)

- Equipment / Utility Related

kWh/ton of refrigeration (on Air-conditioning plant)
% thermal efficiency of a boiler plant
% cooling tower effectiveness in a cooling tower
kWh/Nm^3 of compressed air generated
kWh/litre in a diesel power generation plant.

While such benchmarks are referred to, related crucial process parameters need to be stated for meaningful comparison among similar industries. For instance, in the above case:

- ➢ For a cement plant - type of cement, blaine number (fineness) i.e., Portland and process used (wet/dry) are to be reported alongside kWh/MT figure.

- ➢ For a textile unit - average count, type of yarn i.e., polyester/cotton, is to be reported alongside kWh/kg figure.

- ➢ For a paper plant - paper type, raw material (recycling extent), GSM quality are some important factors to be reported along with kWh/MT, kcal/kg figures.

- ➢ For a power plant / cogeneration plant - plant % loading, condenser vacuum, inlet cooling water temperature, would be important factors to be mentioned alongside heat rate (kcal/kWh).

- ➢ For a fertilizer plant - capacity utilization (%) and on-stream factor are two inputs worth comparing while mentioning specific energy consumption

- ➢ For a foundry unit - melt output, furnace type, composition (mild steel, high carbon steel/cast iron etc.) raw material mix, number or power trips could be some useful operating parameters to be reported while mentioning specific energy consumption data.

- ➢ For an A/C plant - parity of chilled water temperature level is crucial while comparing kW/TR.
- ➢ For a boiler plant - fuel quality, type, steam pressure, temperature, flow are useful comparators alongside thermal efficiency and more importantly, whether thermal efficiency is on gross calorific value basis or net calorific value basis or whether the computation is by direct method or indirect heat loss method, mean a lot in benchmarking exercise for meaningful comparison.

- For a cooling tower - Effectiveness - ambient air wet/dry bulb temperature, relative humidity, air and circulating water flows are required to be reported to make meaningful sense.
- For a compressed air system - specific power consumption - is to be compared at similar inlet air temperature and pressure of generation.
- Diesel power plant performance - is to be compared at similar loading %, steady run condition.

26.2 Energy Performance:

Plant Energy Performance

Plant energy performance (PEP) is the measure of whether a plant is now using more or less energy to manufacture its products than it did in the past: a measure of how well the energy management programme is doing.

Plant energy performance monitoring compares plant energy use of a reference year and the subsequent years considering production output to determine the improvement (or deterioration) that has been made.

However, since the plants' production output varies from year to year, it has significant impact on plant's energy use. For a meaningful comparison it is necessary to determine the energy that would have been required to produce current year's production output had the plant operated in the same way as it did during the reference year. This calculated value can then be compared with the actual value to determine the improvement or deterioration that has taken place since the reference year.

Production Factor

Production factor is the ratio of production in the current year to that in the reference year.

$$\textbf{Production factor} = \frac{\text{Current year's production}}{\text{Reference year's production}}$$

Production factor is used to determine the *energy* that would have been required to produce this year's production output if the plant had operated in the same way as it did in the reference year.

Reference Year Equivalent Energy Use

The *reference year's equivalent energy use (or reference year equivalent)* is the energy that would have been used to produce the current year's production output.

The reference year equivalent is obtained by multiplying the reference year energy use by the production factor (obtained above)

Reference year equivalent = Reference year energy use x Production factor

Plant Energy Performance is the improvement or deterioration from the reference year. It is a measure of plant's energy progress.

$$\textbf{Plant energy performance} = \frac{\text{Reference year equivalent} - \text{Current year's energy}}{\text{Reference year equivalent}} \times 100$$

The energy performance is the measure of energy saved at the current rate of use compared to the reference year rate of use. The greater the improvement, the higher the number will be.

Plant energy performance (PEP) is the starting point for evaluating energy performance. It does not require detailed calculations of the energy used by every place of equipment, the energy use of every process or the energy use of buildings. It utilizes the most effective measure of energy savings, the actual measurement of energy consumption compared to production output. Yearly comparisons minimize seasonal effects.

Sometimes, once a plant has started measuring yearly energy performance, management wants more frequent performance information in order to monitor and control energy use on an on-going basis. In such cases PEP can just as easily be used for monthly reporting as yearly reporting.

26.3 Energy Monitoring and Targeting:

Monitoring is the process of establishing the existing pattern of energy consumption and explaining deviations from existing pattern. Its primary goal is to maintain existing pattern by providing all the necessary data on energy consumption and key related data such as production.

Targeting is the identification of desirable energy consumption level and working towards achieving them. Targets are based on the historical (average or best) data acquired during the monitoring as well as benchmarking with energy performance of similar organizations.

Setting up Monitoring & Targeting

Before initiating M&T, it is important to establish Energy Account Centers (EACs) within an organization. These may be departments, processes or cost centers. Operational managers should be accountable for the energy consumption of the EACs for which they are responsible.

It is important that any proposed M&T programme be designed to suit the needs of the particular organization. From an energy point of view, organization can be characterized in various ways. Typical classifications are by the number of sites covered and the level of metering adopted as follows:

- ✓ Single site with central utility metering
- ✓ Single site with sub-metering
- ✓ Multi-site with central utility metering
- ✓ Multiple-site with sub-metering

Single site with central utility metering is probably best treated as a single EAC, while the introduction of sub-metering enables such site to be broken-up into a number of separate EACs. Where the organization has a number of separate sites, each with central utility meters, the sites should be treated as separate EACs. If the organization has multiple sites, each containing sub-metering, then it should be possible to divide each site into a number of separate EACs.

Key Elements of Monitoring & Targeting System

The key elements of M&T system are:

- ✓ **Recording -**Measuring and recording energy consumption of each EAC within an organization. This involves setting up procedures to ensure regular collection of reliable energy data.

- ✓ **Analyzing & Comparing - Relating** energy consumption to a measured output, such as production quantity for 12-24 months of historical data to obtain standard energy performance for each EAC. Standard energy performance is established through regression analysis of past data. If these data do not exist, then it will be necessary to conduct an energy audit to establish standard energy performance. Standard Energy Performance provides a *base line* for the assessment of future performance. It can also be used as an initial target.

- ✓ **Setting Targets** -Setting energy targets for each EAC. Energy cost savings can be consistently achieved if improvements are made on standard energy performance. Achievable targets should therefore be set which improve on standard energy performance. Targets can be set based on external benchmarking with other similar organization or historical achievement of least energy consumption in the same organization.

- ✓ **Monitoring -**Comparing actual energy consumption to the set target on a regular basis

- ✓ **Reporting -**Reporting the results to management including any variances from the targets which have been set and related performance problems in equipment and systems. Energy management reports should be produced for each EAC on a regular basis. These reports provide the stimulus for improved energy performance, and should also quantify any improvements that are achieved.

- ✓ **Controlling -**Implementing management measures to correct any variances, which may have occurred

Particularly M & T system will involve the following:

- **Checking** the accuracy of energy invoices
- **Allocating** energy costs to specific departments (Energy Accounting Centres)
- **Determining** energy performance / efficiency
- **Recording** energy use, so that projects intended to improve energy efficiency can be checked for results.
- **Highlighting** performance problems in equipment or systems

Benefits of M&T

The ultimate goal is to reduce energy costs through improved energy efficiency and management control measures. Other benefits include:

- ✓ Identify and explain an increase or decrease in energy use
- ✓ Draw energy consumption trends (weekly, seasonal, operational)
- ✓ Improve energy budgeting corresponding to production plans
- ✓ Observe how the organization reacted to changes in the past
- ✓ Determine future energy use when planning changes in operations
- ✓ Diagnose specific areas of wasted energy
- ✓ Develop performance targets for energy management programs / energy action plans

Manage energy consumption rather than accept it as a fixed cost that cannot be controlled.

26.4 Reporting

Annual Energy Consumption Report: This report should be prepared by the energy manager of that facility. Template of that report is given in the Energy Audit Regulation.

Energy Audit Report: This report should be prepared by the energy audit firm (employed by the facility owner) comprising the certified energy auditor. Energy manager of the facility will facilitate the energy audit firm during energy audit activities. Template of the energy audit report is given in the Energy Audit Regulation.

Compliance Report: This report should be prepared by the energy manager of that facility based on the energy audit report and other criteria set by the government. Template of that report is given in the Energy Audit Regulation.

26.5 Instruments and Metering for Energy Audit/Monitoring

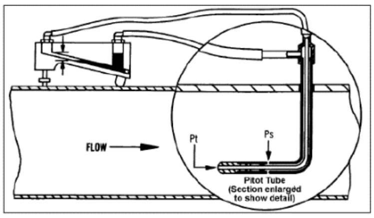
The quantification of energy use in an energy audit/monitoring requires the use of various instruments for monitoring and measurements. These instruments must be portable, durable, easy to operate and relatively inexpensive. The operating instructions for all instruments must be understood and staff should familiarize themselves with the instruments and their operation prior to actual audit use. The key instruments for energy audit are listed in the following Table:

Table 26.1: Key Instruments for Energy Audit

No.	Name of the Instrument	Features and Typical Applications
1.	Power & Harmonic Analyser 	Measures all Electrical and Harmonic Parameters namely, V, A, PF, KW, kVA, kVAR, Hz, and first 50 Harmonics. These instruments can be applied on-line i.e. on running motors without any need to stop the motor. Instant measurements can be taken with hand-held meters, while more advanced ones facilitates cumulative readings with printouts at specified intervals say every 1/2 hr over a shift or a day.
2.	Tachometer (Contact-type) 	*A tachometer is an instrument used to measure the rotational speed of a shaft or wheel in revolutions per minute (rpm). By measuring speed, energy auditor is able to find out belt slip if any and loading.* *A contact type tachometer can be used where direct access is possible.*

3.	Non-Contact Tachometer / Stroboscope 	*Non-contact tachometer allows the users to measure the rotational speed without contacting the object.* *Non-contact instruments are sophisticated and safer. These instruments can measure speed for objects that are visible but not accessible.* *A stroboscopic tachometer employs a variable-frequency, flashing light which makes the rotating component appear to stand still when the frequencies match.*
4.	Lux meter 	A lux meter is a device for measuring illumination or lighting levels. The lux is a unit of measurement of illuminance (brightness). A lux meter works by using a photo cell to capture light. The light is then converted to an electric current and corresponding lux value.
5.	Thermometer  	These thermocouples measures temperatures of flue gas, hot air, hot water by insertion of appropriate probe into the stream. Different types include Fluid Filled, Resistance, Thermocouple and Thermistor. Most HVAC applications require a thermometer with temperature of -50^0C to 175^0C.Boiler and oven stacks require thermometers able to measure up to about 500^0C. By knowing the process temperature, the auditor can determine process equipment efficiency. It also helps us to waste heat recovery potential. For surface temperature, a leaf type probe is used with the same instrument.
6.	Combustion / Flue Gas Analyzers 	Combustion analyzer measures the composition of flue gases in percentage (% O_2 (or) % CO_2), and flue gas temperature. The instrument estimates the combustion efficiency of furnaces, boilers and other fossil fuel-fired devices with an inbuilt programme. Two types are available: digital analyzers and manual combustion analysis kits. Digital combustion analysis equipment performs the measurements and reads out combustion efficiency in percentage. The manual combustion analysis kits typically require multiple measurements including exhaust stack: temperature, oxygen content, and carbon dioxide content. The efficiency of the combustion process can be calculated after determining these parameters. The manual process is tedious and is frequently subject to human error.
6.	Thermometer	These thermocouples measures temperatures of flue gas, hot air, hot water by insertion of appropriate probe into the stream. Different types include Fluid Filled, Resistance, Thermocouple and Thermistor.

	 	Most HVAC applications require a thermometer with temperature of -50^{0}C to 175^{0}C.Boiler and oven stacks require thermometers able to measure up to about 500^{0}C. By knowing the process temperature, the auditor can determine process equipment efficiency. It also helps us to waste heat recovery potential. For surface temperature, a leaf type probe is used with the same instrument.
7.	Fyrite Gas Analyzer 	*This instrument is used for measuring and Analyzing carbon dioxide or oxygen. The instrument contains absorbing fluid which is selective in the chemical absorption of carbon dioxide or oxygen, respectively. Fyrite readings are unaffected by the presence of most background gases in the sample.* *Fyrite accuracy is sufficient for most industrial applications and test procedure is simple.*
8.	Infrared Thermometer (Non-contact type) 	The instrument is basically non-contact type which is able to measure temperature from a distance. Non-contact infrared thermometers, also known as heat guns, are very useful for measuring surface temperatures of steam lines, boiler surfaces, processes temperatures, etc. An infrared thermometer infers temperature from a portion of the thermal radiation sometimes called blackbody radiation emitted by the object being measured (as radiation is characteristic of their temperature). By knowing the amount of infrared energy emitted by the object and its emissivity, the object's temperature can be determined. The heart of the infrared thermometer is the detecting surface, which absorbs infrared energy and converts it to an electrical voltage or current. These instruments typically cover a range from 30^{0}C to 2000^{0}C.
9.	Thermal Imaging Devices 	Thermal cameras are instruments that create pictures of heat rather than light. They measure infrared (IR) energy and convert the data to corresponding images of temperatures. Non-contact infrared imagers provide fast, safe, accurate measurements for objects that are: ▪ Moving or very hot ▪ Difficult to reach ▪ Impossible to shut-off ▪ Dangerous to contact ▪ Where contact would damage, contaminate or change temperature.

10.	Ultrasonic Flow Meter 	Water and other fluid flows in pipelines can be easily measured using ultrasonic sensors mounted on the pipelines. This instrument is used to estimate the flow rates entering or leaving a pump. The meters are used to determine the fluid flow in terms of velocity and flow rate (given the diameter of pipe). This non-contact flow measuring device uses Doppler effect / Ultra sonic principle. A transmitter and a receiver are positioned on opposite sides of the pipe. Modes of operation and measurement are either by Doppler effect (or) Transit Time.
11.	Thermo-anemometer 	This instrument is used for measuring air velocity in ventilation, air-conditioning and refrigeration systems etc.
12.	Thermo-hygrometer 	This instrument measures humidity and temperature for determination of dew point and calculation of heat being carried away by outgoing gases where product drying requires hot air.
13.	Pitot Tube and manometer (Inclined /Digital manometer) 	Air velocity in ducts can be measured using a pitot tube and an inclined manometer for further calculation of flows. The principle is based on measuring the differential (velocity) pressure at various points (traverse points) across the cross-section of the duct. In addition to velocity pressure, this instrument can also determine Static and Total pressures.
14.	Ultrasonic Steam Trap Tester	These instruments operate as electronic stethoscopes. They are able to pick up the very high-pitched sound indicative of freely blowing steam (condensate draining makes a lower-pitched sound). The advantage of ultrasonic testers is that they can listen to one pipe and detect if any of the nearby steam traps have failed. Ultrasonic detecting devices can also be used to identify any type of gas or fluid leaks e.g. compressed air leaks.

		
15.	Leak Detectors  	Compressed air is one of the most costly utilities in a facility today. A simple program of leak inspection and repair helps greatly to reduce energy costs. Ultrasonic Leak Detector has an high quality flexible sensor is mounted on the end of a flexible steel pipe so the ultrasonic sound sensor can access hard to reach areas. The unit converts the ultrasonic noise of a leak into a sound a human can hear such as some beeping sound or LED display. Features of this instrument are • Detects the location of leaks • Detects almost any leak because – Short distance/access not needed – High pressure not needed – Sensitive to sound – Filters background noises This instrument does not measure the size of the leak.
16.	Conductivity Meter 	This instrument is used for spot analysis of the amount of total dissolved solids (TDS) in water especially in case of boiler blow down. An accurate measurement of TDS is required to maintain blow down rate in boilers and optimize energy consumption. TDS meter measures the conductivity of the solution then converts that value to an equivalent TDS reading.
17.	pH meter 	pH meter is used for spot analysis of acidity or alkalinity of a solution/water.. The meter uses the property of certain types of electrodes to exhibit electrical potential when immersed in a solution.
18.	Thermal Insulation scanner	This instrument measures loss of energy in kCal per unit area from hot/cold insulated surfaces. The total heat loss can be obtained by multiplying the value with total surface area.

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