- Example, even with dampers fully closed, the flow may not be zero due to leakage through the dampers. 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. The stable operation of a fan requires that it operates 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 serve as a guide to the selection of the most suitable capacity control system. The 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, 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, the 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.

5.10 Fan Performance Assessment

Fans are tested for field performance by the measurement of flow, head and temperature on the fan side and electrical motor kW input on the motor side.

5.10.1 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, static pressure produces an area of low pressure
- Velocity Pressure
  - Velocity pressure is the pressure along the line of the flow that results from the air flowing through the duct. Velocity pressure is used to calculate air velocity.
- Total Pressure
  - Total pressure is the sum of the static and velocity pressures. 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 (see Figure 5.18).

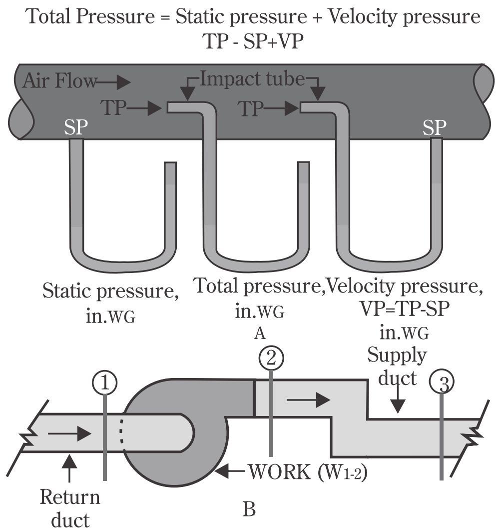

Fig.5.18 Static, total and velocity pressure

- The fan flow is measured using the pitot tube manometer combination, or a flow sensor (the differential pressure instrument) or an accurate anemometer. Care needs to be taken regarding the number of traverse points, straight length sections (to avoid turbulent flow regimes of measurement) upstream and downstream of the measurement location. The measurements can be on the suction or discharge side of the fan and preferably both where feasible.
- Measurement by Pitot tube.

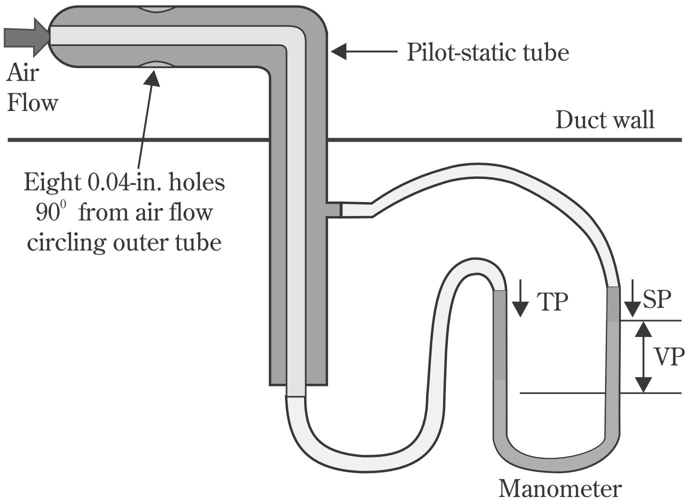

Fig.5.19 Velocity measurement using pitot tube

Fig. 5.19 shows how velocity pressure is measured using a pitot tube and a manometer. Total pressure is measured using the inner tube of the pitot tube and static pressure is measured using the outer tube of the pitot tube. When the inner and outer tube ends are connected to a manometer, we get the velocity pressure. To measure low velocities, it is preferable to use an inclined tube manometer instead of the U tube manometer.

5.10.2 Measurements and Calculations

Velocity Pressure/Velocity Calculation

When measuring velocity pressure, the duct diameter (or the circumference from which the diameter is calculated) should be measured as well. This will allow calculating the velocity and the volume of air in the duct. In most cases, velocity must be measured at several places in the same system.

Velocity pressure varies across the duct. Friction slows the air near the duct walls, so velocity is greater at the centre of the duct. 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 the 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. 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 Fig. 5.20).

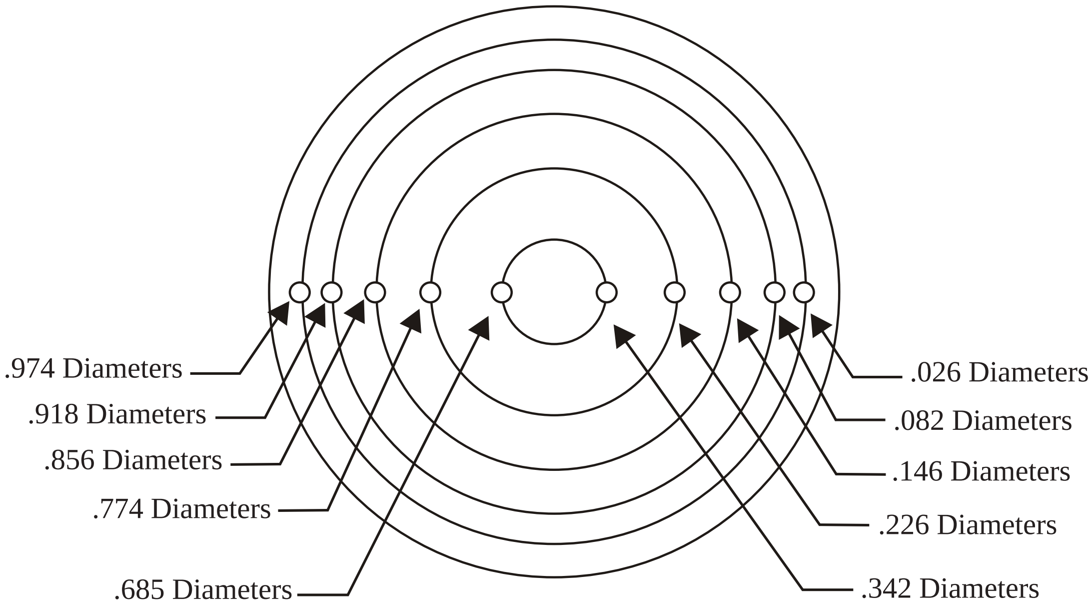

Fig.5.20 Traverse points for circular duct

For the best results, one set of readings should be taken in one direction and another set at a 900 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 at the centre of the duct and calculating it. This value is reduced to an approximate average by multiplying by 0.9.

Air density calculation

The first calculation is to determine the density of the air. To calculate the velocity and volume from the velocity pressure measurements, it is necessary to know the density of the air. Density is dependent on altitude and temperature.

Gas Density $(\gamma) = \frac{273 \times 1.293}{273 + t^{o}C}$

Where,

$t^{0}C$ temperature of gas/air at site condition

Velocity calculation

Once the air density and velocity pressure have been established, the velocity can be determined from the equation:

$$\frac{C_p \times \sqrt{2 \times 9.81 \times \Delta p \times \gamma}}{\gamma}$$

Velocity (v), m/s = $\frac{C_p \times \sqrt{2 \times 9.81 \times \Delta p \times \gamma}}{\gamma}$

Where,

Cp = Pitot tube constant, 0.85 (or) as given by the manufacturer

Δp =Average differential pressure measured by the pitot tube by taking measurements at a number of points over the entire cross section of the duct

γ = Density of air or gas at test conditions

Volume calculation

The volume in a duct can be calculated for the velocity using the equation:

Volumetric flow (Q), m^3/sec = Velocity, v (m/sec) x Area (m^2).

Fan efficiency

Fan manufacturers generally mention fan efficiency in two ways: 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:

$$\text{Fan Mechanical Efficiency}(\eta_{mechanical}), = \frac{\text{Volume in m}^3/\text{sec} * \Delta p \text{ (total pressure)in mmWC}}{102^* \text{power input to fan shaft in kW}} \times 100$$

The static efficiency equation is the same except that outlet velocity pressure is not added to the fan static pressure

$$\text{Fan Static Efficiency}(\eta_{static}), = \frac{\text{Volume in m}^3/\text{sec} * \Delta p \text{ (static pressure)in mmWC}}{102^* \text{power input to fan shaft in kW}} \times 100$$

Drive motor kW can be measured by a load analyser. This kW multiplied by motor efficiency gives the shaft power to the fan.

5.11 Energy Savings Opportunities

- Minimising demand on the fan.
  - Minimising excess air level in combustion systems to reduce FD fan and ID fan load.
  - Minimising air in-leaks in the hot flue gas path to reduce the ID fan load, especially in case of kilns, boiler plants, furnaces, etc. Cold air in-leaks increase ID fan load tremendously due to the density increase of flue gases and in-fact choke up the capacity of the fan, resulting in a bottleneck for the boiler / furnace.
  - In-leaks / out-leaks in air conditioning systems also have a major impact on energy efficiency and fan power consumption and need to be minimised.
- The findings of performance assessment trials will automatically indicate potential areas for improvement, which could be one or more of the following:
  - change of impeller by a high efficiency impeller along with cone
  - change of fan assembly as a whole, by a higher efficiency fan
  - impeller derating (by a smaller dia impeller)
  - 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
  - fan speed reduction by pulley dia modifications for derating
  - option of two speed motors or variable speed drives for variable duty conditions.
  - option of energy efficient flat belts, or, cogged, raw edged V belts in place of conventional V belt systems, for reducing transmission losses
  - adopting inlet guide vanes in place of the discharge damper control
  - minimising system resistance and pressure drops by improvements in the duct system

Summary

- 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.
- A blower is another name for a fan that operates where the resistance to the flow is primarily on the downstream side of the fan. Most manufacturing plants use fans and blowers for ventilation and for industrial processes that need an air flow.
- Fans and blowers provide air for ventilation and industrial process requirements.
- Fan and blower selection depends on the volume flow rate, pressure, type of material handled, space limitations, and efficiency. Fans are divided into two general categories:
    - centrifugal flow
    - axial flow
- In centrifugal flow, airflow changes direction twice – once when entering and then when leaving (forward curved, backward curved or inclined, radial. In axial flow, air enters and leaves the fan with no change in direction (propeller, tube axial, vane axial).
- Blowers can achieve much higher pressures than fans, as high as 1.20 kg/cm^2. Major types are centrifugal blower and positive-displacement blower. Centrifugal blowers look more like centrifugal pumps than fans. The impeller is typically gear-driven and rotates as fast as 15,000 rpm. In multi-stage blowers, air is accelerated as it passes through each impeller.
- Positive-displacement blowers have rotors, which "trap" air and push it through the housing. Positive-displacement blowers provide a constant volume of air even if the system pressure varies.
- 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. System resistance is a function of the configuration of ducts, pickups, elbows and the pressure drops across equipment-for example bagfilter or cyclone.
- Fan characteristics can be represented in the form of fan curve(s). The fan curve is a performance curve for the particular fan under a specific set of conditions. The fan curve is a graphical representation of a number of interrelated parameters.
- 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. The choice of fan type for a given application depends on the magnitudes of the required flow and static pressure. For a given fan type, the selection of the appropriate impeller depends additionally on rotational speed.
- When a fan volume change is required on a permanent basis, and the existing fan can handle the change in the capacity, volume change can be achieved with a speed change. The simplest way to change the speed is with a pulley change.
- Dampers can be located at the inlets or outlets. Dampers provide a means of changing the 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.
- Fans are tested for field performance by the measurement of flow, head and temperature on the fan side and electrical motor kW input on the motor side.
- Energy saving opportunities include, minimising demand on the fan and the findings of performance assessment trials will automatically indicate potential areas for improvement

References

- Yahya, S. M., 2005. *Turbines compressors and fans*, 3rd ed., Tata McGraw-Hill Publication.
- Bleier, F., 1997. *Fan Handbook: Selection, Application, and Design*, 1st ed., McGraw-Hill Professional Publication.
- *Fans and Blowers* [Pdf] Available at: <http://www.enercon.gov.pk/images/pdf/3ch5.pdf> [Accessed 5 July 2013].

- *How to Select a Fan or Blower* [Pdf] Available at: <http://www.cincinnatifan.com/manuals/HowToSelectAFanOrBlower.pdf> [Accessed 5 July 2013].
- 2011. *Fans and Blowers* [Video online] Available at: <https://www.youtube.com/watch?v=M0ZmidNA520> [Accessed 5 July 2013].
- 2008. *Blowers and Industrial Fans* [Video online] Available at: <https://www.youtube.com/watch?v=Ua1vQKWL2P8> [Accessed 5 July 2013].

Recommended Reading

- Abbi, Y. P. & Jain, S., 2006. Handbook on Energy Audit and Environment Management, TERI Press.
- Heumann, W. L., 1997. *Industrial air pollution control systems*. McGraw-Hill Professional publication.
- Srinivasulu, P. & Vaidyanathan, C. V., 1977. *Handbook of machine foundations*. Tata McGraw-Hill Publication.

Self Assessment

1. The efficiency of backward curved fans compared to forward curved fans is______.
   a. higher
   b. lower
   c. same
   d. none

2. Which of the following axial fan types is most efficient?
   a. Propeller
   b. Tube axial
   c. Vane axial
   d. Radial

3. Centrifugal fans increase the speed of an air stream with a_____________impeller.
   a. vibrating
   b. rotating
   c. circulating
   d. moving

4. Which of the following is not a centrifugal fan type?
   a. Vane axial
   b. Radial
   c. Airfoil, backward
   d. Forward curved

5. Axial fans are best suitable for________ application.
   a. large flow, low head
   b. low flow, high head
   c. high head, large flow
   d. low flow, low head

6. The efficiency of forward curved fans compared to backward curved fans is ________.
   a. higher
   b. lower
   c. same
   d. medium

7. Varying the RPM of a fan by 10% varies the pressure by
   a. 19%
   b. 29%
   c. 10%
   d. 11%

8. Varying the RPM of a fan by 10% varies the flow by _______.
    a. 20%
    b. 30%
    c. 40%
    d. 10%

9. Varying the RPM of a fan by 10% varies the power by __________.
    a. 37%
    b. 10%
    c. 27%
    d. 35%

10. The intersection of system curve with fan operating curve is called __________.
    a. design point
    b. operating point
    c. selection point
    d. shut off point

Chapter VI

Pumps and Pumping System

Aim

The aim of this chapter is:

- explain pumps and pumping system
- enlist types of pumps
- explicate efficient system operation

Objectives

The objectives of the chapter are:

- explain centrifugal pump
- explicate pump curves
- elucidate flow control strategies and energy conservation opportunities

Learning Outcome

At the end of this chapter, you will be able to:

- identify a pumping system
- understand the concept of flow control strategies
- comprehend the important factors affecting energy conservation opportunities

6.1 Introduction

- A pump is a device used to move fluids, such as liquids, gases or slurries. A pump displaces a volume by physical or mechanical action. Pumps fall into five major groups:
  - direct lift
  - displacement
  - velocity
  - buoyancy
  - gravity pumps

Their names are self-explanatory, describing methods for moving a fluid.

- Pumps have two main purposes:
  - transfer of liquid from one place to another place (e.g., water from an underground aquifer into a water storage tank)
  - circulate liquid around a system (e.g., cooling water or lubricants through machines and equipment)
- The main components of a pumping system are:
  - pumps
  - prime movers: electric motors, diesel engines or air system
  - piping; used to carry the fluid
  - valves; used to control the flow in the system
  - other fittings, controls and instrumentation
  - end-use equipment; which have different requirements (e.g., pressure, flow) and therefore, determine the pumping system components and configuration

Examples include heat exchangers, tanks and hydraulic machines.

- The pump and the prime mover are typically the most energy inefficient components.

6.2 Types of Pumps

- Pumps have a variety of sizes for a wide range of applications. They can be classified according to their basic operating principles as;
  - dynamic pumps
  - positive-displacement pumps
- Dynamic pumps are also characterized by their mode of operation;a rotating impeller converts kinetic energy into pressure or velocity that is needed to pump the fluid. Dynamic pumps can be sub-classified into the following:
  - Centrifugal pumps

These are the most common pumps used for pumping water in industrial applications. Typically, more than 75% of the pumps installed in an industry are centrifugal pumps. This pump is further described below on account of its vast use.

  - Special effect pumps.

These are particularly used for specialized conditions at an industrial site.

- Positive displacement pumps are distinguished by the way they operate: liquid is taken from one end and positively discharged at the other end for every revolution. Positive displacement pumps are widely used for pumping fluids other than water, mostly viscous fluids. Positive-displacement pumps can be sub-classified into the following:
  - Rotary pumps

If the displacement within a pump is by rotary action of a gear, cam or vanes in a chamber of diaphragm in a fixed casing, it is called rotary pumps. Rotary pumps are further classified into internal gear, external gear, lobe and slide vane etc. These pumps are used for special services with particular conditions existing in industrial sites.

- Reciprocating pumps

If the displacement within a pump is by reciprocation of a piston plunger, it is called reciprocating pumps. Reciprocating pumps are used only for pumping viscous liquids and oil wells.

- Based on principle, any liquid can be handled by any of the pump designs. Based on the use of different pump designs, the centrifugal pump is generally considered to be the most economical, followed by the 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 the increased maintenance costs.

Since, worldwide, centrifugal pumps account for a major part of electricity used by pumps, the focus of this chapter is on the centrifugal pump.

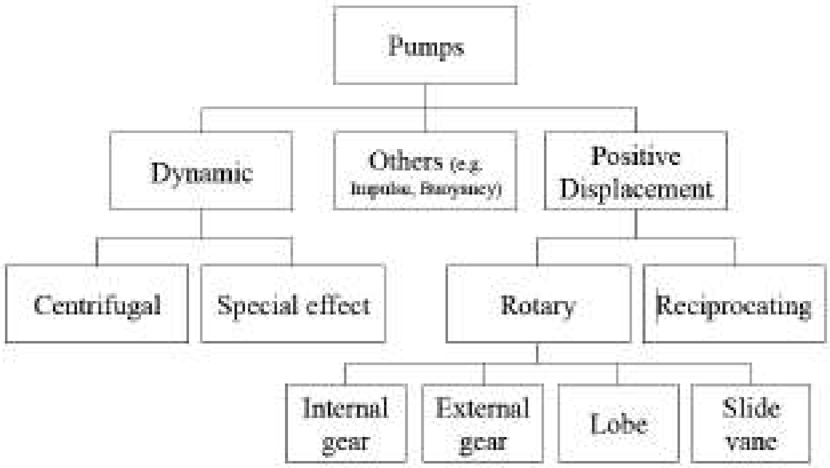

Fig. 6.1 Different types of pumps

6.2.1 Centrifugal Pump

- A centrifugal pump is of a very simple design. The two main parts of the pump are:
  - impeller
  - diffuser
- The 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 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, in case the pump has a multi-stage configuration.
- The pressure (head) that a pump will develop is directly related to the impeller diameter, the number of impellers, the size of the 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 will be the energy required.

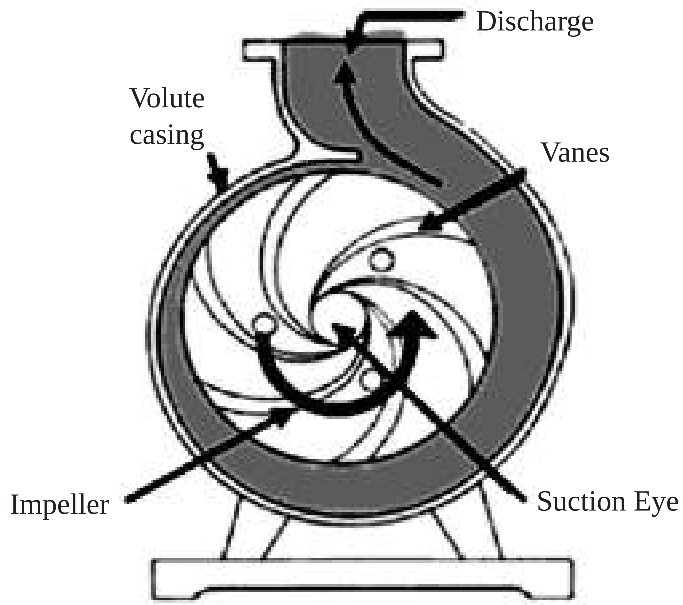

Fig. 6.2 Centrifugal pump

- A centrifugal pump is not positive acting as 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 lesser will be pumped. 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., metres of liquid column.
- The pump generates the same head of liquid irrespective of 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 the centrifugal pump is to draw the pump performance curves showing flow on the horizontal axis and head generated on the vertical axis. Efficiency, Power and NPSH Required (described later), are also all conventionally shown on the vertical axis, plotted against Flow, as illustrated in Fig. 6.3.

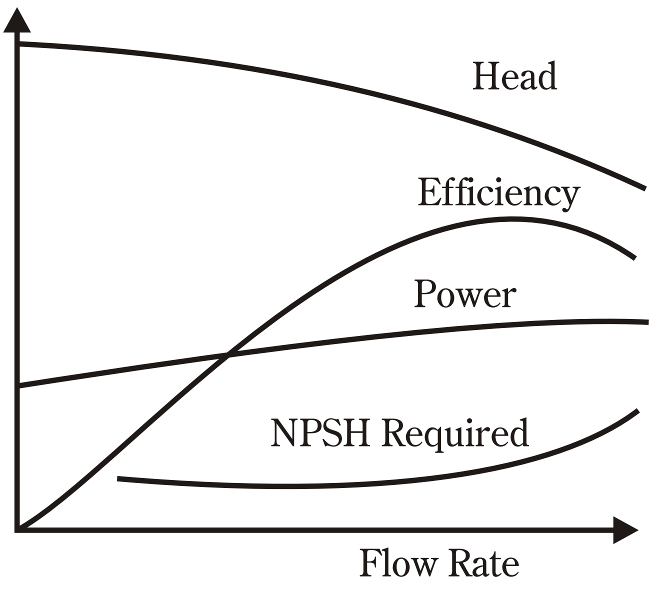

Fig. 6.3 Pump performance curve

- 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 components that comprise a pumping system, including the motor, transmission drive, piping and valves.

6.2.2 Hydraulic Power, Pump Shaft Power and Electrical Input Power

Hydraulic power Ph = $\frac{= Q(m^3/s) \times \text{Total head}, h_d - h_s(m) \times \rho(kg/m^3) \times g(m/s^2)}{1000}$

Where,

h_d-discharge head

h_s-suction head

ρ-density of the fluid

g-acceleration due to gravity

Pump shaft power Ps = Hydraulic power, Ph / pump efficiency, ηpump

Electrical input power = $\frac{\text{Pump shaft power } P_s}{\eta_{motor}}$

6.3 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 the heat exchanger.
- 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.
- The static head is simply the difference in the height of the supply and destination reservoirs, as in Fig.6.4. In this illustration, the flow velocity in the pipe is assumed to be very small.

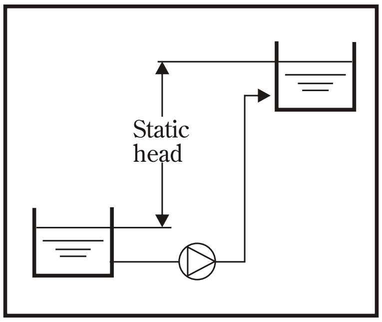

Fig. 6.4 Static head

- Another example of a system with only static head includes, pumping into a pressurised vessel with short pipe runs. The static head is independent of flow and graphically would be shown as in Fig.6.5.

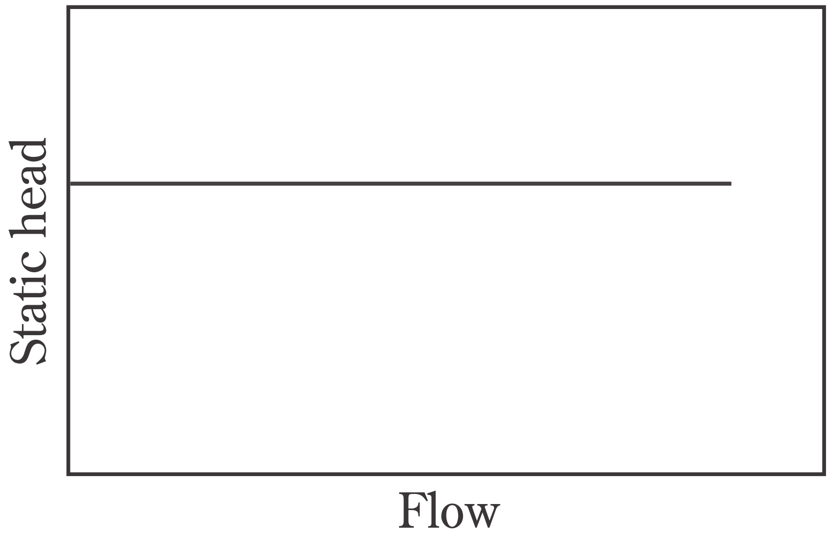

Fig. 6.5 Static head vs. flow

- The 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 metres) 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 Fig.6.6.

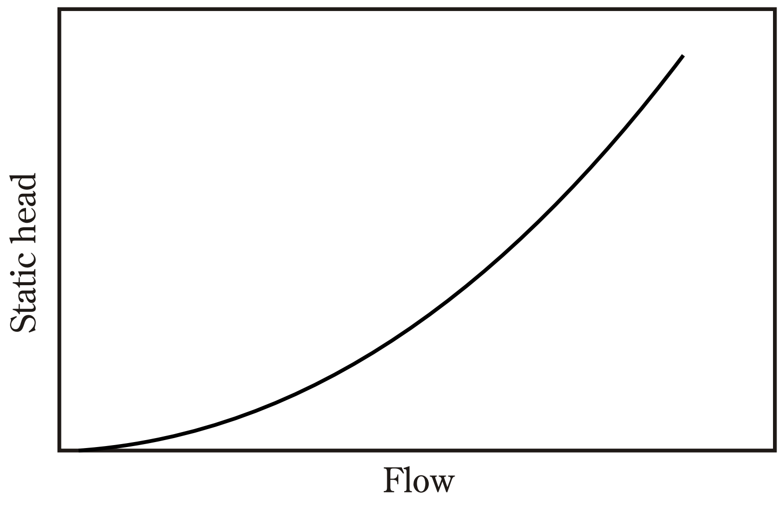

Fig. 6.6 Friction head vs. flow

- Most systems have a combination of the static and the friction head. The system curves for two cases are shown in Fig.6.7 and Fig.6.8. The ratio of static to friction head over the operating range influences the benefits achievable from variable speed drives which shall be discussed later.

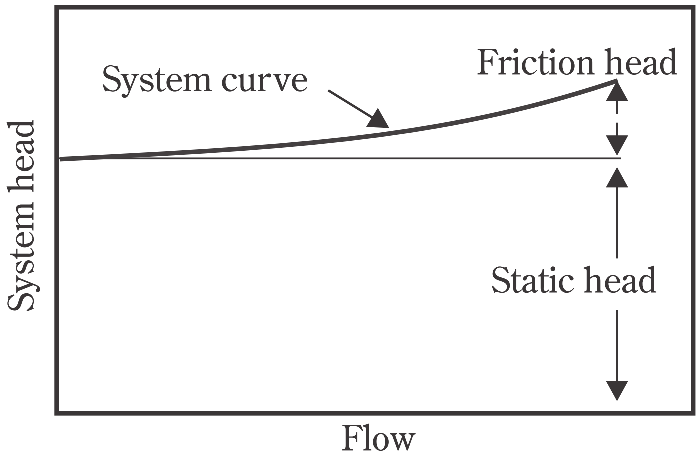

Fig. 6.7 System with high static head

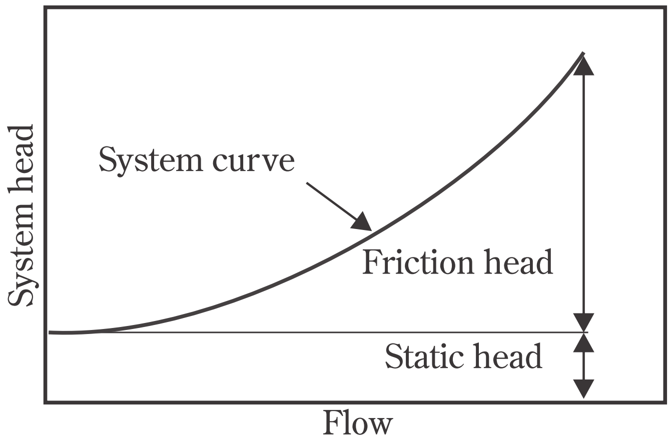

Fig. 6.8 System with low static head

- 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 minimised to reduce the pumping cost. But after eliminating unnecessary pipe fittings and length, further reduction in the friction head will require a larger diameter pipe, which adds to the installation cost.

6.4 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 Fig.6.9

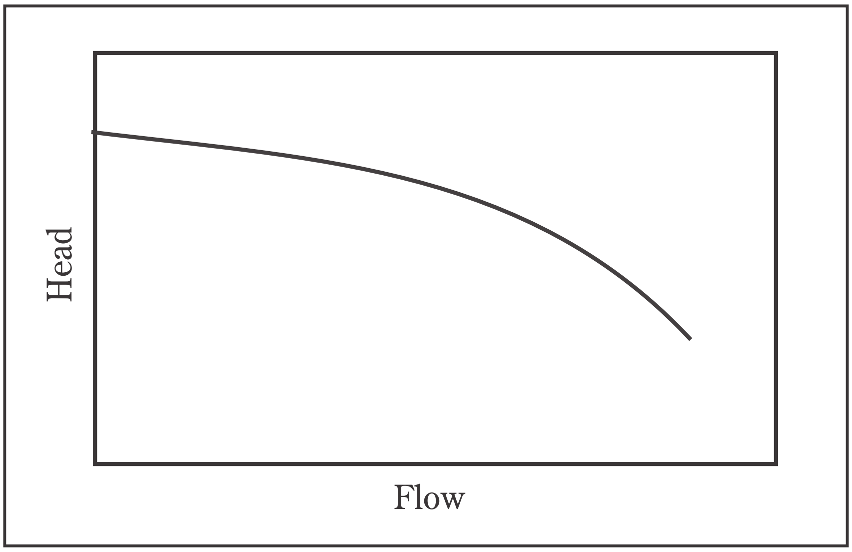

Fig. 6.9 Head-flow curve

6.4.1 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. Refer fig.6.10.

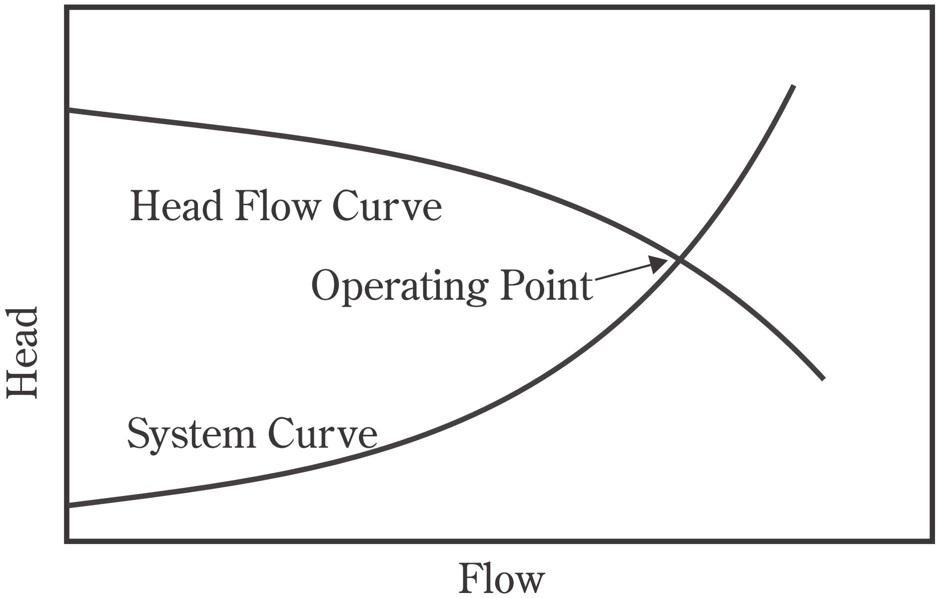

Fig. 6.10 Pump operating point

- If the actual system curve is different in reality to that calculated one, 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.

6.5 Factors Affecting Pump Performance

Factors which affect the performance of the pump are discussed in detail below:

6.5.1 Matching Pump and System Head-flow Characteristics

- Centrifugal pumps are characterised 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 the highest at one particular flow rate.
- Fig.6.11 mentioned 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.

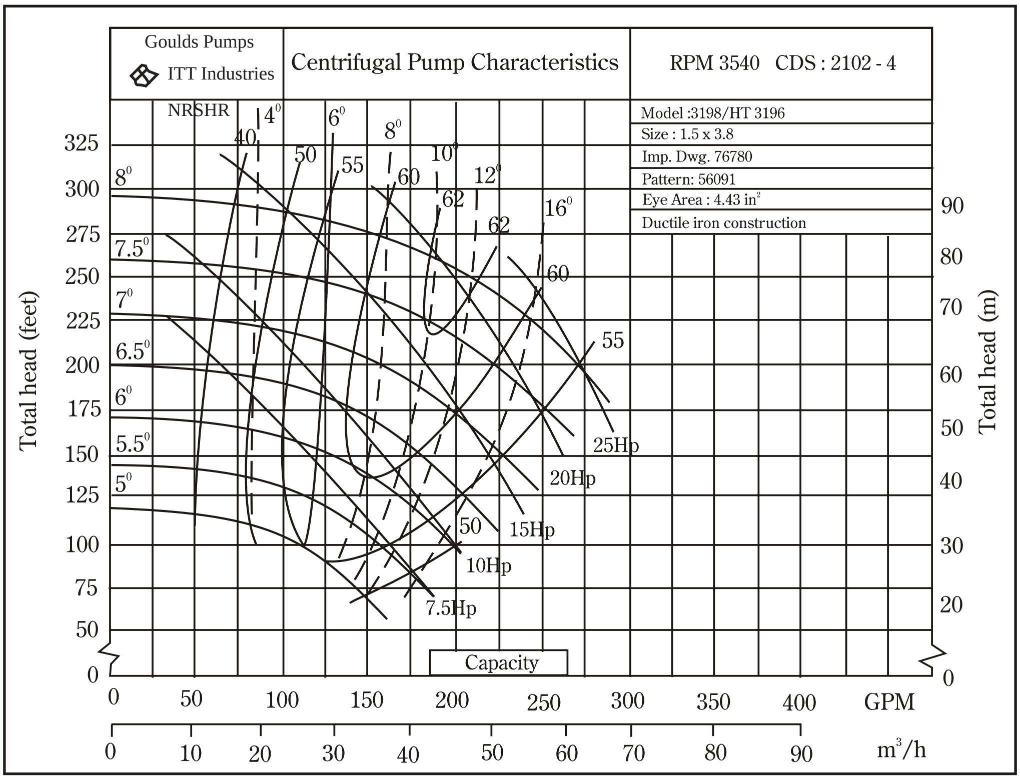

Fig. 6.11 Typical centrifugal pump performance curve

6.5.2 Effect of Over Sizing the Pump

- As mentioned earlier, pressure losses to be overcome by the pumps are a function 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; example, the system curve depends upon the height or the elevation, diameter and length of the piping, the number and type of fittings and pressure drops across various equipment for example 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 Fig.6.12 shows the effect on system curve with throttling.

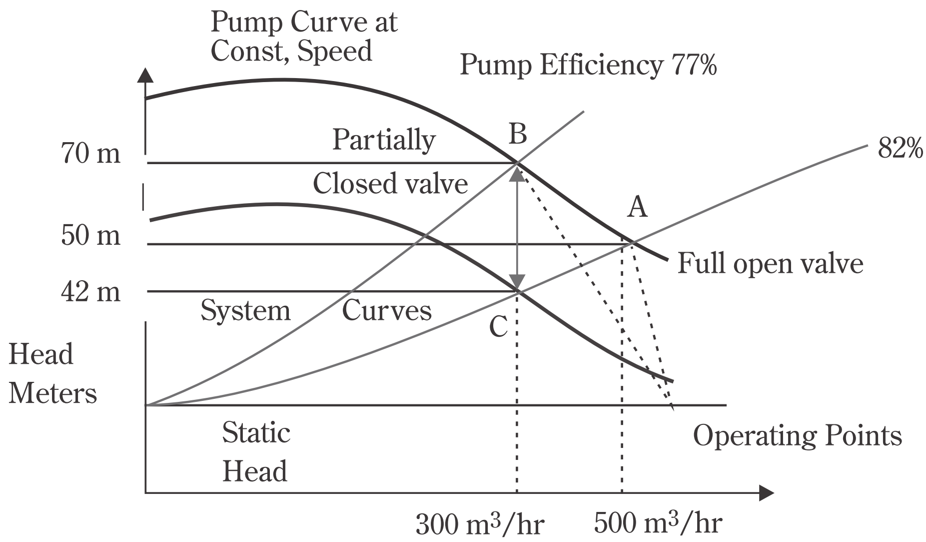

Fig. 6.12 Effect on system curve with throttling

- 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 curve PA.
- Suppose, the operating conditions are estimated to be 500 m^3/hr flow and 50m head, a pump curve is chosen, which intersects the system curve (Point A) at the pump's best efficiency point (BEP). But, in actual operation, we find that 300 m^3/hr is sufficient. The reduction in the flow rate has to be effected 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, as shown as the curve PB.

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 /hr at 70 m head. The red double arrow line shows the additional pressure drop due to throttling.

Note -The best efficiency point has shifted from 82% to 77% efficiency.

- So what we want is to actually operate at point C which is 300 m /hr on the original system curve. The head required at this point is only 42 metres.
- What we now need is a new pump 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 pump curve QD represents either of these options.

6.5.3 Energy Loss in Throttling

Consider a case (see fig.6.13) where we need to pump 68 m^3/hr of water at 47m head. The pump characteristic curves (A…E) for a range of pumps are given in Fig.6.13.

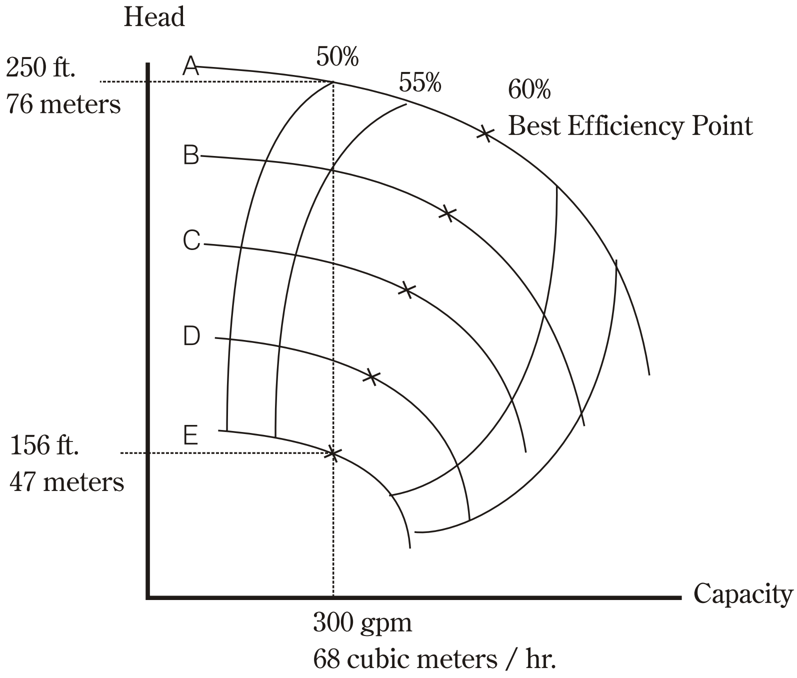

Fig. 6.13 Pump characteristic curves

If we select E, then the pump efficiency is 60%.
Hydraulic Power = Q (m^3/s) x Total head, hd - hs (m) x ρ (kg/m^3) x g (m/s^2) / 1000

$$= \frac{(68/3600) \times 47 \times 1000 \times 9.81}{1000}$$

= 8.7 kW

Shaft Power = 8.7 / 0.60 = 14.5 Kw
Motor Power = 14.5 / 0.9 = 16.1Kw (considering a motor efficiency of 90%)

If we select A, the pump efficiency is 50% (drop from earlier 60%).
Obviously, this is an oversize pump. Hence, the pump has to be throttled to achieve the desired flow. Throttling increases the head to be overcome by the pump. In this case, head is 76 metres.
Hydraulic Power = Q (m^3/s) x Total head, hd - hs(m) x ρ(kg/m^3) x g(m/s^2) / 1000

$$= \frac{(68/3600) \times 76 \times 1000 \times 9.81}{1000}$$

= 14 kW

Shaft Power =14 / 0.50 = 28 Kw
Motor Power = 28 / 0.9 = 31 Kw (considering a motor efficiency of 90%)
Hence, additional power drawn by A over E is

31 -16.1 = 14.9 kW

Extra energy used = 8760 hrs/yr x 14.9 = 1, 30,524 kwh/annum
= Rs. 5, 22, 096/annum
In this example, the extra cost of the electricity is more than the cost of purchasing a new pump.

6.6 Efficient Pumping System Operation

- To understand a pumping system, one must realise that all of its components are interdependent. While examining or designing a pump system, the process demands must be established first and the most energy efficient solution should be introduced.

Example, does the flow rate have to be regulated continuously or in steps? Can on-off batch pumping be used? What are the needed flow rates and how are they distributed in time?

- The first step to achieve energy efficiency in the pumping system is to target the end-use. A plant water balance would establish a usage pattern and highlight areas where water consumption can be reduced or optimised. Good water conservation measures alone may eliminate the need for some pumps.
- Once flow requirements are optimised, then the pumping system can be analysed for energy conservation opportunities. Basically this means matching the pump to the requirements by adopting the proper flow control strategies.
- Common symptoms that indicate opportunities for energy efficiency in pumps are given in Table 6.1.

Symptom	Likely Reason	Best Solutions
Throttle valve-controlled systems	Oversized pump	Trim impeller, smaller impeller, variable speed drive, two speed drive, lower rpm
Throttle valve-controlled systems	Oversized pump	Trim impeller, smaller impeller, 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 a 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

Table 6.1 Symptoms indicating potential opportunity for energy savings

6.6.1 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 the impeller peripheral velocity and the generated head.
- Peripheral velocity is directly related to the 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 Fig.6.3 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 to the rotodynamic pump performance parameters of flow, head and power absorbed, to speed are known as the Affinity Laws.
- According to the Affinity Law,

$$Q \ \alpha \ N$$
$$H \ \alpha \ N^2$$
$$P \ \alpha \ N^3$$

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 and is given as;

$$\mathbf{Q_1 / Q_2 = N_1 / N_2}$$

Example: $100 / Q_2 = 1750/3500$

$Q_2 = 200\ m^3/hr$

Head : Head is proportional to the square of speed

$H_1 / H_2 = (N_{12}) / (N_{22})$

Example: $100 / H_2 = 1750^2 /3500^2$

$H_2 = 400m$

Power (kW): Power is proportional to the cube of speed

$(kW)1/kW_2 = (N_{13})/(N_{23})$

Example : $5/kW_2 = 17503/ 35003$

$kW_2 = 40$

- As seen from the above laws, doubling the speed of the centrifugal pump will increase the power consumption by eight times. Conversely a small reduction in speed will result in drastic reduction in power consumption.
- This forms the basis for energy conservation in centrifugal pumps with varying flow requirements. The implications of this can be better understood as shown in an example of a centrifugal pump in Fig.6.14 below.

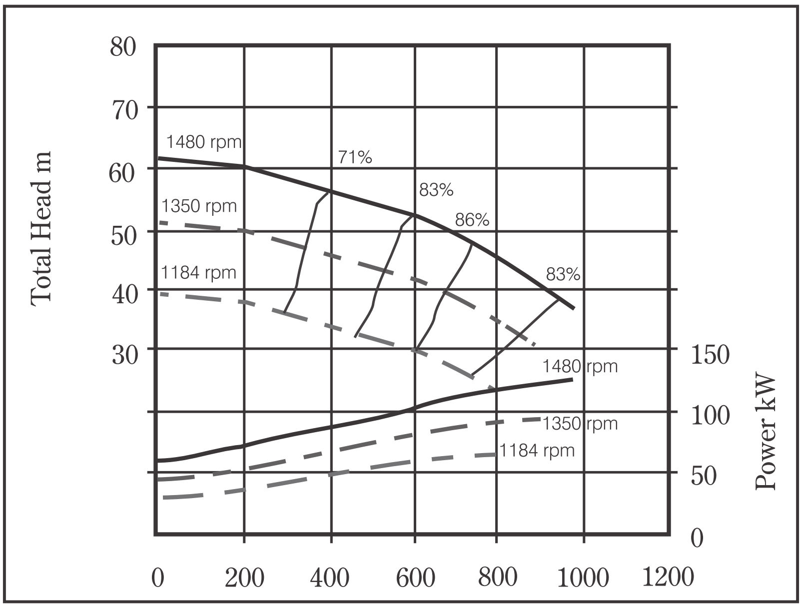

Fig. 6.14 Example of speed variation effecting centrifugal pump performance

- Points of equal efficiency on the curves for the 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).
- 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.

6.6.2 Effects of Impeller Diameter Change

- Changing the impeller diameter gives a proportional change in the peripheral velocity, so it follows that there are equations similar to the affinity laws, for the variation of performance with the 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 Fig.6.15 compared with Fig.6.14.

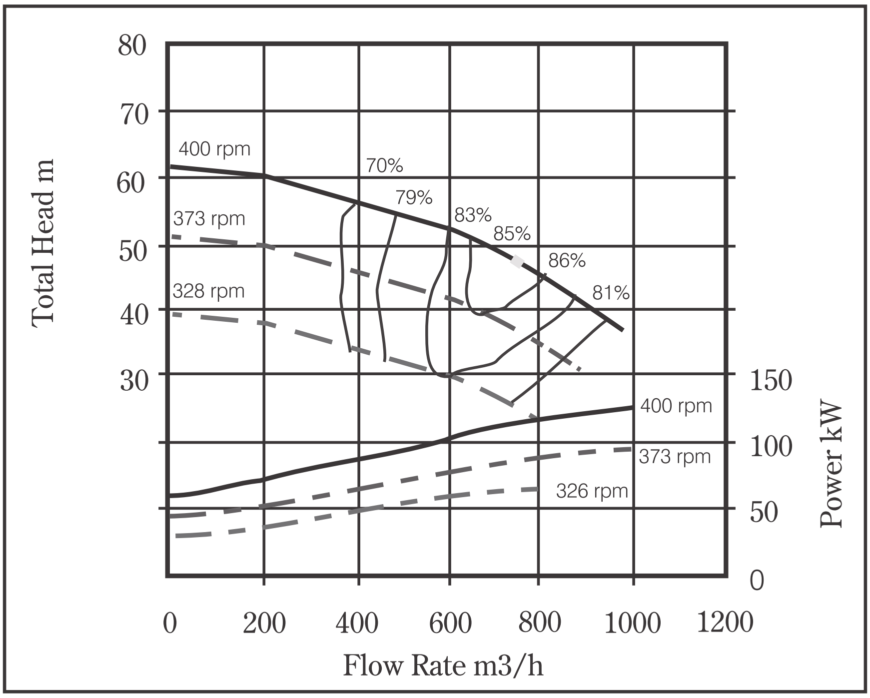

Fig. 6.15 Example effect of impeller diameter reduction on centrifugal pump performance

- 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.
- Example, reducing the speed by 50% typically results in a reduction of efficiency by 1 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 change in diameter is more than 5%, the accuracy of the squared and cubic relationships can fall off and the pump manufacturer's performance curves should be referred to for precise calculations.
- 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.

6.6.3 Pump Suction Performance (NPSH)

- 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 mentioned below;
  - the collapsing cavitation bubbles can erode the vane surface, especially when pumping water-based liquids
- noise and vibration are increased, with possible shortened seal and bearing life

- the cavity areas will initially partially choke the impeller passages and reduce pump performance. In extreme cases, a total loss of pump developed head occurs
- The value by which the pressure in the pump suction exceeds the liquid vapour pressure, it is expressed as a head of liquid and referred to as Net Positive Suction Head Available (NPSHA). This is a characteristic of system design.
- The value of NPSH needed at the pump suction to prevent the pump from cavitating 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 is 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 to the head with cavitation free performance. At this point, cavitation is present and a prolonged operation at this point usually lead to damage. So a margin is usually applied by which NPSHA should exceed NPSHR.
- As would be expected, the NPSHR increases as the flow through the pump increases.(see fig 6.3). In addition, as flow increases in the suction pipe work, 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 the same way as pump head and conversion of NPSHR from one speed to another can be made using the following equations;

$$Q \propto N$$
$$NPSHR \propto N^2$$

- 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.

6.7 Flow Control Strategies

Different strategies to control flow are:

6.7.1 Pump Control by Varying Speed

- To understand how speed variations change the duty point, the pump and system curves are over-laid. Two systems which are considered:
  - one with only friction loss
  - another where the static head is high in relation to the friction head
  - It will be seen that the benefits are different.
- 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 an order such that the efficiency first increases as the speed is reduced and then decreases.
- This can extend the useful range of variable speed operation in a system with a 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 the 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 hence reducing the speed increases the 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 the seal life is increased providing the duty point remains within the allowable operating range.

- In corollary to the above statement, small increase in the speed of a pump significantly increases the 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 vibrations from both the pump and motor will increase, although for small increase, the change will be small. If the liquid contains abrasive particles, increasing speed will give a corresponding increase in the surface wear in the pump and pipe work.
- 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 5m/s.

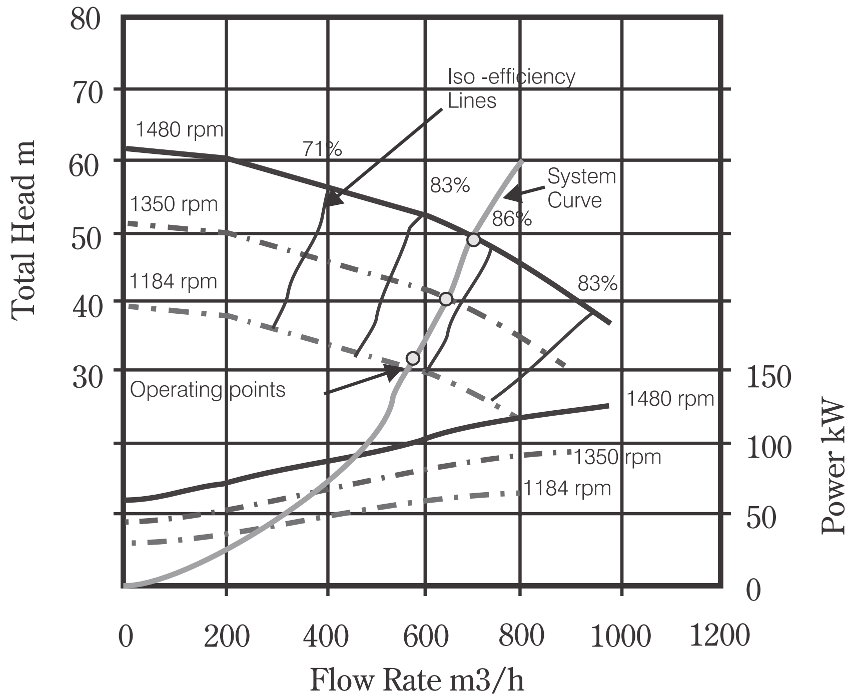

Fig. 6.16 Example of the effect of pump speed change in a system with only friction loss

According to the Fig.6.16,

- 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
- Affinity laws are obeyed, which means that there is a substantial reduction in the power absorbed accompanying the reduction in the flow and head, making variable speed the ideal control method for systems with friction loss

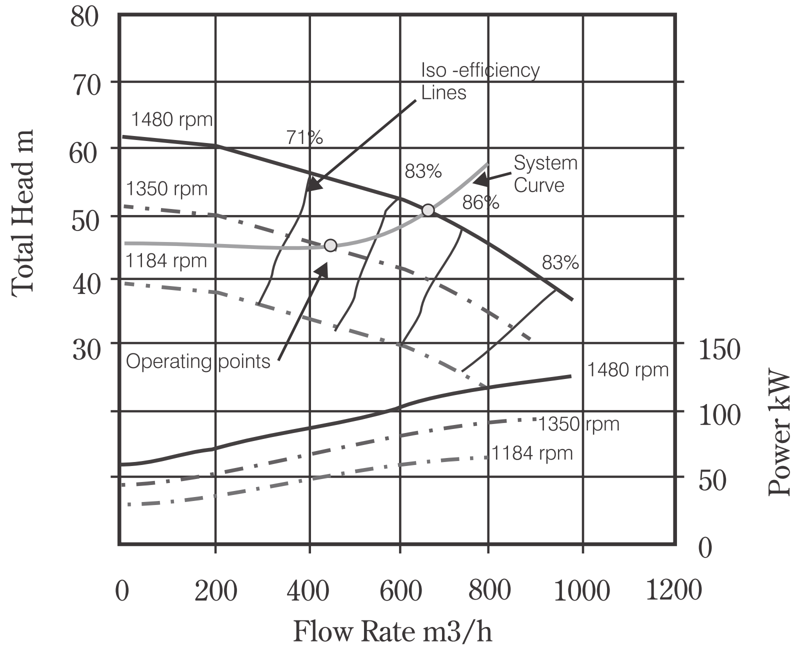

Fig. 6.17 Example for the effect of pump speed change for a system with high static head

Based on the Fig.6.17,

- in a system where the static head is high, as illustrated, 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 the 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

6.7.2 Pumps in Parallel Switched to Meet Demand

- Another energy efficient method of flow control, particularly for systems where the 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 Fig.6.18.

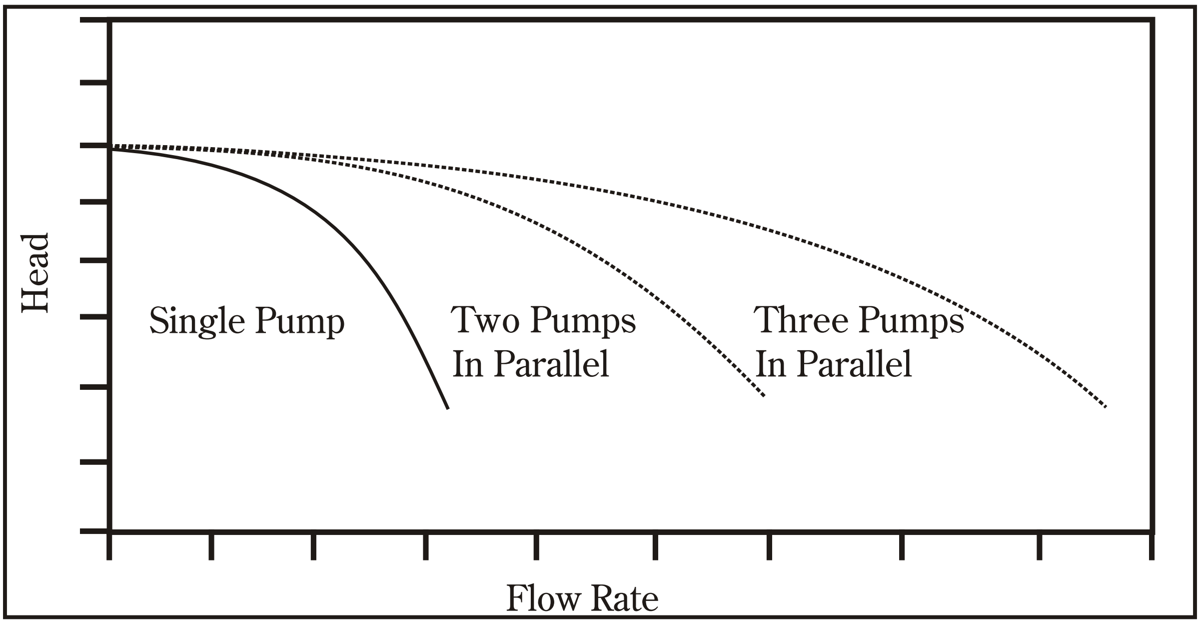

Fig. 6.18 Typical head-flow curves for pumps in parallel

- 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 Fig.6.19, the operating point of the pumps on their performance curves moves to a higher head and hence, a 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 static, the flow rate would be proportional to the number of pumps operating.

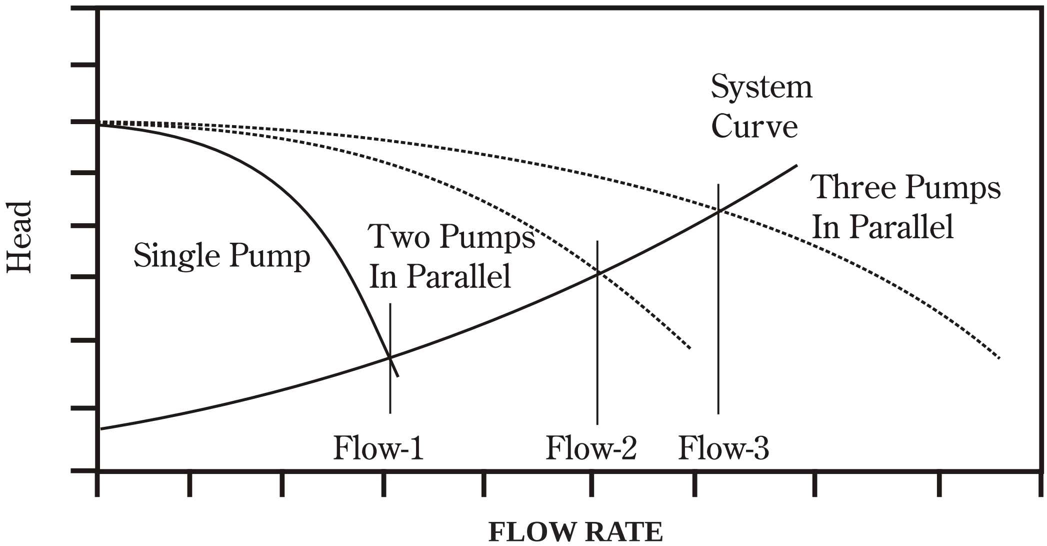

Fig. 6.19 Typical head-flow curves for pumps in parallel, with system curve illustrated

- 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 while 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 Fig.6.19 that if 1 or 2 pumps were stopped then the remaining pump(s) would operate well along the curve, where the NPSH is higher and vibration level increased, giving an increased risk of operating problems.

6.7.3 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 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 is acceptable, this is an effective approach to minimise energy consumption.
- The stop/start operation leads to 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 peak” energy tariffs by arranging the run times during the low tariff periods.
- To minimise energy consumption with stop start control, it is better to pump at flow rate as low as possible for the process to permit. This minimises friction losses in the pipe and an appropriately small pump can be installed. Example, pumping at half the flow rate for twice as long can reduce energy consumption to a quarter.

6.7.4 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.

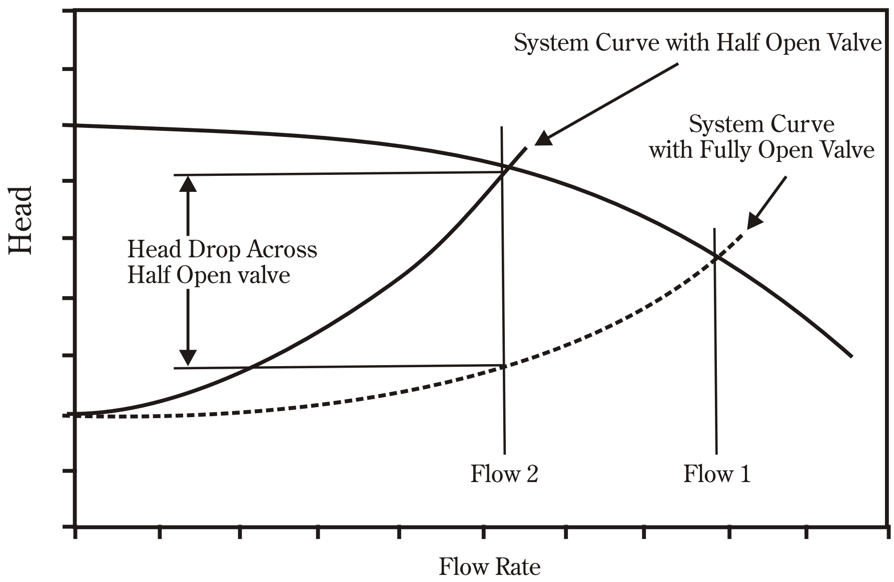

Fig. 6.20 Control of pump flow by changing system resistance using a valve

- To understand how the flow rate is controlled, see Fig.6.20. 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 the 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 Fig.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.

6.7.5 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 a 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.

6.8 Fixed Flow Reduction

6.8.1 Impeller Trimming

- Impeller trimming refers to the process of machining the diameter of an impeller to reduce the energy added to the system fluid.
- 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 Fig.6.21 (a) & (b) for before and after impeller trimming).

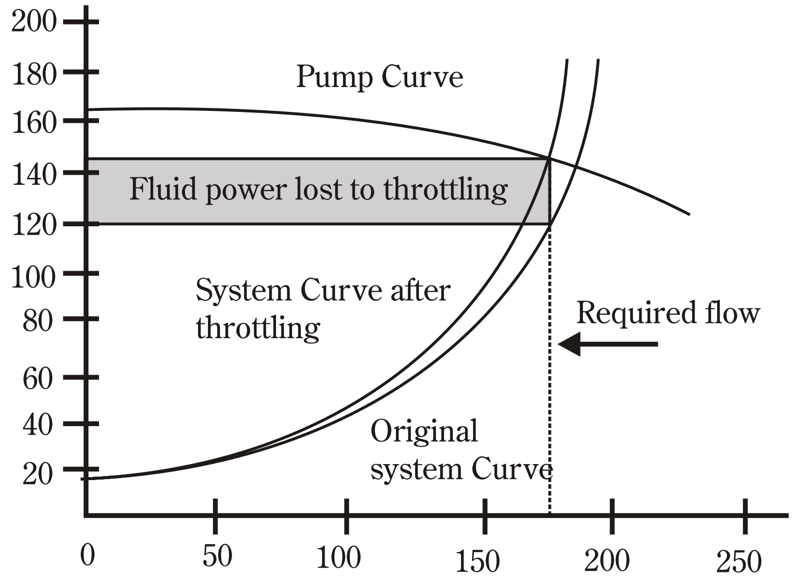

Fig. 6.21(a) Before impeller trimming

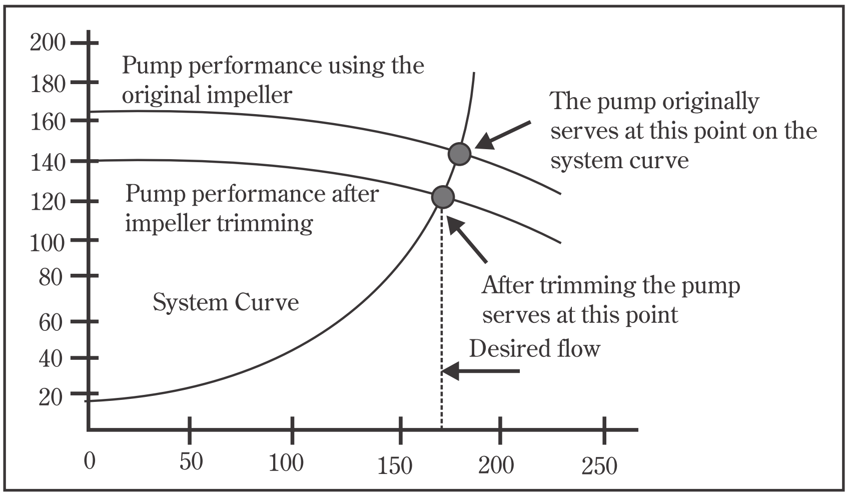

Fig. 6.21(b) After impeller trimming

- Impeller trimming reduces tip speed, which in turn directly lowers the amount of energy imparted to the system fluid and lowers both the flow and pressure generated by the pump.
- The Affinity Laws, which describe centrifugal pump performance, provide a theoretical relationship between the impeller size and the pump output (assuming constant pump speed).

Where,
Q = flow
H = head
BHP = brake horsepower of the pump motor
Subscript 1 = original pump
Subscript 2 = pump after impeller trimming
D = Diameter

$$Q_2 = (D1/D_2)Q_1$$
$$H_2 = (D1/D_2)^2\ H_1$$
$$BHP_2 = (D_1/D_2)^3\ BHP_1$$

Trimming an impeller changes its operating efficiency, and the non-linearties of the Affinity Laws with respect to impeller machining complicate the prediction of pump performance. Consequently, impeller diameters are rarely reduced below 70 percent of their original size.

6.8.2 Meeting Variable Flow Reduction

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
  - 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 (VFDs).
- 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 a high static head.

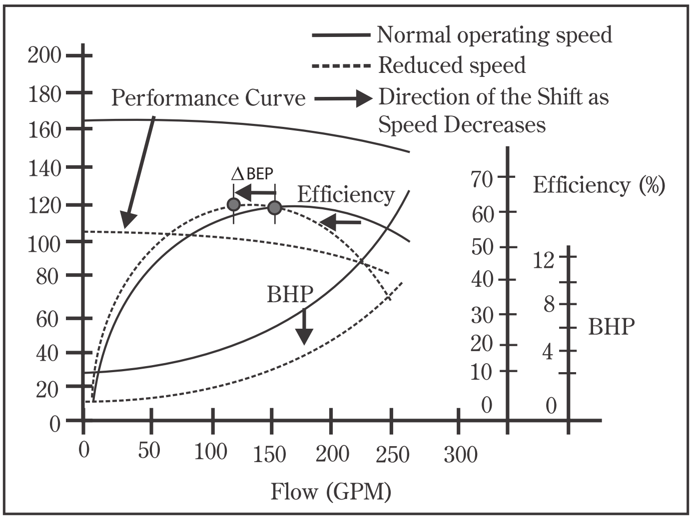

Fig. 6.22 Effect of VFD

- For many systems, VFDs offer a means to improve the pump operating efficiency despite changes in operating conditions. The effect of slowing pump speed on pump operation is illustrated by the three curves in Fig.6.23.

- When a VFD slows a pump, its head/flow and brake horsepower (BHP) curves drop down 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.
- VFDs may offer operating cost reductions by allowing a 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.
- Example, in many systems, increasing flow through by-pass lines does not impact the backpressure on a pump noticeably. 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 fluid 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 -6 times higher than normal operating currents.
- This high current fades 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.

6.9 Steps for Energy Efficiency in Pumping System

- Ensure adequate NPSH at site of installation.
- Ensure availability of basic instruments at pumps like pressure gauges, flow meters.
- Operate pumps near the best efficiency point.
- Modify pumping systems and pump losses to minimise 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 fluid temperature differentials to reduce pumping rates in case of heat exchangers. Repair seals and packing to minimise water loss by dripping.
- Balance the system to minimise flows and reduce pump power requirements.
- Avoid pumping head with a free-fall return (gravity); Use siphon effect to advantage
- Conduct water balance to minimise 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.
- Optimise the number of stages in the multi-stage pump in case of head margins. Reduce system resistance by pressure drop assessment and pipe size optimisation.

Summary

- A pump is a device used to move fluids, such as liquids, gases or slurries.
- Centrifugal pumps are the most common pumps used for pumping water in industrial applications. Typically, more than 75% of the pumps installed in an industry are centrifugal pumps.
- Affinity laws states the relations between Power, Pressure, Flow and Speed.
- System resistance is an obstruction to flow. This is mainly caused by various components like pipes, valves, flanges, bends, etc. Each of these presents resistance in the form of a pressure drop across it and consumes energy. Hence, it is essential to reduce the system resistance to the bare minimum possible.
- 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).
- Flow can be controlled by various methods. The best method depends on the type of application and the operating point. The strategy should be well planned so that the maximum efficiency can be achieved.
- Many opportunities exist for energy savings in pumping systems. These include reduction in the system resistance, preventing leakages, checking the foot valve, impeller trimming, speed control. Again, speed can be controlled by pulley change, dual speed motor, variable speed drive etc.
- The best operating point for a pump is the intersection of the Pump Performance Curves and the operating characteristics of the pump as given by manufacturer.
- The value by which the pressure in the pump suction exceeds the liquid vapour pressure, and is expressed as a head of liquid, referred to be the Net Positive Suction Head Available (NPSHA).
- In stop/start 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 wet well, an elevated tank or an accumulator type pressure vessel.
- Impeller trimming refers to the process of machining the diameter of an impeller to reduce the energy added to the system fluid.
- Ensure adequate NPSH at site of installation; ensure availability of basic instruments at pumps like pressure gauges, flow meters, operate pumps near the best efficiency point, modify pumping systems and pump losses to minimise throttling are few steps for energy efficiency in pumping system.

References

- Rishel, J., Durkin, T. & Kincaid, B., 2006. *HVAC Pump Handbook,* 2nd ed., McGraw-Hill Professional publication.
- Menon, E. S., 2009. *Working Guide to Pump and Pumping Stations: Calculations and Simulations*,1st ed., Gulf Professional Publishing.
- *Pumps and Pumping System* [Pdf] Available at: < http://www.beeindia.in/energy_managers_auditors/documents/guide_books/3Ch6.pdf> [Accessed 5 July 2013].
- *Chapter 6 Introduction to Pumping Systems* [Pdf] Available at: < dec.alaska.gov/water/opcert/Docs/Chapter6.pdf> [Accessed 5 July 2013].
- 2011. *System Head Curves:How to have a successful pumping system* [Video online] Available at: < https://www.youtube.com/watch?v=okKKZiRqrPI> [Accessed 5 July 2013].
- 2012. *Progressing Cavity Pumping System* [Video online] Available at: < https://www.youtube.com/watch?v=v5VnnBtXtlc> [Accessed 5 July 2013].

Recommended Reading

- 2004. *Variable Speed Pumping: A Guide to Successful Applications*, Elsevier Ltd.
- Mackay, R. C., 2004. *The Practical Pumping Handbook*, Elsevier Science publication.
- Nourbakhsh, A., Jaumotte, A., Hirsch, C. & Parizi, H. B., 2007. *Turbopumps and Pumping Systems*, 1st ed., Springer Publication.

Self Assessment

1. If the speed of the pump is doubled, power goes up by _____.
    a. 2 times
    b. 6 times
    c. 8 times
    d. 4 times

2. Friction losses in a pumping system is _________ .
    a. proportional to Q
    b. proportional to Q^2
    c. proportional to Q^3
    d. proportional to Q^4

3. The first step to achieve energy efficiency in the pumping system is to target ________.
    a. the end-use
    b. the start-use
    c. the middle-use
    d. the begin-use

4. Power is proportional to _______.
    a. square of speed
    b. cube of speed
    c. square root of speed
    d. cube root of speed

5. Flow is proportional to ________.
    a. square of speed
    b. cube of speed
    c. square root of speed
    d. speed

6. 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 _____.
    a. gravitation
    b. cavitation
    c. invitation
    d. vaporisation

7. The value, by which the pressure in the pump suction exceeds the liquid vapour pressure, is expressed as a head of liquid and referred to as _______.
    a. NPSH
    b. NPSHR
    c. NPSHA
    d. NPPSHR

8. The process of machining the diameter of an impeller to reduce the energy added to the system fluid is called_______.
    a. impeller filling
    b. impeller edging
    c. impeller bordering
    d. impeller trimming

9. A device used to move fluids, such as liquids, gases or slur is called _______.
    a. pump
    b. motor
    c. blower
    d. fan

10. Relations between Power, Pressure, Flow and Speed is known as _______.
    a. centrifugal law
    b. axial law
    c. affinity law
    d. parallel law

Chapter VII

Cooling Tower

Aim

The aim of this chapter is:

- explain cooling towers and types
- explicate efficient system operation of cooling towers
- define assessment of cooling towers

Objectives

The objectives of the chapter are:

- explain performance evaluation of cooling towers
- elucidate flow control strategies
- describe energy saving opportunities of cooling towers

Learning outcome

At the end of this chapter, you will be able to:

- define a cooling tower
- identify types of cooling tower
- understand the concept of efficient system operation, flow control strategies and energy saving opportunities

7.1 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. A typical closed loop cooling tower system is shown in Fig. 7.1.

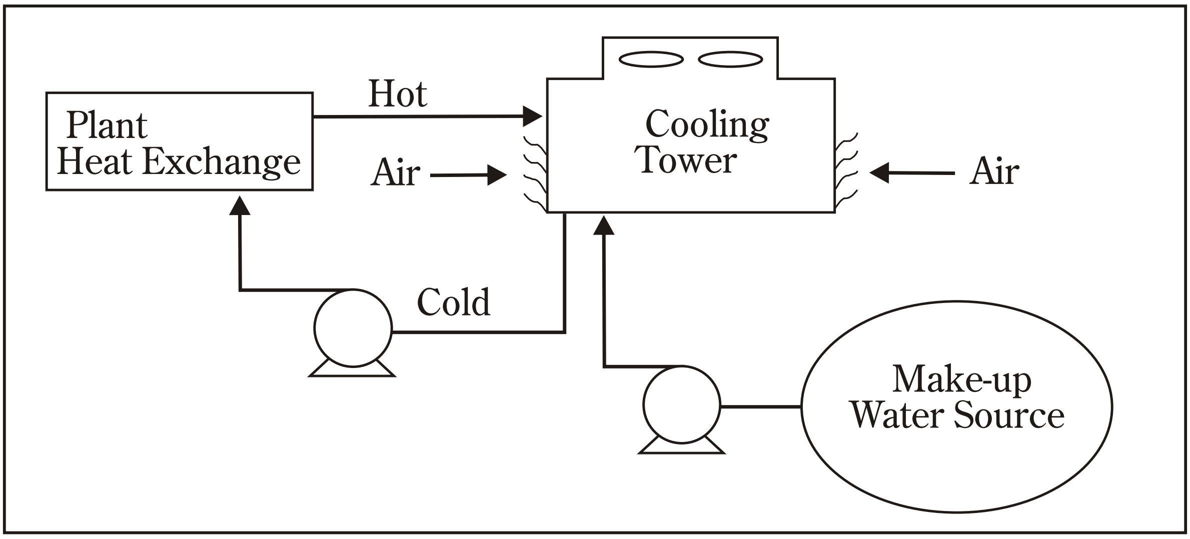

Fig. 7.1 Cooling water system

7.1.1 Cooling Tower Types

- Cooling towers fall into two main categories;
  - natural draft
  - 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 m /hr. These types of towers are used only by utility power stations.
- Mechanical draft towers utilise large fans to force or suck air through circulated water. The water falls downward over fill surfaces, which helps to increase the contact time between the water and the air - this helps to 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, let us learn about it more.

7.1.2 Mechanical Draft Towers

- Mechanical draft towers are available in the following airflow arrangements:
  - counter flow induced draft
  - counter flow forced draft
  - cross flow induced draft
- In the counter flow induced draft design, hot water enters at the top, while air is introduced from the bottom and exits at the top. Both forced and induced draft fans are used.
- In cross flow induced draft towers, the water enters at the top and passes over the fill. Air however, is introduced at the side either on one side (single-flow tower) or opposite sides (double-flow tower).
- An induced draft fan draws air across the wetted fill and expels it through the top of the structure. Fig. 7.2 illustrates various cooling tower types.

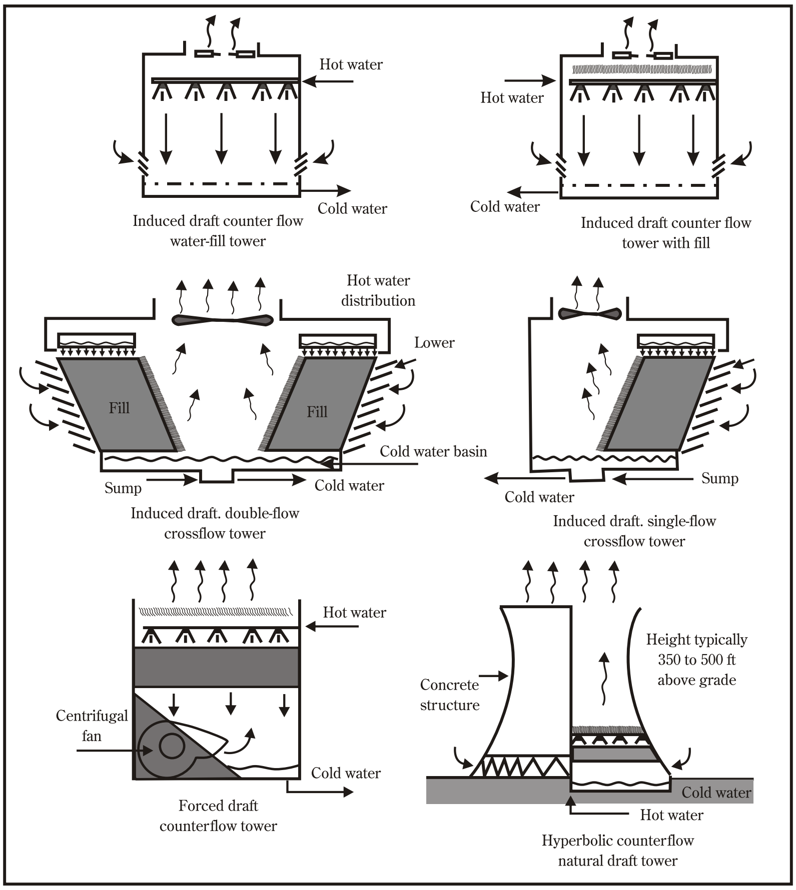

Fig. 7.2 Cooling tower types

- Mechanical draft towers are available in a large range of capacities. Normal capacities range from approximately 10 tons, 2.5 m^3/hr flow to several thousand tons and m^3/hr. Towers can be factory built or field erected; example, concrete towers are only field erected.
- Many towers are constructed so that they can be grouped together to achieve the desired capacity. Thus, many cooling towers are assemblies of two or more individual cooling towers or “cells.”
- The number of cells they have e.g., an eight- cell tower, often refers to such towers. Multiple-cell towers can be linear, square, or round depending upon the shape of the individual cells and whether the air inlets are located at the sides or bottoms of the cells.

7.1.3 Components of a Cooling Tower

The basic components of an evaporative tower are as follows:

- frame and casing
  - fill
  - cold water basin
  - drift eliminators
  - air inlet
  - louvers
  - nozzles
  - fans
- Frame and casing: Most towers have structural frames that support the exterior enclosures (casings), motors, fans and other components. With some smaller designs such as, some glass fibre 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. The 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. The 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 the 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 fills. 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 designs 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 such a design, the tower is mounted on legs to 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 equalise airflow 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.

7.1.4 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 fibre 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 fibre rather than wood panels (casing) over the wood framework. The inlet air louvers may be glass fibre, the fill may be plastic, and the cold water basin may be steel.
- Larger towers sometimes, are made of concrete. Many tower casings and basin are constructed of galvanised steel or where corrosive atmosphere is a problem, stainless steel.
- Sometimes a galvanised tower has a stainless steel basin. Glass fibre 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 fibre 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 fibre reinforced plastic.

7.2 Cooling Tower Performance

The important parameters, from the point of determining the performance of cooling towers, are:

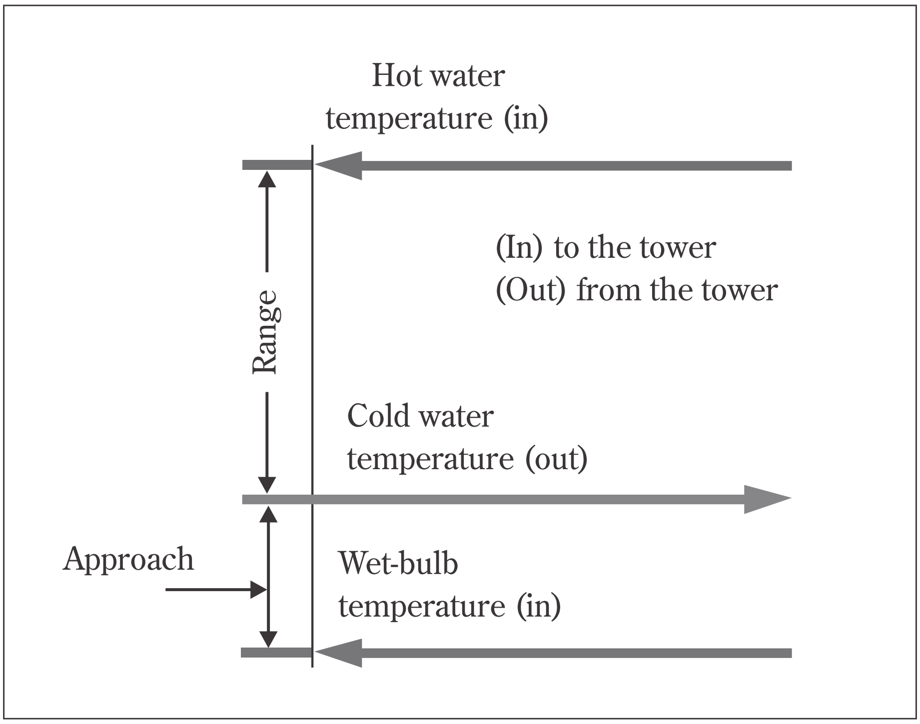

Fig. 7.3 Range and approach

- "Range" is the difference between the cooling tower water inlet and outlet temperature. (see fig. 7.3).
- "Approach" is the difference between the cooling tower outlet cold water temperature and the ambient wet bulb temperature. Although, both range and approach should be monitored, the "Approach" is a better indicator of cooling tower performance (see fig.7.3).
- 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).
- Cooling capacity is the heat rejected in kCal/hr or TR, given as a product of the mass flow rate of water, specific heat and temperature difference.
- 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 m^3. An empirical relation used often is:

Evaporation loss (m^3/hr) = 0.00085 x 1.8 x circulation rate (m^3/hr) x (T_1 –T_2)

where,
$T_1 - T_2$ = Temperature difference between inlet and outlet water
Source: Perry's Chemical Engineers Handbook (Page: 12-17)

- Cycles of concentration (C.O.C) is the ratio of dissolved solids in circulating water to the dissolved solids in make up water.

- Blow down losses depend upon cycles of concentration and the evaporation losses and is given by relation:

Blow Down = Evaporation Loss / (C.O.C. – 1)

- 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:

$$L\left(T_1 - T_2\right) = \left(h_2 - h_1\right) G$$

Where, $\frac{L}{G} = \frac{h_2 - h_1}{T_1 - T_2}$

L/G = liquid to gas mass flow ratio (kg/kg)

T_1 = hot water temperature (^{0}C)

T_2 = cold water temperature (^{0}C)

h_2 = enthalpy of air-water vapour mixture at exhaust wet-bulb temperature (same units as above)

h_1 = enthalpy of air-water vapour mixture at inlet wet-bulb temperature (same units as above)

7.2.1 Factors Affecting Cooling Tower Performance

- Capacity
  - Heat dissipation (in kCal/hour) and circulated flow rate (m^3/hr) are not sufficient to understand cooling tower performance. Other factors which we will see, must be stated along with the flow rate m^3/hr.
- Example, a cooling tower sized to cool 4540 m^3/hr through a 13.9^{0}C range might be larger than a cooling tower to cool 4540 m^3/hr through 19.5^{0}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 ^{0}C = Heat Load in kcals/hour / Water Circulation Rate in LPH
  - Thus, range is a function of the heat load and the flow circulated through the system. Cooling towers are usually specified to cool a certain flow rate from one temperature to another temperature at a certain wet bulb temperature.

Example, the cooling tower might be specified to cool 4540 m^3/hr from 48.9^{0}C to 32.2^{0}C at 26.7^{0}C wet bulb temperature.

Cold Water Temperature (32.2^{0}C) Wet Bulb Temperature(26.7^{0}C) = Approach(5.5^{0}C)

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

As a generalisation, the closer the approach to the wet bulb, the more expensive the cooling tower due to increased size. Usually a 2.8^{0}C approach to the design wet bulb is the coldest water temperature that cooling tower manufacturers will guarantee. If the 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.

- 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 the 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, oversized 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 -1523kCal/kW/hr(18 kg/cm^2 compression)

Wet bulb t emperature

Wet bulb temperature is an important factor in the performance of evaporative water cooling equipment. It is a controlling factor from the aspect of the 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 the 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 the thermal conditions and tower capability.

Initial selection of towers with respect to the 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 the inlet-wet bulb is the wet bulb temperature of the air entering the tower. The latter can be, and often is, affected by discharge vapours being recirculated 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.

Table 7.1 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 16.67^0C range at a 26.7^0C design wet bulb. The overall width of all towers is 21.65 metres; the overall height, 15.25 metres, and the pump head, 10.6 m approximately.

Approach ^{0}C	2.77	3.33	3.88	4.44	5.0	5.55
Hot Water ^{0}C	46.11	46.66	47.22	47.77	48.3	48.88
Cold Water ^{0}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

Table 7.1.Approach vs. cooling tower size

(4540m^3/hr; 16.67^0C Range 26.7^0C Wet Bulb; 10.7m Pump Head)

Approach and flow

Suppose a cooling tower is installed that is 21.65 m wide, 36.9 m long, 15.24m high, has three 7.32 m diameter fans and each is powered by 25 kW motors, the cooling tower cools from 3632 m^3/hr water from 46.1^0C to 29.4^0C at 26.7^0C WBT dissipating 60.69 million kCal/hr. Table 7.2 shows what would happen with additional flow but with the range remaining constant at 16.67^0C. The heat dissipated varies from 60.69 million kCal/hr to 271.3 million kCal/hr.

Flow m^3/hr	**Approach ^{0}C**	**Cold Water ^{0}C**	**Hot Water ^{0}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	5.00	32.18	48.89	101.28
7150.5	5.56	33.29	50.00	119.48
8736	6.67	35.29	51.67	145.63
11590	6.67	37.80	54.45	191.63
13620	8.33	40.56	57.22	226.91
16276	11.1	43.33	60.00	271.32

Table 7.2 Flow vs. approach for a given tower

(Tower is 21.65m × 36.9M; Three 7.32M Fans; Three 25kW Motors; 16.7^0C Range with 26.7^0C Wet Bulb)

To meet the increased heat load, a 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 a 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 and 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 five 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 m^3/hr cooling tower selected for a 16.67^{0}C range and a 4.45^{0}C approach to 21.11^{0}C wet bulb would be larger than a 4540m^3/hr tower selected for a 16.67^{0}C range and a 4.45^{0}C approach to a 26.67^{0}C wet bulb. Air at the higher wet bulb temperature is capable of picking up more heat. Assume that the wet bulb he air temperature of the air is increased by approximately 11.1^{0}C. As air removes heat from the water in the tower, each kg of air entering the tower at 21.1^{0}C wet bulb would contain 18.86 kCals and if it were to leave the tower at 32.2^{0}C wet bulb, it would contain 24.17 kCal per kg of air.

In the second case, if each kg of air entering the tower at 26.67^{0}C wet bulb would contain 24.17 kCals and were to leave at 37.8^{0}C wet bulb, it would contain 39.67kCal per kg of air. In going from 21.10C to 32.2^{0}C, 12.1kCal per kg of air is picked up, while 15.5kCal/kg of air is picked up in going from 26.67^{0}C to 37.8^{0}C.

Fill Media Effects

In a cooling tower, hot water is distributed above the fill media which flows down and is cooled due to evaporation with the intermixing air. Air draft is achieved with the 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 the appropriate water distribution, drift eliminator, fan, gearbox and motor. Power savings in a cooling tower, with the 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 the surface area of the heat exchange, time of heat exchange (interaction) and turbulence in water effecting thoroughness of intermixing. Fill media in a cooling tower is responsible to achieving all of above.

Splash and Film Fill Media

As the name indicates, splash fill media generates the required heat exchange area by the splashing action of water over the fill media and hence breaking into smaller water droplets. Thus, the 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 fill sheets. Thus the area of heat exchange is the surface area of the fill sheets, which is in contact with air. Due to the fewer requirements of the 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 highly turbid waters. For sea water, low clog film fills are considered the best choice in terms of power savings and performance as compared to conventional splash type fills.

7.3 A Typical Comparison 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 -45m^2/m^3	150m^2/m^3	85 -100m^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

Table 7.3 Typical comparisons between various fill media

7.4 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 comparisons of Cross flow Splash Fill, Counter Flow Tower with Film Fill and Splash fill are shown in Table 7.4. The power consumption is least in Counter Flow Film Fill followed by Counter Flow Splash Fill and Cross-Flow Splash Fill.

	Counter Flow Film Fill	Counter Flow Splash Fill	Cross-Flow Splash Fill
Fill Height, Metre	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, Metre	7.2	10.9	12.05

Table 7.4 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^{0}C
Cold Water Temperature: 32.5^{0}C
Design Wet Bulb Temperature: 27.6^{0}C

7.5 Efficient System Operation

7.5.1 Cooling Water Treatment

Cooling water treatment is mandatory for any cooling tower whether with splash fill or with film type fill for controlling suspended solids, algae growth etc. With increasing costs of water, efforts to increase Cycles of Concentration (COC), by Cooling Water Treatment would help to reduce make up water requirements significantly. In large industries, power plants, COC improvement is often considered as a key area for water conservation.

7.5.2 Drift Loss in the Cooling Towers

It is very difficult to ignore the drift problem in cooling towers. Now-a-days most of the end user specifications call for 0.02% drift loss.With technological development and the processing of PVC, manufacturers have brought about a big change in the drift eliminator shapes and the possibility of making efficient designs of drift eliminators that enable the end user to specify the drift loss requirement to as low as 0.003–0.001%.

7.5.3 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 the air power developed/ work done by the fan; this may be also termed as the fan output and input kW which depends on fan efficiency.
Fan efficiency in turn is greatly dependent on the profile of the blade. An aerodynamic profile with the optimum twist, taper and higher coefficient of lift to coefficient of drop ratio can provide the fan a total efficiency as high as 85–92 %. However, this efficiency is drastically affected by factors such as tip clearance, obstacles to airflow and inlet shape, etc.

As the metallic fans are manufactured by adopting either the extrusion or the casting process, it is always difficult to generate the ideal aerodynamic profiles. The FRP blades are normally hand moulded, which facilitates the generation of the optimum aerodynamic profile to meet specific duty conditions more efficiently. Cases reported where the 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 a simple pay back period of 6–7 months.Also, due to their light weight, FRP fans need low starting torque resulting in the use of lower HP motors. The light weight of the fans also increases the life of the gear box, motor and bearings and allows for easy handling and maintenance.

7.5.4 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 pyschrometer.
- Exhaust air WBT and DBT at each cell using a whirling psychrometer.
- CW inlet temperature at the risers or the top of the 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 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 are given below:

- Observations
  - Unit Loan 1 and 3 of the Station = 398 MW
  - Mains Frequency = 49.3
  - Inlet Cooling Water Temperature ^{0}C = 44 (Rated 43^{0}C)
  - Outlet Cooling Water Temperature = 37.6 (Rated 33^{0}C)
  - Air Wet Bulb Temperature near Cell ^{0}C = 29.3 (Rated 27.5^{0}C)
  - Air Dry Bulb Temperature men Cell ^{0}C = 40.8^{0}C

- Number of CT Cells on line with water flow = 45 (Total 48)
- Total Measured Cooling Water Flow m3/hr = 70426.75
- Measured CT Fan Flow m3/hr = 989544

- Analysis
  - CT water Flow/Cell, m3/hr = 1565 m^3/hr (1565000 kg/hr) (Rated 1875 m^3/hr)
  - CT Fan air Flow, m3/hr (Avg.) = 989544 m^3/hr (Rated 997200 m^3/hr)
  - CT Fan air Flow kg/hr (Avg.) @ Density of 1.08kg/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 $= \frac{\text{Range}}{(\text{Range} + \text{Approach})} \times 100$

    $= \frac{6.4}{(6.4+8.3)} \times 100$

    = 43.53

  - Rated % CT Effectiveness = 100 × (43 – 33) / (43 – 27.5)

    = 64.5%

Cooling Duty Handled/Cell in kCal =1565×6.4×103
(i.e. Flow*Temperature Difference in kCal/hr)=10016×103kCal/hr(Rated 18750×103kCal/hr)

- Evaporation Losses in m3/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
  = 24.33

- 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 36.2kW average. Replacement by efficient hollow FRP fan blades is recommended

7.6 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, 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 switched on and others switched 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 minimise fan energy while achieving the desired control of the Cold water temperature.

7.7 Energy Saving Opportunities in Cooling Towers

- Follow the manufacturer's recommended clearances around cooling towers and relocate or modify structures that interfere with the air intake or exhaust.
- Optimise 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 minimise algae growth that contribute to fouling.
- Optimise 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 10C cooling water temperature increase may increase A/C compressor kW by 2.7%. A 10C drop in cooling water temperature can give a heat rate saving 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 the water load during summer and times when the approach is high and the increase air flow during monsoon times and when the approach is narrow.
- Monitor approach, effectiveness and cooling capacity for continuous optimisation 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 the case of small units.
- Optimise process CW flow requirements, to save on pumping energy, cooling load, evaporation losses (directly proportional to circulation rate) and blow down losses.

Some typical problems and their trouble shooting for cooling towers are given in Table 7.5.

Problem/ Difficulty	Possible Causes	Remedies/ Rectifying Action
Excessive absorbed current/electrical load	1. Voltage Reduction	Check the voltage
	2a. Incorrect angle of axial fan blades	Adjust the blade angle
	2b. Loose belts on centrifugal fans (or speed reducers)	Check belt tightness
	3. Overloading owing to excessive air flow-fill has minimum water loading per m^2 of tower section	Regulate the water flow by means of the value
	4. Low ambient air temperature	The motor is cooled proportionately and hence delivers more than name plate power
Drift/ carry-over of water outside the unit	1. Uneven operation of spray nozzles	Adjust the nozzle orientation and eliminate any dirt
	2. Blockage of the fill pack	Eliminate any dirt at the top of the fill
	3. Defective or displaced droplet eliminators	Replace or realign the eliminators
	4. Excessive circulating water flow (possibly owing to too high pumping head)	Adjust the water flow-rate by means of the regulating valves. Check for absence of damage of the fill.
Loss of water from basins/pans	1. Float-valve not at correct level	Adjust the make-up valve
	2. Lack of equalising connections	Equalise the basins of towers operating in parallel
Lack of cooling and hence increase in temperatures owing to increased temperature range	1. Water flow below the design valve	Regulate the flow by means of the valves
	2. Irregular airflow or lack of air	Check the direction of rotation of the fans and/or belt tension (broken belt possible)
	3a. Recycling of humid discharge air	Check the air descent velocity
	3b. Intake of hot air from other sources	Install deflectors
	4a. Blocked spray nozzles (or even blocked spray tubes)	Clean the nozzles and/or the tubes
	4b. Scaling of joints	Wash or replace the item

Table 7.5 Typical problems and trouble shooting for cooling towers problem

Summary

- Cooling tower is a heat exchanger where heat from hot water is dissipated to the ambient and the cold water is sent back to process. The performance of the cooling tower is the ratio of the range to approach.
- The different types of cooling towers are natural draft and forced 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 m /hr. These types of towers are used only by utility power stations
- Mechanical draft towers utilise large fans to force or suck air through circulated water. The water falls downward over fill surfaces, which helps increase the contact time between the water and the air - this helps maximise heat transfer between the two
- The basic components of an evaporative tower are: Frame and casing, fill, cold water basin, drift eliminators, air inlet, louvers, nozzles and fans.
- 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.
- Range is the difference of temperature between inlet and outlet water. Approach is the difference of temperature between the outlet water temperature and the wet bulb temperature. Hence as the outlet water temperature approaches towards the wet bulb temperature, the effectiveness of the cooling tower approaches 100%.
- 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
- Energy saving opportunities exists based on fan blade material, material used for construction, piping, etc.

References

- Frayne, C., 1999. *Cooling water treatment: Principles and practice*, Chemical Pub. Co publication.
- Kroger, D., 2004. *Air-cooled Heat Exchangers And Cooling Towers: Thermal-flower Performance Evaluation and Design*, Volume 2. Pennwell Books Publication.
- *Cooling Tower* [Pdf] Available at: < www.beeindia.in/energy_managers_auditors/documents/.../3Ch7.pdf> [Accessed 5 July 2013].
- *Cooling Tower Fundamentals- SPX Cooling Technologies* [Pdf] Available at: < spxcooling.com/pdf/Cooling-Tower-Fundamentals.pdf> [Accessed 5 July 2013].
- 2012. *What are Cooling Towers?* [Video online] Available at: <https://www.youtube.com/watch?v=KbxHk7go7UU> [Accessed 5 July 2013].
- 2012. *How a Cooling Tower Works?* [Video online] Available at: < https://www.youtube.com/watch?v=z9-cVGrR9OE> [Accessed 5 July 2013].

Recommended Reading

- Gurney, J. D. & Cotter, I. A., 1966. Cooling towers, McMillan & sons.
- Stanford, H. W., 2003. HVAC *Water Chillers and Cooling Towers: Fundamentals, Application, and Operation* (Dekker Mechanical Engineering),1st ed., CRC Press publication.
- McCoy, J. W., 1983. *The Chemical Treatment of Cooling Water*, 2nd ed., Chemical Publishing Company Publication

Self Assessment

1. Natural draft cooling towers are mainly used in _______.
    a. steel industry
    b. alumina industry
    c. fertilizer industry
    d. power stations

2. Better indicator for cooling tower performance is ____.
    a. Wet bulb temperature
    b. Dry bulb temperature
    c. Range
    d. Approach

3. Cooling tower effectiveness is the ratio of__________.
    a. Range/(range + approach)
    b. Approach/(range + approach)
    c. Range/Approach
    d. Approach/Range

4. Cooling tower reduces circulation water temperature close to ________.
    a. dry bulb temperature
    b. ambient wet bulb temperature (WBT)
    c. dew point temperature
    d. wet bulb temperature

5. The ratio of dissolved solids in circulating water to the dissolved solids in make up water is termed as ____.
    a. liquid gas ratio
    b. cycles of concentration
    c. cooling tower effectiveness
    d. dry bulb temperature

6. Which one of the following has maximum effect on cooling tower performance?
    a. Fill media
    b. Drift
    c. Louvers
    d. Casing

7. Use of very large concrete chimneys to introduce air through the media is seen in __________.
    a. Warming draft towers
    b. Mechanical draft towers
    c. Cooling draft towers
    d. Natural draft towers

8. In the ____________________ draft design, hot water enters at the top, while air is introduced at the bottom and exits at the top.
   a. counter flow forced draft
   b. cross flow induced draft
   c. counter flow induced draft
   d. cross flow forced draft

9. Recirculation raises the effective wet bulb temperature of the air entering the tower with corresponding increase in the ____________.
   a. hot water temperature
   b. warm water temperature
   c. medium water temperature
   d. cold water temperature

10. __________ is a direct function of the quantity of water circulated and the heat load
    a. Range
    b. Flow
    c. Heat load
    d. Approach

Chapter VIII

Lighting System

Aim

The aim of this chapter is:

- explain lighting systems
- elucidate the types of lamp and light source
- explicate the choice of lighting

Objectives

The objectives of the chapter are:

- explain the basic terms in lighting system
- enlist lamp types and their features
- describe energy conservation avenues

Learning outcome

At the end of this chapter, you will be able to:

- identify light distribution
- define the types of lamp and light source
- understand the choice of lighting and luminance requirements

8.1 Introduction

Lighting is an essential service in all the industries. Power consumption by industrial lighting varies between 2–10% of the total power depending on the type of industry. Innovation and continuous improvement in the field of lighting, has given rise to tremendous energy saving opportunities in this area. Lighting is an area which provides a major scope to achieve energy efficiency at the design stage, by the incorporation of modern energy efficient lamps, luminaries and gears, apart from good operational practices.

8.2 Basic Terms in Lighting Systems and Features

- Lamps

The lamp is an equipment, which produces light. The most commonly used lamps are described briefly as follows:

- Incandescent Lamps

Incandescent lamps produce light by means of a filament heated to incandescence by the flow of electric current through it. The principal parts of an incandescent lamp, also known as GLS (General Lighting Service) lamp include the filament, the bulb, the fill gas and the cap.

- Reflector Lamps

Reflector lamps are basically incandescent and are provided with a high quality internal mirror which exactly follows the parabolic shape of the lamp. The reflector is resistant to corrosion, thus making the lamp maintenance free and output efficient.

- Gas Discharge Lamps

The light from a gas discharge lamp is produced by the excitation of gas contained in either a tubular or elliptical outer bulb.

The most commonly used discharge lamps are as follows:

- fluorescent tube lamps (FTL)
- compact fluorescent lamps (CFL)
- mercury vapour lamps
- sodium vapour lamps
- metal halide lamps

- Luminaire

The luminaire is a device that distributes filters or transforms the light emitted from one or more lamps. Luminaires include 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 luminaires are reflection, absorption, transmission and refraction.

- Control Gear

The gears used in lighting equipment are as stated:

  - Ballast

A current limiting device, to counter the negative resistance characteristics of any discharge lamp. In case of fluorescent lamps, it aids the initial voltage build up, required for starting.

  - Ignitors

These are used for starting high intensity Metal Halide and Sodium vapour lamps.

  - Illuminance

This 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 in the interior and is commonly called the working plane.

The illuminance provided by an installation affects both the performance of tasks and the appearance of space.

- Lux (lx)

This is the illuminance produced by a luminous flux of one lumen, uniformly distributed over a surface area of one square metre. One lux is equal to one lumen per square metre.

- Luminous Efficacy (lm/W)

This is the ratio of luminous flux emitted by a lamp to the power consumed by the lamp. It is a reflection of the efficiency of energy conversion from electricity to light.

- Colour Rendering Index (RI)

It is a measure of the degree to which the colours of surfaces illuminated by a given light source conform to those of the same surfaces under a reference illuminent; suitable allowance having been made for the state of Chromatic adaptation.

8.3 Lamp Types and their Features

Table 8.1 shows the various types of lamps available along with their features.

Type of Lamp	Lumens/ Watt		Colour Rendering Index	Typical Application	Typical Life (hours)
	Range	Avg.			
Incandescent	8–18	14	Excellent	Homes, restaurants, general lighting, emergency lighting	1000
Fluorescent Lamps	46–60	50	Good w.r.t coating	Offices, shops, hospitals, homes	5000
Compact fluorescent lamps (CFL)	40–70	60	Very good	Hotels, shops, homes offices	8000–10000
High pressure mercury (HPMV)	44–57	50	Fair	General lighting in factories garages, car parking, flood lighting	5000
Halogen lamps	18–24	20	Excellent	Display, flood lighting, stadium exhibition grounds, construction areas	2000–4000
High pressure sodium (HPSV) Son	67–121	90	Fair	General lighting in factories, warehouses, street lighting	6000–12000
Low pressure sodium (LPSV) SOX	101–175	150	Poor	Roadways, tunnels canals, street lighting	6000–12000
Incandescent	8–18	14	Excellent	Homes, restaurants, general lighting, emergency lighting	1000

Table 8.1 Luminous performance characteristics of commonly used luminaries

8.4 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 the subjective effect of illuminance Therefore, the following scale of illuminance 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 illuminance 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 illuminance. 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 in exceptional cases where low reflectances 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, a 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 details give the recommended illuminance range for different tasks and activities for the chemical sector. The values are related to the visual requirements of the task, to the user's satisfaction, to practical experience and to the need for the cost effective use of energy (Source IS 3646 (Part I): 1992).
For the recommended illumination in other sectors, you may refer to the Illuminating Engineers Society Recommendations Handbook.

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

Table 8.2 Recommended illuminance range for different tasks and activities for the chemical sector

8.5 Methodology of Lighting System Energy Efficiency Study

A step-by-step approach for assessing the energy efficiency of the lighting system is as stated:

Step-1:

Inventorise the Lighting System elements and transformers in the facility as per the following typical format (Table 8.3 and 8.4).

S. No.	Plant Location	Lighting Device & Ballast Type	Rating in Watts Lamp & Ballast	Population Numbers	No. of hours/Day

Table 8.3 Device rating, population and use profile

S.No	Plant Location	Lighting Transformer Rating (kVA)	Numbers Installed	Meter Provisions Available Volts /Amps/kW/Energy

Table 8.4 Lighting transformer/rating and population profile

In case of distribution boards (instead of transformers) being available, fuse ratings may be inventorised along the above pattern in place of transformer kVA.

Step-2:

With the aid of a lux meter, measure and document the lux levels at various plant locations at the working level, as day time lux and night time lux values alongside the number of lamps “ON” during measurement.

Step-3:

With the aid of a portable load analyser, measure and document the voltage, current, power factor and power consumption at various input points, namely the distribution boards or the lighting voltage transformers at the same as that of the lighting level audit.

Step-4:

Compare the measured lux values with standard values as reference and identify locations as under lit and over lit areas.

Step-5:
Collect and analyse the failure rates of lamps, ballasts and the actual life expectancy levels from past data.

Step-6:
Based on careful assessment and evaluation bring out improvement options which could include:

- Maximise sunlight use through use of transparent roof sheets, north light roof, etc.
- Examine the scope for replacements of lamps by more energy efficient lamps, with due consideration to luminiare, colour rendering index, lux level as well as expected life comparison.
    - Replace conventional magnetic ballasts by more energy efficient ballasts, with due consideration to the life and power factor apart from watt loss.
    - Select interior colours for light reflection.
    - Modify layout for optimum lighting.
    - Provide individual / group controls for lighting for energy efficiency such as:
    - On / off type, voltage regulation type (for illuminance control)
    - Group control switches / units
    - Occupancy sensors
    - Photocell controls
    - Timer operated controls
    - Pager operated controls
    - Computerised lighting control programmes
    - Install input voltage regulators / controllers for energy efficiency as well as longer life expectancy for lamps where higher voltages, fluctuations are expected.
    - Replace energy efficient displays like LED's in place of lamp type displays in control panels / instrumentation areas, etc.

8.6 Case Examples

8.6.1 Energy Efficient Replacement Options

Lamp efficacy is the ratio of light output in lumens to the power input to lamps in watts. Over the years, developments in lamp technology have led to improvements in the efficacy of lamps. However, the low efficacy lamps, such as incandescent bulbs, still constitute a major share of the lighting load. High efficacy gas discharge lamps suitable for different types of applications offer an appreciable scope for energy conservation. Typical energy efficient replacement options, along with the percent energy saving, are given in Table-8.5

Sector	Lamp type		Power saving	
	Existing	Proposed	Watts	%
Domestic/Commercial	GLS 100 W	*CFL 25 W		
Industry	GLS 13 W	*CFL 9 W		
	GLS 200 W	Blended 160 W		
	TL 40 W	TLD 36 W		
	HPMV 250 W	HPSV 150 W		
	HPMV 400 W	HPSV 250 W		

Table 8.5 Savings by use of high efficacy lamps
(* Wattages of CFL includes energy consumption in ballasts.)

Energy Saving Potential in Street Lighting

The energy saving potential, in typical cases of replacement of inefficient lamps with efficient lamps in street lighting is given in Table 8.6

Existing lamp Replaced units Saving

Existing lamp			Replaced units			Saving	
Type	W	Life hrs.	Type	W	Life	W	%
GLS	GLS	TL	HPMV	HPMV	HPMV	200	300
2×40	125	250	400	1000	1000	5000	5000
5000	5000	ML	ML	TL	HPSV	HPSV	HPSV
160	250	2×36	70	150	250	5000	5000
5000	12000	12000	12000	40	50	8	25
100	150	7	17	6	44	40	38

Table 8.6 Saving potential by use of high efficacy lamps for street lighting

8.7 Some Good Practices in Lighting

- Installation of energy efficient fluorescent lamps in place of “Conventional” fluorescent lamps.
- Energy efficient lamps are based on the highly sophisticated tri-phosphor fluorescent powder technology.
- They offer excellent colour rendering properties in addition to the very high luminous efficacy.

8.7.1 Installation of Compact Fluorescent Lamps (CFL's) in Place of Incandescent Lamps

Compact fluorescent lamps are generally considered best for the replacement of lower wattage incandescent lamps. These lamps have an efficacy ranging from 55–65 lumens/Watt. The average rated lamp life is 10,000 hours, which is 10 times longer than that of a normal incandescent lamp. CFLs are highly suitable for places such as Living rooms, Hotel lounges, Bars, Restaurants, Pathways, Building entrances, Corridors, etc.

8.7.2 Installation of Metal Halide Lamps in Place of Mercury/Sodium Vapour Lamps

Metal halide lamps provide a high colour-rendering index when compared with mercury and sodium vapour lamps. These lamps offer an efficient white light. Hence, metal halide is the choice for colour critical applications where higher illumination levels are required. These lamps are highly suitable for applications such as assembly line, inspection areas, painting shops, etc. Metal halide lamps are recommended where the colour rendering is more critical.

8.7.3 Installation of High Pressure Sodium Vapour (HPSV) Lamps for Applications where Colour Rendering is not Critical

High-pressure sodium vapour (HPSV) lamps offer more efficacy. But the colour rendering property of HPSV is very low. Hence, they are recommended for applications such street lighting, yard lighting, etc.

8.7.4 Installation of LED Panel Indicator Lamps in Place of Filament Lamps

- Panel indicator lamps are used widely in industries for monitoring, fault indication, signalling, etc. Conventionally, filament lamps are used for these purposes, but have the disadvantages as stated:
- High energy consumption (15 W/lamp)
- Failure of lamps is high (Operating life less than 10,000 hours)
- Very sensitive to voltage fluctuations. Recently, the conventional filament lamps are being replaced with Light Emitting Diodes (LEDs)

LEDs have the following merits over filament lamps.

- Lesser power consumption (Less than 1 W/lamp)
- Withstand high voltage fluctuations in the power supply
- Longer operating life (more than 1,00,000 hours)
- LEDs are recommended to be installed for panel indicator lamps at the design stage.

8.7.5 Light Distribution

Energy efficiency cannot be obtained by the mere selection of more efficient lamps alone. Efficient luminaires along with lamps of high efficacy achieve the optimum efficiency. Mirror-optic luminaires with a high output ratio and bat-wing light distribution can save energy. For achieving better efficiency, luminaires that have light distribution characteristics appropriate for the task interior should be selected.

It should be ensured that luminaires fitted with a lamp should minimise discomfort glare and that veiling reflections are minimised. The installation of suitable luminaires depends upon height - Low, Medium and High Bay. Luminaires for high intensity, discharge lamps are classified as follows:

- Low bay, for heights less than 5 metres.
- Medium bay, for heights between 5–7 metres.
- High bay, for heights greater than 7 metres.

The system layout and fixing of the luminaires play a major role in achieving energy efficiency. This also varies from application to application. Hence, fixing the luminaires at the optimum height and the usage of mirror optic luminaires leads to energy efficiency.

8.7.6 Light Control

The simplest and the most widely used form of controlling a lighting installation is the "On-Off" switch. The initial investment for this set up is extremely low, but the resulting operational costs may be high. This does not provide the flexibility for the control of the lighting, where it is not required.

Hence, a flexible lighting system has to be provided, which will offer switch-off or reduction in the lighting level,

when not needed. The following light control systems can be adopted at the design stage:

- Grouping of the lighting system, to provide greater flexibility in lighting control.
- Grouping of the lighting system, which can be controlled manually or by timer control.
- Installation of microprocessor based controllers
- Another modern method is the usage of microprocessor/infrared controlled dimming or switching circuits. Lighting control can be obtained by using logic units located in the ceiling, which can take pre-programme commands and activate specified lighting circuits. The advanced lighting control system uses movement detectors or lighting sensors, to feed signals to the controllers.

Optimum usage of day lighting

- Whenever the orientation of a building permits, daylight can be used in combination with electric lighting. This should not introduce a glare or a severe imbalance of brightness in the visual environment. Usage of day lighting (in offices/air conditioned halls) will have to be very limited, because the air conditioning load will increase on account of the increased solar heat dissipation into the area. In many cases, a switching method, to enable reduction of electric light in the window zones during certain hours, has to be designed.
    - Installation of an "exclusive" transformer for lighting
    - In most of the industries, the lighting load varies between 2 to 10%. Most of the problems faced by the lighting equipment and the "gear" are due to the "voltage" fluctuations. Hence, the lighting equipment has to be isolated from the power feeders. This provides a better voltage regulation for the lighting. This will reduce the voltage related problems, which in turn increases the efficiency of the lighting system.
    - Installation of the servo stabiliser for a lighting feeder

Wherever, the installation of an exclusive transformer for lighting is not economically attractive, the servo stabiliser can be installed for the lighting feeders. This will provide a stabilised voltage for the lighting equipment. The performance of "gear" such as chokes, ballasts, will also improve due to the stabilised voltage.

This set up also provides the option to optimise the voltage level fed to the lighting feeder. In many plants, during the non-peaking hours, voltage levels are on the higher side. During this period, voltage can be optimised without any significant drop in the illumination level.

- Installation of high frequency (HF) electronic ballasts in place of conventional ballasts

New high frequency (28-32 kHz) electronic ballasts have the following advantages over the traditional magnetic ballasts:

- energy savings up to 35%.
- less heat dissipation, which reduces the air conditioning load
- lights instantly.
- improved power factor.
- operates on low voltage load.
- lighter in weight.
- increases the life of the lamp.

The advantage of HF electronic ballasts outweighs the initial investment (higher costs when compared with conventional ballast). In the past the failure rate of the electronic ballast in Indian Industries was high. Recently, many manufacturers have improved the design of the ballast leading to drastic improvements in their reliability. The life of the electronic ballast is high especially when used in a lighting circuit fitted with an automatic voltage stabiliser. Table 8.7 gives the type of luminaire, gear and controls used in the different areas of industry.

Location	Source	Luminaire	Gear	Controls
Plant	HID/FTL	Industrial rail reflector : High bay Medium bay Low bay	Conventional/ low loss electronic ballast	Manual/electronic
Office	FTL/CFL	FTL/CFL	Electronic/low loss	Manual/auto
Yard	HID	Flood light	Suitable	Manual
Road peripheral	HID/PL	Street light luminaire	Suitable	Manual

Table 8.7 Types of luminaire with their gear and controls used in different industrial locations

Summary

- Power consumption by industrial lighting varies between 2–10% of the total power depending on the type of industry. Innovation and continuous improvement in the field of lighting, has given rise to tremendous energy saving opportunities in this area.
- The various terms used in Illumination Engineering include incandescent lamps, reflector lamps, gas discharge lamps, luminaire, control gear, ballast, igniters, illuminance, lux, luminous efficacy, colour rendering index.
- 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 the subjective effect of illuminance
- Incandescent lamps, fluorescent lamps, Compact Fluorescent Lamps, High Pressure Mercury Vapour Lamps, Halogen Lamps, High Pressure Sodium Vapour Lamps, and Low Pressure Sodium Vapour Lamps are the different types of luminaries.
- A step by step approach can be obtained to assess the performance of the Illumination System. The methodology includes the measurement of lux levels and comparing these with the standards. Apart from this there are many steps involved.
- The biggest energy saving opportunity in Illumination Engineering is the replacement of conventional copper wound chokes with electronic ballasts. The other opportunities include designing buildings to give the maximum sunlight during the day time.

References

- Chen, K.,1999. *Energy Management in Illuminating Systems*,1st ed., CRC Press Publication.
- Levermore, G., 2000. *Building Energy Management Systems: An Application to Heating, Natural Ventilation, Lighting and Occupant Satisfaction*, 2nd ed., Spon Press Publication.
- *Lighting System* [Pdf] Available at: <www.beeindia.in/energy_managers_auditors/documents/.../3Ch8.pdf> [Accessed 5 July 2013].
- *Lighting Systems Made Easy* [Pdf] Available at: <www.leprecon.com/catalogs/280075BLightingMadeEasy.pdf> [Accessed 5 July 2013].
- 2013. *Smart LED Lighting System* [Video online] Available at: <https://www.youtube.com/watch?v=YHBaVmpcdso> [Accessed 5 July 2013].
- 2010. *LED Mobile Lighting System* [Video online] Available at: <https://www.youtube.com/watch?v=3CiOw04ZNT8> [Accessed 5 July 2013].

Recommended Reading

- Patterson, E. G., 2001. Lighting Systems: Advanced Course, Thomson Learning.
- Beggs, C., 2009. *Energy: Management, Supply and Conservation*, 2nd ed., Butterworth-Heinemann publication.
- Lindsey, J. L., 1997. *Applied illumination engineering*, 2nd ed., The Fairmont Press, Inc.Publication.

Self Assessment

1. Which of the following light source has least life?
   a. Sodium vapour
   b. Mercury Vapour
   c. Halogen
   d. Incandescent

2. Colour rendering index of incandescent lamp is:
   a. Fair when compared to HPSV lamp
   b. Poor when compared to LPSV lamp
   c. Same when compared to HPMV lamp
   d. Excellent when compared to fluorescent lamp

3. One lux is equal to ___.
   a. One lumen per meter
   b. One lumen per m3
   c. One lumen per m2
   d. One lumen

4. Colour rendering index of Halogen lamps compared to low pressure sodium vapour lamps is ___.
   a. Poor
   b. Excellent
   c. Average
   d. Very poor

5. The colour rendering property of HPSV is very ___________
   a. high
   b. medium
   c. low
   d. dull

6. Which of the following is the best definition of illuminance?
   a. Time rate of flow of light energy
   b. Luminous flux incident on an object per unit area
   c. Flux density emitted from an object without regard for direction
   d. Flux density emitted from an object in a given direction

7. The ratio of luminous flux emitted by a lamp to the power consumed by the lamp is ___.
   a. Illuminance
   b. Lux
   c. Luminous Efficacy
   d. CRI

8. Ignitors are used for starting____.
   a. FTL
   b. CFL
   c. Sodium vapour lamps
   d. HTL

9. A device that distributes and filters the light emitted from one or more lamps is ___.
   a. Control gear
   b. Lamp
   c. Luminaire
   d. Starter

10. GLS stands for_____.
    a. General Lamp source
    b. General Lamp Service
    c. General Lighting Service
    d. General Lighting Source

Chapter IX

DG Set Systems

Aim

The aim of this chapter is to:

- explain the diesel generating system
- enlist factors affecting selection
- explicate motor efficiency

Objectives

The objectives of the chapter are to:

- explain the four stroke diesel engine
- explicate the DG set as a system
- elucidate energy performance assessment of diesel conservation avenues

Learning outcome

At the end of this chapter, you will be able to:

- define diesel generator captive power plants
- identify selection and installation factors
- understand the concept of motor efficiency

9.1 Introduction

The Diesel engine is a 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 of 700– 9000C. 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 the compression ignition (CI) engine.

Diesel generating (DG) sets can be classified according to cycle types as:

- two stroke
- 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.

9.1.1 The Four Stroke Diesel Engine

The 4 stroke operations in a diesel engine 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 upto 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 opens and the rising piston discharges the spent gases from the cylinder.

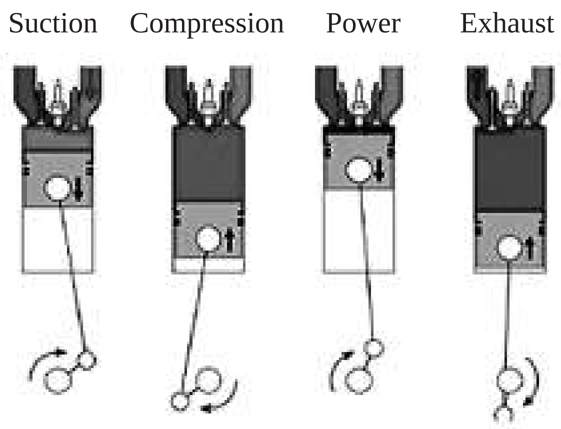

Fig. 9.1 Schematic diagram of a four stroke diesel engine

Since power is developed only during 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 configurations, for example, 4 or 6 cylinders, in-line, horizontally opposed, vee or radial configurations.

9.1.2 The DG Set as a System

A diesel generating set should be considered as a system since its successful operation depends on the well-matched performance of the components, namely:

- the diesel engine and its accessories.
- the ac generator.
- the control systems and switchgear.
- the foundation and power house civil works.
- the connected load with its own components like heating, motor drives, lighting, etc.

It is necessary to select components with the highest efficiency and operate them at their optimum efficiency levels to conserve energy in this system.

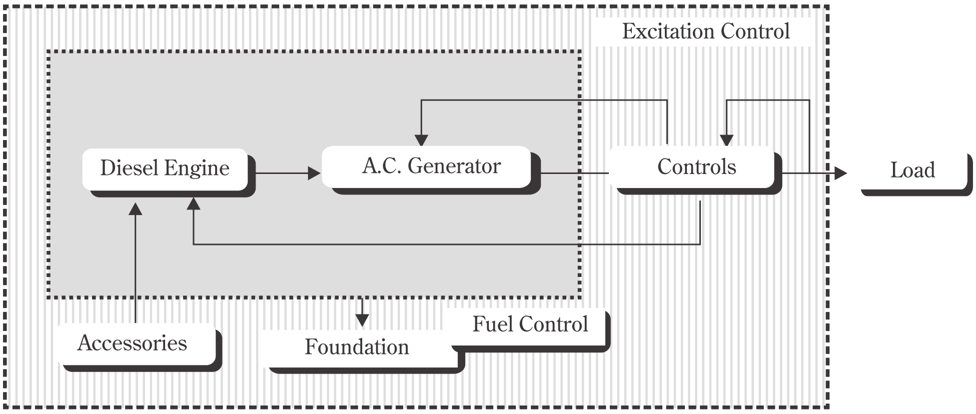

Fig. 9.2 Diesel generator system

9.1.3 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 for the end use. This prevents overloading the machine by absorbing the extra load during the starting of the motors or switching on 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 the fuel efficiency will be the 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 the 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.
- The 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 to 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 ranges 4–15 MW. For continuous operation, the low speed diesel engine is more cost-effective than the high speed diesel engine.

The advantages of adopting Diesel Power Plants are:

- low installation cost,
- short delivery and installation periods,
- higher efficiency (as high as 43 -45 %),
- more efficient plant performance under part loads,
- suitable for different types of fuels such as low sulphur heavy stock and heavy fuel oil in case of large capacities.

Minimum cooling water requirements.
Adapted with the air cooled heat exchanger in areas where water is not available,
Short start up time.

A brief comparison of the different types of captive power plants (combined gas turbine and steam turbine, conventional steam plant and diesel engine power plant) is given in Table 9.1. It can be seen from the table that the captive diesel plant wins over the other two in terms of thermal efficiency, capital cost, space requirements, auxiliary power consumption, plant load factor, etc.

Description	Units GT & ST	Combined Steam Plant	Conventional Power Plants	Diesel Engine
Thermal Efficiency	%	40–46	33–36	43–45
Initial Investment of Installed Capacity	Rs. / 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

Table 9.1 Comparison of different types of captive power plants

9.1.4 Diesel Engine Power Plant Developments

- Diesel engine developments have been steady and impressive. Specific fuel consumption has come down from a value of 220 g/kWh in the 1970s to a value of around 160 g/kWh in the present times.
- The 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 to further increase the engine rated output. The net result lower fuel consumption per kWh and further increase in overall thermal efficiency.

- The diesel engine is able to burn the poorest quality fuel oils, unlike the 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 give the same thermal efficiency and power output as a regular fuel oil engine.

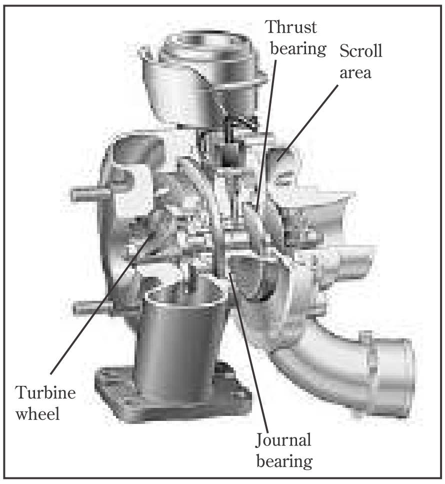

Fig. 9.3 Turbocharger

9.2 Selection and Installation Factors

9.2.1 Sizing of a Genset

- 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:
Connected Load = 650kW
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

- For an existing installation, record the current, voltage and power factor (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 conduct its normal operations. Non-essential loads should be switched off to find the realistic current taken for running essential equipment. This will give a fair idea of current taken from which the rating of the set can be calculated.

For an existing installation:
kVA = v3V I
kVA Rating = kVA / Load Factor where Load factor = Average kVA / Maximum kVA

- 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 the DG set. Then, applying a diversity factor depending on the industry, process involved and guidelines obtained from other similar units, the correct capacity can be arrived at.

9.2.2 High Speed Engine or Slow/Medium Speed Engine

The normal accepted definition of the 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. Other features and comparisons between high and medium / slow speed engines are mentioned below:

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
Type of use	Continuous use	Intermittent use
Period between overhauls*	8000 hours	3200
Direct operating cost (includes lubricating oils, filters, etc.	Less	High

* Typical recommendations from manufacturers

Keeping the above factors and available capacities of the DG sets in mind, the economic cost for both the engines should be worked out before arriving at a decision.

9.2.3 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 when 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.

9.2.4 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 the summer months. This is to some extent true and precautions have to be taken to ensure that the cooling water temperature does not exceed the prescribed limits.
- However, from the 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 the summer months.

9.2.5 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, installing circuit protection is strongly recommended.
- 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.

9.2.6 Parallel Operation with Grid

- Running the DG set in parallel with the mains from the supply undertakings can be done in consultation with the 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.

9.2.7 Maximum Single Load on a 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 the 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 the auto transformer starter, and with this starting, the HP of the largest motor can be upto 75 % of the kVA of the Genset.

9.2.8 Unbalanced Load Effects

It is always recommended that the load be much balanced as much as possible, since unbalanced loads can 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.

9.2.9 Neutral Earthing

Electricity rules clearly specify that two independent earths to the body and a neutral should be provided to give adequate protection to the equipment in case of an earth fault, and also to drain away any leakage potential from the equipment to the earth for safe working.

9.2.10 Site Condition Effects on Performance Derating

Site conditions with respect to altitude, intake temperature and cooling water temperature derate diesel engine output as shown in the following Tables: 9.2 and 9.3.

Correction Factors For Engine Output				
Altitude Correction			Temperature Correction	
Altitude Meters over MSL	**Non Super Charged**	**Super Charged**	**Intake oC**	**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 – 9.2 Altitude and intake temperature corrections

9.3 Operational Factors

9.3.1 Load Pattern and 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 DG set.
- Overloads, which appear insignificant and harmless on electricity board supply, may become detrimental to a DG set, and hence overload on the DG set should be carefully analysed. Diesel engines are designed for 10% overload for 1 hour in every 12 hours of operation. A.C. generators are designed to meet 50% overload for 15 seconds as specified by standards.
- The DG 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 sets to ensure good performance. Alongside alternator loading, 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 to give high efficiency.
- Engine manufacturers offer curves indicating % Engine Loading vs. fuel Consumption in grams/BHP. Optimal engine loading corresponding to the best operating point is desirable for energy efficiency.
- Alternators are sized for kVA ratings with the highest efficiency attainable at a loading of around 70% and more. Manufacturers’ curves can be referred to for the best efficiency point and corresponding kW and kVA loading values.

9.3.2 Sequencing of Loads

- The captive diesel generating set has certain limits in handling 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 the transient load brings down the transient load handling capability, and in case of A.C. generators, it increases the transient voltage dip.
- Hence, great care is required in sequencing the load on DG set/s. It is advisable to start the load with the highest transient kVA first, followed by other loads in the descending order of the starting kVA. This will lead to optimum sizing and better utilisation of the transient load handling capacity of the DG set.

Water Temperature 0C	Flow %	Derating %
25	100	0
30	125	3
35	166	5
40	166	8

Table.9.3 Derating due to air inter cooler water inlet temperature

9.3.3 Load Pattern

- In many cases, the load will not be constant throughout the day. If there is a substantial variation, 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 the load increases. A typical case may be an establishment demanding substantially different powers in the first, second and third shifts.
- By parallel operation, D.G. sets can be run at optimum operating points near optimum, 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 the critical load in the captive power system.

9.3.4 Load Characteristics

- Some of the load characteristics influence the efficient use of a D.G.set. These characteristics are entirely load dependent and cannot be controlled by the D.G.set. The extent of detrimental influences of these characteristics can be reduced in several cases.
    - Power Factor

The load power factor is entirely dependent on the load. The A.C. generator is designed for a power factor of 0.8 lag as specified by standards. A lower power factor demands higher excitation currents and results in increased losses. Over sizing A.C.generators for operations 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 the A.C. generator lead to an unbalanced set of voltages and additional heating in the A.C. generator. When other connected loads like motor loads are fed with an unbalanced set of voltages, additional losses occur in the motors as well. Hence, the load on the A.C. generators should be balanced as far as possible. Where single-phase loads are predominant, consideration should be given to procuring a single phase A.C. generator.

Transient Loading
On many occasions, to contain the transient voltage dip arising due to the transient load application, a specially designed generator may have to be selected. Many times non-standard combination of the engine and the A.C. generator may have to be procured. Such a combination ensures that the prime mover is not unnecessarily over sized who add to capital cost and running cost.

Special Loads
Special loads like the rectifier/thyristor loads, welding loads, furnace loads need an application check. The manufacturer of the diesel engine and AC generator should be consulted for proper recommendations so that the desired utilisation of the 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 a DG motor driven generator set. Such an alternative ensures that special design of the AC generator is restricted to that portion of the load which requires high purity rather than increasing the price of the DG set by a specially designed AC generator for complete load.

Waste Heat Recovery in DG Sets

A typical energy balance in a DG set indicates the following break-up:

Input :	100%	Thermal Energy
Outputs :	35%	Electrical Output
	4%	Alternator Losses
	33%	Stack Loss through Flue Gases
	24%	Coolant Losses
	4%	Radiation Losses

Among these, stack losses through fine gases or the exhaust flue gas losses on account of existing flue gas temperature of 3500C to 550C, constitute the major area of concern towards operational economy. It would be realistic to assess the Waster Heat Recovery (WHR) potential in relation to quantity, temperature margin, in kcals/ hour as:

Potential WHR=(kWh Output/Hour) x (8 kg Gases/kWh Output)x 0.25 kcal/kg0C×(tg -1800C)

Where tg is the gas temperature after Turbocharger, (the criteria being that limiting exit gas temperature cannot be less than 1800C, 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 800kW loading, and with 4800C exhaust gas temperature, the waste heat potential works out to:

800kWh x 8 kg gas generation / kWh output x 0.25 kCal/kg0C X (480 - 180),

i.e., 4, 80,000 kCal/hr

While the above method only yields the potential for heat recovery, the actual realisable 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:

- DG Set loading, temperature of exhaust gases

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 the DG set results in erratic flue gas quantity and temperature profile at entry to the heat recovery unit, thereby leading to possible cold end corrosion and other problems.

- Hours of operation

The number of hours of operation of the DG set has an influence on the thermal performance of the waste heat recovery unit. With continuous DG Set operations, cost benefits are favourable

- Back pressure on the DG set

Back pressure in the gas path caused by an additional pressure drop in the 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. The choice of convective waste heat recovery systems with adequate heat transfer areas are known to provide reliable service

100% Load	11.84 kgs/Sec	3700C
90% Load	10.80 kgs/Sec	3500C
70% Load	9.08 kgs/Sec	3300C
60% Load	7.50 kgs/Sec	3250C
If the normal load is 60%, the flue gas parameters for waste heat recovery unit would be 320oC inlet temperature, 180oC outlet temperature and 27180kgs/Hour gas flow. At 90% loading, however, values would be 355oC and 32,400 kgs/Hour, respectively		

Table 9.4 Typical flue gas temperature and flow pattern in a 5-mw dg set at various loads

The configuration of the 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 the Indian Industry. Waste heat recovery and one interesting configuration deployed is the installation of the waste heat boiler in the flue gas path along with a vapour absorption chiller, to produce 80C chilled water working on steam from waste heat.

Favourable incentives offered by the Government of India for energy efficient equipment and technologies (100% depreciation at the end of first year), make the waste heat recovery option viable. The payback period is only about 2 years

9.4 Energy Performance Assessment of DG Sets

- Routine energy efficiency assessment of DG sets on the shop floor involves the following typical steps:
- Ensure reliability of all instruments used for trial.
- Collect technical literature, characteristics, and specifications of the plant.
- Conduct a 2 hour trial on the DG set, ensuring a steady load, wherein the following measurements are logged at 15 minute intervals.
  - Fuel consumption (by dip level or by flow meter)
  - Amps, volts, PF, kW, kWh
  - Intake air temperature, Relative Humidity (RH)
  - Intake cooling water temperature
  - Cylinder-wise exhaust temperature (as an indication of engine loading)
  - Turbocharger RPM (as an indication of loading on engine)
  - Charge air pressure (as an indication of engine loading)
  - Cooling water temperature before and after the charge air cooler (as an indication of cooler performance)
  - Stack gas temperature before and after turbocharger (as an indication of turbocharger performance).
- The fuel oil/diesel analysis is referred to from an oil company data.
- Analysis: The trial data is to be analysed with respect to:
  - Average alternator loading.
  - Average engine loading.
  - Percentage loading on the alternator.
  - Percentage loading on the engine.
  - Specific power generation kWh/litre.
  - Comments on the turbocharger performance based on the RPM and gas temperature difference.
  - Comments on charge air cooler performance.
  - Comments on load distribution among various cylinders (based on exhaust temperature, the temperature to be ± 5% of mean and high/low values indicate disturbed condition).
  - Comments on housekeeping issues like drip leakages, insulation, vibrations, etc.

A format as shown in Table 9.5 is useful for monitoring performance

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

Table 9.5 Typical format for DG set monitoring

9.5 Energy Saving Measures for DG Sets

- Ensure steady load conditions on the DG set, and provide cold, dust free air at the intake (use of air washers for large sets, in case of dry, hot weather, can be considered).
- Improve air filtration.
- Ensure fuel oil storage, handling and preparation as per manufacturers' guidelines/oil company data.
- Consider fuel oil additives in case they benefit fuel oil properties for DG set usage.
- Calibrate fuel injection pumps frequently.
- Ensure compliance with the maintenance checklist.
- Ensure steady load conditions, avoiding fluctuations, imbalance in phases, harmonic loads.
- In case of a base load operation, consider the waste heat recovery system adoption for the steam generation or refrigeration chiller unit incorporation. Even the Jacket Cooling Water is amenable for heat recovery, vapour absorption system adoption.
- In terms of fuel cost economy, consider the partial use of biomass gas for generation. Ensure tar removal from the gas for improving availability of the engine in the long run.
- Consider parallel operation among the DG sets for improved loading and fuel economy thereof.
- Carry out regular field trials to monitor DG set performance, and maintenance planning as per requirements.

Summary

- The CI engine works in two modes such as two stroke and four stroke. In two stroke engines there is lot of wastage of fuel since exhaust and fuel inlets are open simultaneously for a small duration. Four stroke engines are more economical in large sizes and cause less pollution.
- The 4 stroke operations in a diesel engine are: induction stroke, compression stroke, ignition and power stroke and exhaust stroke
- A DG set is selected on the basis of the connected load, load factor, largest single motor to be started, and many more considerations.
- 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 to 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.
- Diesel engine developments have been steady and impressive. Specific fuel consumption has come down from a value of 220 g/kWh in the 1970s to a value of around 160 g/kWh in the present times.
- The normal accepted definition of the high-speed engine is 1500 rpm.
- 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 when only the short-fall in power depending upon the extent of power cut prevailing - needs to filled up.
- Parts of the exhaust gases are used to drive a small turbocharger pump which helps in pushing and atomising the fuel. Hence it helps in improving efficiency in the DG set.
- DG set performance is assessed in the ratio of energy produced in kWH per litre of diesel (Fuel) consumed.
- Heat recovery from exhaust gases gives one of the best opportunities in energy savings
- Energy Saving Measures for DG Sets include to ensure steady load conditions on the DG set, and provide cold, dust free air at the intake (use of air washers for large sets, in case of dry, hot weather, can be considered). Improve air filtration. Also to ensure fuel oil storage, handling and preparation as per manufacturers' guidelines/ oil company data.

References

- Mahon, L. L. J., 1992. *Diesel Generator Handbook*, Newnes publication.
- Brady, R. N. & Dagel. J. F., *Diesel Engine and Fuel System Repair,* 5th ed., Prentice Hall Publication.
- *DG Set System* [Pdf] Available at: < www.beeindia.in/energy_managers_auditors/documents/.../3Ch9.pdf> [Accessed 5 July 2013].
- *Assembly of Diesel Generator Set* [Pdf] Available at: < www.dcmsme.gov.in/publications/pmryprof/electrical/ch2.pdf> [Accessed 5 July 2013].
- 2008. *Diesel Engines: Fuel System Design* [Video online] Available at: < https://www.youtube.com/watch?v=Gh_mvWESGHw> [Accessed 5 July 2013].
- 2012. *Diesel Electric Set-Non Functional Mock up* [Video online] Available at: < https://www.youtube.com/watch?v=NwTKhe9iztE> [Accessed 5 July 2013].

Recommended Reading

- Abdulqadar, M., 2006. *Diesel Generator Auxillary Systems and Instruments*, Lulu.com Publication.
- Kaltschmitt, M., Streicher, W. & Wiese, A., 2009. *Renewable energy: technology, economics, and environment*. Springer publication.
- Wharton, J., 2006. *Diesel Engines*, Butterworth-Heinemann.

Self Assessment

1. Two stroke and four stroke are classifications of ________.
    a. DG set
    b. CI set
    c. DM set
    d. CF set

2. The 4 stroke operations in a diesel engine are: induction stroke, compression stroke, ignition , power stroke and __________.
    a. drain stroke
    b. refresh stroke
    c. exhaust stroke
    d. master stroke

3. The engine power rating should be _____more than the power demand for the end use.
    a. 20–30 %
    b. 10–20 %
    c. 50–40 %
    d. 30–40 %

4. Efficiency on adopting Diesel Power Plants is ____________.
    a. 15–10%
    b. 50–60%
    c. 24–42%
    d. 43–45%

5. Which of the following statements is true?
    a. A water-cooled DG set is not advisable than an air cooled set
    b. An air cooled DG set is better than a water- cooled set
    c. A water-cooled DG set is better than an air cooled set
    d. An air cooled DG set is not advisable than a water cooled set

6. DG set performance is assessed in the ratio of ____________.
    a. energy produced in kWH per litre of diesel (Fuel) consumed.
    b. energy produced in kV per litre of diesel (Fuel) consumed.
    c. energy produced in kWA per litre of diesel (Fuel) consumed.
    d. energy produced in WH per litre of diesel (Fuel) consumed.

7. ________from exhaust gases gives one of the best opportunities in energy savings.
    a. Warmth recovery
    b. Heat recovery
    c. Water recovery
    d. Air recovery

8. In two stroke engines there is lot of wastage of fuel since _________.
    a. exhaust and fuel inlets are closed
    b. exhaust and fuel inlets are not present
    c. exhaust and fuel inlets are blocked
    d. exhaust and fuel inlets are open

9. _________ in the gas path caused by an additional pressure drop in the waste heat recovery unit is another key factor.
    a. Back pressure
    b. Front pressure
    c. Upward pressure
    d. Downward pressure

10. The number of hours of operation of the DG set has an influence on the ______ performance of the waste heat recovery unit.
    a. hydro
    b. tidal
    c. wind
    d. thermal

Chapter X

Energy Efficient Technologies in Electrical Systems

Aim

The aim of this chapter is to:

- elucidate maximum demand controllers
- explicate soft starters with energy savers and variable speed drives
- explain energy efficient transformers

Objectives

The objectives of the chapter are to:

- explain energy efficient technologies in electrical systems
- define electronic ballast and occupancy sensors
- explicate energy saving potential of each technology

Learning outcome

At the end of this chapter, you will be able to:

- identify factors affecting energy efficient transformers
- understand the concept of energy efficient lighting controls
- define energy efficient motors

10.1 Maximum Demand Controllers

- High-tension (HT) consumers have to pay a maximum demand charge in addition to the usual charge for the number of units consumed. This charge is usually based on the highest amount of power used during some period (say 30 minutes) during the metering month.
- The maximum demand charge often represents a large proportion of the total bill and may be based on only one isolated 30 minute episode of high power use. Considerable savings can be realised by monitoring power use and turning off or reducing non-essential loads during such periods of high power use.
- Maximum Demand Controller (See Fig.10.1) is a device designed to meet the need of industries conscious of the value of load management. An alarm is sounded when demand approaches a preset value. If corrective action is not taken, the controller switches off non-essential loads in a logical sequence.
- This sequence is predetermined by the user and is programmed jointly by the user and the supplier of the device. The plant equipments selected for load management are stopped and restarted as per the desired load profile. The demand control scheme is implemented by using suitable control contactors. Audio and visual annunciations could also be used.

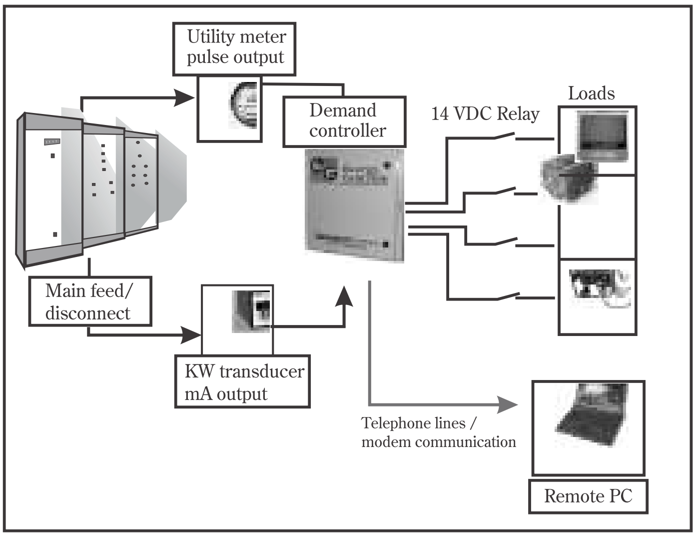

Fig. 10.1 Maximum demand controller

10.2 Automatic Power Factor Controllers

Various types of automatic power factor controls are available with relay / microprocessor logic. Two of the most common controls are: Voltage Control and kVAr Control

10.2.1 Voltage Control

- Voltage alone can be used as a source of intelligence when the switched capacitors are applied at a point where the circuit voltage decreases as circuit load increases. Generally, where they are applied, the voltage should decrease as the circuit load increases and the drop in voltage should be around 4 - 5 % with increasing load.
- Voltage is the most common type of intelligence used in substation applications when maintaining a particular voltage is of prime importance. This type of control is independent of the load cycle. During light load time and low source voltage, this may give a leading PF at the substation, which is to be taken note of.

10.2.2 Kilovar Control

- Kilovar sensitive controls (see Fig. 10.2) are used at locations where the voltage level is closely regulated and not available as a control variable. The capacitors can be switched to respond to a decreasing power factor as a result of the change in system loading.

- This type of control can also be used to avoid a penalty on the low power factor by adding capacitors in steps as the system power factor begins to lag behind the desired value. Kilovar control requires two inputs - current and voltage from the incoming feeder, which are fed to the PF correction mechanism, either the microprocessor or the relay.

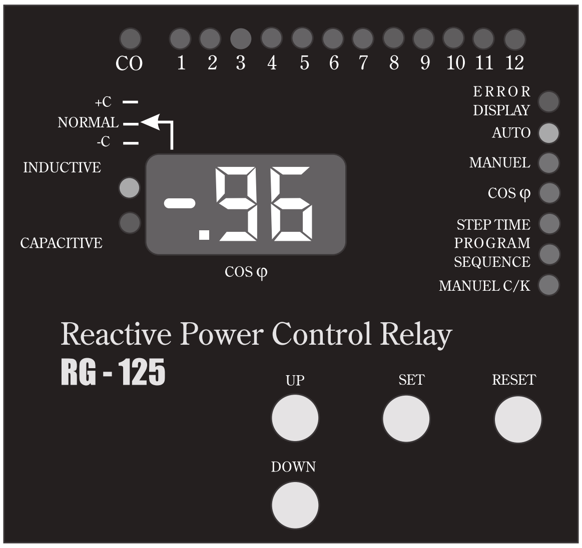

Fig.10.2 Reactive power control relay

10.2.3 Automatic Power Factor Control Relay

- It controls the power factor of the installation by giving signals to switch on or off power factor correction capacitors. Relay is the brain of the control circuit and needs contactors of the appropriate rating for switching on/off the capacitors on/off.
- There is a built-in power factor transducer, which measures the power factor of the installation and converts it to a DC voltage of appropriate polarity. This is compared with a reference voltage, which can be set by means of a knob calibrated in terms of the power factor.
- When the power factor falls below the setting, the capacitors are switched on in sequence. The relays are provided with the First in First out (FIFO) and First in Last Out (FILO) sequences.
- The capacitors controlled by the relay must be of the same rating and they are switched on/off in linear sequence. To prevent over correction hunting, a dead band is provided. This setting determines the range of phase angle over which the relay does not respond; the relay acts only when the PF goes beyond this range.
- When the load is low, the effect of the capacitors is more pronounced and may lead to hunting. Under current blocking (low current cut out) shuts off the relay, switching off all capacitors one by one in a sequence, when the load current is below setting.
- Special timing sequences ensure that the capacitors are fully discharged before they are switched in. This avoids a dangerous over voltage transient. The solid state indicating lamps (LEDS) display various functions that the operator should know and also indicate each capacitor switching stage.

10.2.4 Intelligent Power Factor Controller (IPFC)

This controller determines the rating of the capacitance connected at each step during the first hour of its operation and stores them in memory. Based on this measurement, the IPFC switches on the most appropriate steps, thus eliminating the hunting problems normally associated with capacitor switching.

10.3 Energy Efficient Motors

Minimising Watt Loss in Motors

Improvements in motor efficiency can be achieved without compromising motor performance - at a higher cost - within the limits of existing design and manufacturing technology.

Fig. 10.3 Energy efficient motors

- From Table 10.1, it can be seen that any improvement in motor efficiency must result from reducing the Watt losses. In terms of the existing state of electric motor technology, a reduction in watt losses can be achieved in various ways.

Watts 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 I2R	Use of more copper and larger conductors increases cross sectional area of stator windings. This lowers resistance (R) of the windingsand reduces losses due to current flow (I).
3. Rotor I2R	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. Stray Load Loss	Use of optimised design and strict quality control procedures minimizes stray load losses.

Table 10.1 Watt loss area and efficiency improvement

- All of these changes to reduce motor losses are possible with the existing motor design and manufacturing technology. They would, however, require additional materials and/or the use of higher quality materials and improved manufacturing processes resulting in increased motor cost.

Simply Stated: REDUCED LOSSES = IMPROVED EFFICIENCY

- Thus energy-efficient electric motors reduce energy losses through an improved design, better material, and improved manufacturing techniques. Replacing a motor may be justifiable solely on the electricity cost savings derived from an energy-efficient replacement.
- This is true if the motor runs continuously, as power rates are high, the motor is oversized for the application, or its nominal efficiency has been reduced by damage or previous rewinds. Efficiency comparison for standard and high efficiency motors is shown in Figure 10.4.

STANDARD vs HIGH EFFICIENCY MOTORS
(Typical 3-Phase induction Motor)

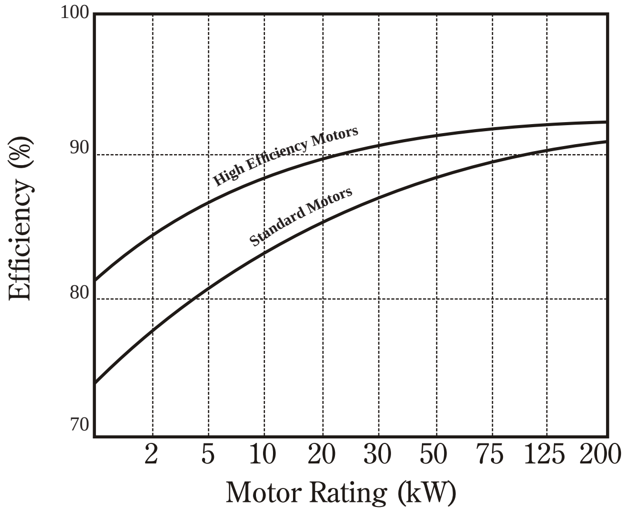

Fig. 10.4 Efficiency range for standard and high efficiency motors

10.3.1 The Technical Aspects of Energy Efficient Motors

- Energy-efficient motors last longer, and may require less maintenance. At lower temperatures, bearing grease lasts longer; the required time between re-greasing increases. Lower temperatures translate to long lasting insulation. Generally, motor life doubles for each 100 C reduction in operating temperature.
- Select energy-efficient motors with a 1.15 service factor, and design for operation at 85% of the rated motor load.
- Electrical power problems, especially poor incoming power quality can affect the operation of energy-efficient motors.
- Speed control is crucial in some applications. In polyphase induction motors, slip is a measure of motor winding losses. The lower the slip, the higher the efficiency. Less slippage in energy efficient motors results in speeds about 1% faster than in standard counterparts.
- Starting torque for efficient motors may be lower than for standard motors. Facility managers should be careful when applying efficient motors to high torque applications.

10.4 Soft Starter

- When starting, an AC Induction motor develops more torque than is required at full speed. This stress is transferred to the mechanical transmission system resulting in excessive wear and the premature failure of chains, belts, gears, mechanical seals, etc.
- Additionally, rapid acceleration also has a massive impact on electricity supply charges with high in-rush currents drawing +600% of the normal run current.
- The use of Star Delta only provides a partial solution to the problem. Should the motor slow down during the transition period, the high peaks can be repeated and can even exceed the direct online current.
- The soft starter (see figure 10.5) provides a reliable and economical solution to these problems by delivering a controlled release of power to the motor, thereby providing smooth, stepless acceleration and deceleration. The motor life will be extended as the damage to windings and bearings is reduced.

Fig. 10.5 Soft Starter

- Soft Start and Soft Stop are built into 3 phase units, providing controlled starting and stopping with a selection of ramp times and current limit settings to suit all applications (see Figure 10.6).

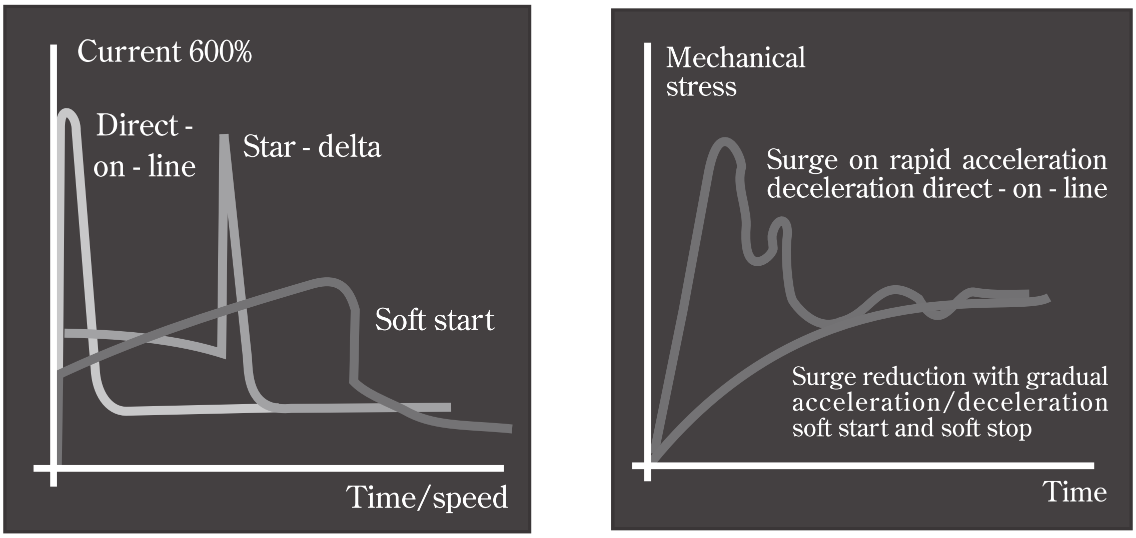

Fig. 10.6 Soft Starter: Starting current, Stress profile during starting

- Advantages of Soft Start
  - Less mechanical stress
  - Improved power factor
  - Lower maximum demand
  - Less mechanical maintenance

10.5 Variable Speed Drives

10.5.1 Speed Control of Induction Motors

- The induction motor is the workhorse of the industry. It is cheap rugged and provides high power to weight ratio. On account of high cost-implications and limitations of the D.C. System, induction motors are preferred for variable speed applications, the speed of which can be varied by changing the supply frequency.
- The speed can also be varied through a number of other means, including, varying the input voltage, varying the resistance of the rotor circuit, using multi- speed windings, using Scherbius or Kramer drives, using mechanical means such as gears and pulleys and eddy-current or fluid coupling, or by using rotary or static voltage and frequency converters.

10.5.2 The Variable Frequency Drive

- The VFD operates on a simple principle. The rotational speed of an AC induction motor depends on the number of poles in that stator and the frequency of the applied AC power. Although the number of poles in an induction motor cannot be altered easily, variable speed can be achieved through a variation in the frequency.
- The VFD rectifies the standard 50 cycle AC line power to DC, then synthesises the DC to a variable frequency AC output. Motors connected to VFD provide variable speed mechanical output with high efficiency. These devices are capable of up to a 9:1 speed reduction ratio (11 percent of full speed), and a 3:1 speed increase (300 percent of full speed).
- In recent years, the technology of AC variable frequency drives (VFD) has evolved into highly sophisticated digital microprocessor control, along with high switching frequency IGBTs (Insulated Gate Bi Polar Transistors) power devices.
- This has led to significantly advanced capabilities from the ease of programmability to expanded diagnostics. The two most significant benefits from the evolution in technology have been those of cost and reliability, in addition to the significant reduction in physical size.

10.5.3 Variable Torque Vs. Constant Torque

- Variable speed drives, and the loads that are applied to, can generally be divided into two groups: constant torque and variable torque. The energy savings potential of variable torque applications is much greater than that of constant torque applications.
- Constant torque loads include vibrating conveyors, punch presses, rock crushers, machine tools, and other applications where the drive follows a constant V/Hz ratio.
- Variable torque loads include centrifugal pumps and fans, which make up the majority of HVAC applications.

10.5.4 Why Variable Torque Loads Offer Greatest Energy Savings

- In variable torque applications, the torque required varies with the square of the speed, and the horsepower required varies with the cube of the speed, resulting in a large reduction of horsepower for even a small reduction in speed.
- The motor will consume only 12.5% as much energy at 50% speed than it will at 100% speed. This is referred to as the Affinity Laws, which define the relationships between speed, flow, torque, and horsepower. The following laws illustrate these relationships:
    - Flow is proportional to speed
    - Head is proportional to (speed)2
    - Torque is proportional to (speed)2
    - Power is proportional to (speed)3

10.5.5 Tighter Process Control with Variable Speed Drives

- No other AC motor control method compares to variable speed drives when it comes to accurate process control. Full-voltage (across the line) starters can only run the motor at full speed, and soft starts and reduced voltage soft starters can only gradually ramp the motor up to full speed, and back down to shutdown. Variable speed drives, on the other hand, can be programmed to run the motor at a precise speed, to stop at a precise position, or to apply a specific amount of torque.
- In fact, modern AC variable speed drives are very close to the DC drive in terms of fast torque response and speed accuracy. However, AC motors are much more reliable and affordable than DC motors, making them far more prevalent.
- Most drives used in the field utilise the Volts/Hertz type control, which means they provide open-loop operation. These drives are unable to retrieve feedback from the process, but are sufficient for the majority of variable speed drive applications.

- Many open-loop variable speed drives do offer slip compensation though, which enables the drive to measure its output current and estimate the difference in actual speed and the set point (the programmed input value). The drive then automatically adjusts itself towards the set point based on this estimation.
- Most variable torque drives have Proportional Integral Differential (PID) capability for fan and pump applications, which allow the drive to hold the set point based on actual feedback from the process, rather than relying on estimation.
- A transducer or transmitter is used to detect process variables such as pressure levels, liquid flow rate, air flow rate, or liquid level. Then the signal is sent to a PLC (Programmable Logic Controller), which communicates the feedback from the process to the drive. The variable speed drive uses this continual feedback to adjust itself to hold the set point.
- High levels of accuracy for other applications can also be achieved through drives that offer the closed-loop operation. Closed-loop operation can be accomplished with either a field-oriented vector drive, or a sensorless vector drive.
- The field-oriented vector drive obtains process feedback from an encoder, which measures and transmits to drive the speed and/or rate of the process, such as a conveyor, machine tool, or extruder. The drive then adjusts itself accordingly to sustain the programmed speed, rate, torque, and/or position.

10.5.6 Extended Equipment Life and Reduced Maintenance

- Single-speed starting methods start motors abruptly, subjecting the motor to a high starting torque and to current surges that are up to 10 times the full-load current. Variable speed drives, on the other hand, gradually ramp the motor up to the operating speed to lessen mechanical and electrical stress, reducing maintenance and repair costs, and extending the life of the motor and the driven equipment.
- Soft starts, or reduced-voltage soft starters (RVSS), are also able to step a motor up gradually, but drives can be programmed to ramp up the motor much more gradually and smoothly, and can operate the motor at less than full speed to decrease wear and tear.
- Variable speed drives can also run a motor in specialised patterns to further minimise mechanical and electrical stress. For example, a S-curve pattern can be applied to a conveyor application for smoother control, which reduces the backlash that can occur when a conveyor is accelerating or decelerating.
- Typical full-load efficiencies are 95% and higher. High power units are still more efficient. The efficiency of VSDs generally decreases with speed but since the torque requirement also decreases with speed for many VSD applications, the absolute loss is often not very significant.
- The power factor of a VSD drops drastically with speed, but at low power requirement the absolute kVAr requirement is low, so the loss is also generally not significant. In a suitable operating environment, frequency controllers are relatively reliable and need little maintenance.
- A disadvantage of static converters is the generation of harmonics in the supply, which reduces motor efficiency and reduces motor output. In some cases it may necessitate using a motor with a higher rating.

10.5.7 Eddy Current Drives

- This method employs an eddy-current clutch to vary the output speed. The clutch consists of a primary member coupled to the shaft of the motor and a freely revolving secondary member coupled to the load shaft.
- The secondary member is separately excited using a DC field winding. The motor starts with the load at rest and a DC excitation is provided to the secondary member, which induces eddy-currents in the primary member. The interaction of the fluxes produced by the two currents gives rise to a torque at the load shaft.
- By varying the DC excitation, the output speed can be varied to match the load requirements. The major disadvantage of this system is relatively poor efficiency particularly at low speeds. (See Figure 10.7).

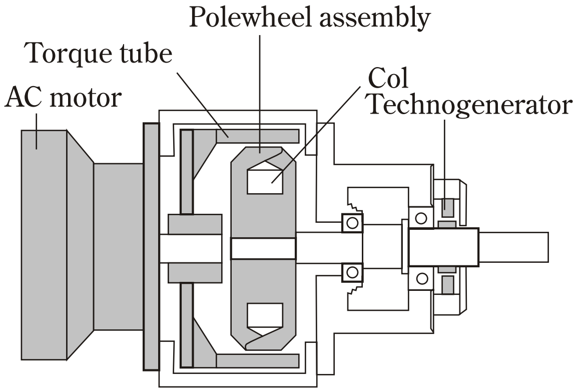

Fig. 10.7 Eddy current drive

10.5.8 Slip Power Recovery Systems

Slip power recovery is a more efficient alternative speed control mechanism for use with slip-ring motors. In essence, a slip power recovery system varies the rotor voltage to control speed, but instead of dissipating power through resistors, the excess power is collected from the slip rings and returned as mechanical power to the shaft or as electrical power back to the supply line. Because of the relatively sophisticated equipment needed, slip power recovery tends to be economical only in relatively high power applications and where the motor speed range is 1:5 or less.

10.5.9 Fluid Coupling

Fluid coupling is one way of applying varying speeds to the driven equipment, without changing the speed of the motor.

10.5.10 Construction

- Fluid couplings (see figure 10.8) work on the hydrodynamic principle. Inside every fluid coupling are two basic elements the impeller and the runner and together they constitute the working circuit. One can imagine the impeller as a centrifugal pump and the runner as a turbine.
- The impeller and the rotor are bowl shaped and have a large number of radial vanes. They are suitably enclosed in a casing, facing each other with an air gap. The impeller is connected to the prime mover while the rotor has a shaft bolted to it. This shaft is further connected to the driven equipment through a suitable arrangement.
- Thin mineral oil of low viscosity and good-lubricating qualities is filled in the fluid coupling from the filling plug provided on its body. A fusible plug is provided on the fluid coupling which blows off and drains out oil from the coupling in case of sustained overloading.

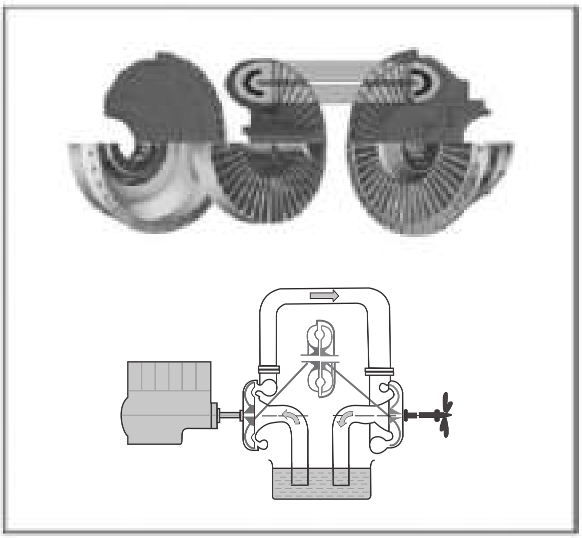

Fig. 10.8 Fluid coupling

10.5.11 Operating Principle

- There is no mechanical inter-connection between the impeller and the rotor and power is transmitted by the virtue of the fluid filled in the coupling. When the impeller is rotated by the prime mover, the fluid flows out radially and then axially under the action of the centrifugal force.
- It then crosses the air gap to the runner and is directed towards the bowl axis and back to the impeller. To enable the fluid to flow from the impeller to the rotor, it is essential that there is a difference in head between the two and thus it is essential that there is a difference in RPM known as slip between the two.
- Slip is an important and inherent characteristic of a fluid coupling resulting in several desired advantages. As the slip increases, more and more fluid can be transferred.
- However when the rotor is at a standstill, the maximum fluid is transmitted from the impeller to the rotor and the maximum torque is transmitted from the coupling. This maximum torque is the limiting torque. The fluid coupling also acts as a torque limiter.

10.5.12 Characteristics

- Fluid coupling has a centrifugal characteristic during starting, thus enabling a no-load start up of the prime mover, which is of great importance. The slipping characteristic of the fluid coupling provides a wide range of choice of power transmission characteristics.
- By varying the quantity of oil filled in the fluid coupling, the normal torque transmitting capacity can be varied. The maximum torque or limiting torque of the fluid coupling can also be set to a pre-determined safe value by adjusting the oil filling. The fluid coupling has the same characteristics in both directions of rotation.

10.6 Energy Efficient Transformers

- Most energy loss in the dry-type transformers occurs through heat or vibration from the core. The new high-efficiency transformers minimise 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. However the latest technology is to use amorphous material a metallic glass alloy for the core (see Figure 10.9).
- The expected reduction in energy loss over conventional (Si Fe core) transformers is roughly around 70%, which is quite significant. By using an amorphous core with unique physical and magnetic properties, these new types of transformers have increased efficiencies even at low loads - 98.5% efficiency at 35% load.
- Electrical distribution transformers made with amorphous metal cores provide excellent opportunity to conserve energy right from the installation. Though these transformers are a little costlier than conventional iron core transformers, the overall benefit towards energy savings compensate for the higher initial investment. At present amorphous metal core transformers are available up to 1600 kVA.

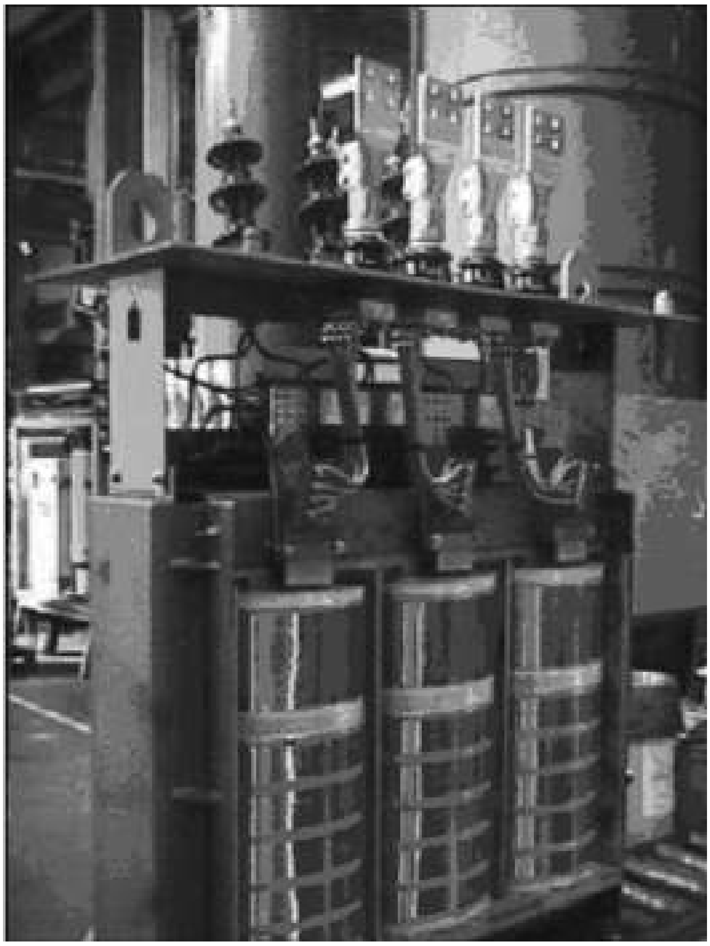

Fig. 10.9 1600 kVA amorphous core transformer

10.7 Electronic Ballast

Various information regarding the elctronic ballast is as follows:

10.7.1 Role of Ballast

- In an electric circuit, the ballast acts as a stabiliser. The fluorescent lamp is an electric discharge lamp. The two electrodes are 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. Current flow takes place through an atmosphere of low-pressure mercury vapour.
- 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 auxillary circuit housed in a casing is known as the ballast.

10.7.2 Conventional vs. Electronic Ballasts

- Conventional ballasts make use of the kick caused by a sudden physical disruption of the current in an inductive circuit to produce the high voltage required for starting the lamp and then rely on a reactive voltage drop in the ballast to reduce the voltage applied across the lamp.
- On account of the mechanical switch (starter) and low resistance of the filament when cold, the uncontrolled filament current generally tends to go beyond the limits specified by Indian standard specifications. With high values of current and flux densities, the operational losses and temperature rise are on the higher side in the conventional choke.

- The high frequency electronic ballast overcomes the above drawbacks. The basic functions of electronic ballast are:
  - To ignite the lamp
  - To stabilise the gas discharge
  - To supply power to the lamp
- The electronic ballasts (see fig. 10.10) make use of modern power semiconductor devices for their operation. The circuit components form a tuned circuit to deliver power to the lamp at a high resonant frequency (in the vicinity of 25 kHz) and voltage is regulated through an in-built feedback mechanism. It is now well established that the fluorescent lamp efficiency in the kHz range is higher than those attainable at low frequencies.
- At lower frequencies (50 or 60 Hz), the electron density in the lamp is proportional to the instantaneous value of the current because the ionisation state in the tube is able to follow the instantaneous variations in the current. At higher frequencies (kHz range), the ionisation state cannot follow the instantaneous variations of the current and hence the ionisation density is approximately constant, proportional to the RMS (Root Mean Square) value of the current. Another significant benefit resulting from this phenomenon is the absence of the stroboscopic effect, thereby significantly improving the quality of light output.
- One of the biggest advantages of electronic ballast is the enormous energy savings it provides. This is achieved in two ways.
- The first is its amazingly low internal core loss, quite unlike old fashioned magnetic ballasts.
  - The second is increased light output due to the excitation of the lamp phosphors with high frequency.
- If the period of frequency of excitation is smaller than the light retention time constant for the gas in the lamp, the gas will stay ionised and, therefore, produce light continuously. This phenomenon along with the continued persistence of the phosphors at high frequency will improve the light output from 8-12 percent. This is possible only with the high frequency electronic ballast.

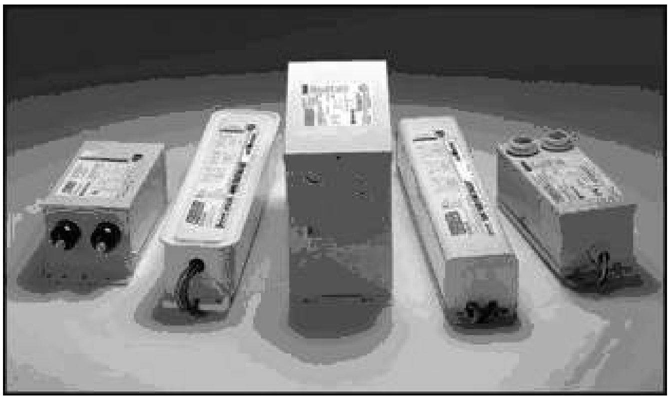

Fig. 10.10 Electronic ballasts

10.8 Energy Efficient Lighting Controls

10.8.1 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 movements are 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 a 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.

10.8.2 Timed Based Control

Timed-turn off 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 (see fig. 10.11).

Fig. 10.11 Timed-turn off switch

Types and Features

- The oldest and most common type of timed-turn off 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-turn off 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 preset 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-turn off switches are available with a wide range of time spans. The choice of the 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.

10.8.3 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

10.8.4 Localised Switching

Localised 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 localised 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.

Summary

- The new technologies available for improving energy efficiency are the maximum demand controller, automatic power factor controller, energy efficient motors, occupancy sensors etc.
- Automatic Power Factor connects and disconnects the part of the capacitor bank depending on the variation of the power factor. If required, the power factor is set at 0.99. Whenever the power factor tends to go below this, it will connect additional capacitors. Alternatively, whenever the power factor tends to go above this, it will disconnect some of the capacitors so that the power factor remains around the set value.
- Occupancy sensors are used to sense the presence and absence of human beings in a room and based on this, electrical appliances in the room such as AC, lights, etc. can be switched On or Off respectively. Broadly, four types of sensors are used. They are infra-red, acoustic, ultra-sonic and microwave type.
- Automatic demand controllers are microprocessor based instruments which can track the average power consumption and predict the maximum demand that is likely to occur. Based on the setting of the demand they can cut in or cut out the non-priority load.
- The soft starter provides a reliable and economical solution to these problems by delivering a controlled release of power to the motor, thereby providing smooth, stepless acceleration and deceleration. The motor life will be extended as the damage to windings and bearings is reduced.
- The VFD operates on a simple principle. The rotational speed of an AC induction motor depends on the number of poles in that stator and the frequency of the applied AC power. Although the number of poles in an induction motor cannot be altered easily, variable speed can be achieved through a variation in the frequency.
- Variable speed drives, and the loads that are applied to, can generally be divided into two groups: constant torque and variable torque. The energy savings potential of variable torque applications is much greater than that of constant torque applications.
- Slip power recovery is a more efficient alternative speed control mechanism for use with slip-ring motors.
- The new product in the market for improvement in energy efficiency is as electronic ballast. Electronic ballasts, there are timer based controls available for street light control.
- Also timer based voltage control during the night time say 12 midnight to 6 am results in a lot of energy savings in street lighting. A daylight sensor to switch off street lights is also an effective tool for energy savings.

References

- Gilbert, M., 2004. *Renewable and Efficient Electric Power Systems,* Wiley-IEEE Press publication.
- Randolph, J. & Gilbert, M. *Energy for Sustainability: Technology, Planning, Policy*, 1st ed., Island Press Publication.
- *Energy Efficient Technologies in Electrical Systems* [Pdf] Available at: <beeindia.in/energy_managers_auditors/documents/guide.../3Ch10.pdf> [Accessed 5 July 2013].
- *Chapter 6 Energy Efficient Electrical Systems* [Pdf] Available at: <www.teriin.org/ResUpdate/reep/ch_6.pdf> [Accessed 5 July 2013].
- 2008. *Energy-efficient technology for the entire building* [Video online] Available at: <https://www.youtube.com/watch?v=Sn3aRBjAqDw> [Accessed 5 July 2013].
- 2008. *Energy-Efficient Building Systems* [Video online] Available at: <https://www.youtube.com/watch?v=1mTbrfhBDZU> [Accessed 5 July 2013].

Recommended Reading

- Bertoldi, P. & Parasiliti F., *Energy Efficiency in Motor Driven Systems,* Springer.
- Meier, A., 2006. *Electric Power Systems: A Conceptual Introduction* (Wiley Survival Guides in Engineering and Science). Wiley-IEEE Press publication.
- Khartchenko, N., 1997. *Advanced Energy Systems* (Energy Technology Series), 1st ed., Taylor & Francis Publication.

Self Assessment

1. Maximum demand controller is used to ___________.
    a. switch off essential loads in a logical sequence
    b. exceed the demand of the plant
    c. switch off non-essential loads in a logical sequence
    d. control the power factor of the plant

2. _________ controls the power factor of the installation by giving signals to switch on or off power factor correction capacitors.
    a. KILOVAR
    b. Automatic power factor control relay
    c. Intelligent power factor controller
    d. Maximum demand controller

3. Capacitors with automatic power factor controller when installed in a plant:
    a. Reduces active power drawn from grid
    b. Reduces the reactive power drawn from grid
    c. Reduces the voltage of the plant
    d. Increases the load current of the plant

4. __________ determines the rating of capacitance connected in each step during the first hour of its operation and stores them in memory.
    a. Maximum demand controller
    b. Intelligent power factor controller
    c. Automatic power factor controller
    d. KILOVAR

5. Eddy current drive can be a retrofit for ________.
    a. constant speed system requirement
    b. single speed system requirement
    c. dual speed system requirement only
    d. variable speed system requirement

6. Variable speed cannot be obtained with ____.
    a. DC motors controller
    b. AC motor controller
    c. soft starter controller
    d. AC and DC controllers

7. Energy savings potential of variable torque applications compared to constant torque application is:
    a. Higher
    b. Lower
    c. Equal
    d. Similar

8. As an energy efficient application, slip power recovery system fits well for ____.
    a. Squirrel cage and slip ring motors
    b. DC motor
    c. Slip ring motors only
    d. AC motor

9. The basic functions of electronic ballast excludes one of the following:
    a. To ignite the lamp
    b. To stabilize the gas discharge
    c. To reduce lumen output of the lamp
    d. To supply power to the lamp

10. Application of occupancy sensors is well suited for ___.
    a. Day light based controllers
    b. Night based controllers
    c. Motor controllers
    d. Movement or noise detector in room space

Case Study I

Innovative High-Voltage Technology Supports Wind Power Transfer from Remote Californian Desert

Wind and solar farms have sprung up across the southwest deserts of California to help feed the energy starved population centers on the west coast of the United States. To facilitate transfer of this clean renewable energy, San Diego Gas and Electric (SDG&E) constructed a large 500 kilovolt (kV) switching substation at Ocotillo. Such high-voltage switching substations require relatively small amounts of low- and medium-voltage alternating current (AC) to run vital auxiliary and control applications. Usually the power supplied to auxiliary loads at substations is delivered by either a distribution line or the tertiary winding of the main power transformer, but at this remote site neither solution was available.

SDG&E engineers saw a standard single phase power transformer as the simplest solution to the problem, ABB engineers instead identified a more cost-effective way to tackle the problem. They suggested the gas-insulated SSVT "TIP." The challenge was that ABB had a solution that was only rated up to 420 kV with outputs up to 600V, whereas the site application required a 525 kV product and a medium-voltage (7.2 kV) output at 333 kilovolt-amperes (kVA).

The BIL of the existing ABB's TIP 420kV matched the transformer requirements for Ocotillo substation, but the unit required re-qualifying for 525kV by using bigger cores and tank, and designing the bushing for medium-voltage output to ensure efficient transfer of power from the SSVT to the distant control room. After discussions between ABB's factory in Italy, where its gas-insulated SSVTs are developed, and SDG&E, the right-sized SSVT was identified and a modification proposed. The new optimized solution proved to be compact, cost effective and energy efficient.

After customer design reviews, two units were manufactured to meet the critical schedule set by SDG&E. The units successfully passed design and witness tests by SDG&E, together with the stringent seismic shock tests required for the region. In less than seven months ABB was able to design, manufacture, test and deliver an upgraded product on time. The units have been installed and successfully energized on site to the customer's satisfaction.

(Source: http://www.abb.com/cawp/seitp202/2ae2f7d66d7d3663c1257b780041823f.aspx)

Questions

1. Wind and Solar farms have sprung up across the southwest deserts of California for what purpose?

Answer

Wind and solar farms have sprung up across the southwest deserts of California to help feed the energy starved population centers on the west coast of the United States.

2. ABB was able to design , manufacture, test and deliver an upgraded product on time within how many months?

Answer

In less than seven months ABB was able to design, manufacture, test and deliver an upgraded product on time. The units have been installed and successfully energized on site to the customer's satisfaction.

3. What was the challenge for ABB?

Answer

The challenge was that ABB had a solution that was only rated up to 420 kV with outputs up to 600V, whereas the site application required a 525 kV product and a medium-voltage (7.2 kV) output at 333 kilovolt-amperes (kVA).

Case Study II

Emerging Energy-Efficient Technologies in Industry

Increasingly, industry is confronted with the challenge of moving toward a cleaner, more sustainable path of production and consumption, while increasing global competitiveness. Technology will be essential for meeting these challenges. At some point, businesses are faced with investment in new capital stock. At this decision point, new and emerging technologies compete for capital investment alongside more established or mature technologies. Understanding the dynamics of the decision-making process is important to perceive what drives technology change and the overall effect on industrial energy use. From a policy-making perspective, the better we understand technology developments the more effective we will be in utilizing our future research dollars and in undertaking sound strategy development.

This report focuses on the long-term potential for energy-efficiency improvement in industry. In 2002, the industrial sector consumed 33% of the primary energy and was responsible for 30% of the energy-related greenhouse gas (GHG) emissions in the U.S. Due to the extremely diverse character of the industrial sector, it is not possible to provide an all-encompassing discussion of technology trends and potentials. Instead we focus on a number of key technology areas that illustrate the significant potential energy savings available to industry, given a sustained state, federal and private R&D effort. These include: near net shape casting, membranes, gasification, motor systems, and advanced cogeneration. The discussion of each of these technologies provides a detailed assessment of the potential for future contributions to energy efficiency improvement, economics and performance, as well as the potential development path, including promising areas for research, demonstration or other support. Some of these technologies have particular applications for a specific industry (e.g. near net shape casting in the metal producing sectors and black liquor gasification in the pulp and paper industry), while others can be found in many industries (e.g. advanced motor systems, membranes and advanced cogeneration applications).

The results demonstrate that the United States is not running out of technologies to improve energy efficiency and economic and environmental performance, and will not run out in the foreseeable future. The five technology areas alone can potentially result in total primary energy savings of just over 2,600 TBtu by 2025, or nearly 6.5% of total industrial energy use by 2025. The savings are additional to energy savings found in the AEO 2004 reference case forecasts. The technical potential of these technologies in the long term is roughly three times larger, while additional technologies beyond the five covered in this report are currently available or under development.

(Source: http://industrial-energy.lbl.gov/node/131)

Questions

1. How much percentage of primary energy was consumed by the industrial sector in 2002?
2. How much percentage of the energy-related greenhouse gas (GHG) emissions in the U.S was consumed by the industrial sector in 2002?
3. What are the key technology areas that illustrate the significant potential energy savings available to industry, given a sustained state, federal and private R&D effort?

Case Study III

Rowan University, a growing 10,000-student state university in southern New Jersey, was seeking a reliable and cost-effective alternative to purchasing power from the electric grid. Rising energy costs, aging equipment and an extensive expansion project led the university to develop a comprehensive Master Plan with a strong energy component to address the anticipated 50% increase in student population by 2010. It was decided to set up a cogeneration plant.

The new co-generation plant was expected to save the university $1 million annually when compared to the cost of purchasing all its electricity from the grid. High-temperature flue gases are used to produce steam for dual purposes. Primarily, the steam drives a 2,300-ton York centrifugal chiller for chilled water application. Secondarily, the steam piped through the district steam loop provides hot water, heating and laboratory usage.

The inherent variable speed technology makes the turbine drive the most efficient cooling technology for CHP as it operates throughout the cooling season and is ideally paired with gas turbine systems.

Both the electric chillers and steam turbine chiller are derived from the same basic design.

Complementing this technology, traditional electric chillers provide an additional 2,000 tons of chilled water capacity. The hybrid chiller plant allows Rowan to take advantage of favourable off-peak rates for both natural gas and electric energy and helps guarantee redundancy to ensure continuous operation in the wake of power outages.

By generating its own power, Rowan enabled the electric utility to reduce its greenhouse emissions by 8,000 tons of CO2. This is the equivalent of planting nearly 1.1 million trees, or taking 1,139 cars off the road, and constitutes 30 percent of the university's greenhouse gas reduction target as a member of the New Jersey Higher Education Partnership for Sustainability.

Questions

1. What is the principle adopted here to achieve energy efficiency?
2. How has the energy efficiency plan helped Rowan University?
3. What are the environmental benefits of the energy efficiency plan?

Bibliography

References

- 2008. *Blowers and Industrial Fans* [Video online] Available at: <https://www.youtube.com/watch?v=Ua1vQKWL2P8> [Accessed 5 July 2013].
- 2008. *Diesel Engines: Fuel System Design* [Video online] Available at: < https://www.youtube.com/watch?v=Gh_mvWESGHw> [Accessed 5 July 2013].
- 2008. *Energy-Efficient Building Systems* [Video online] Available at: <https://www.youtube.com/watch?v=1mTbrfhBDZU> [Accessed 5 July 2013].
- 2008. *Energy-efficient technology for the entire building* [Video online] Available at: <https://www.youtube.com/watch?v=Sn3aRBjAqDw> [Accessed 5 July 2013].
- 2008. *Principles of Refrigeration* [Video online] Available at: < https://www.youtube.com/watch?v=b527al9D_rY&list=PL95C8D5AC21D8955B> [Accessed 5 July 2013].
- 2009. *How electric motors work*, [Video online] Available at: <https://www.youtube.com/watch?v=Q2mShGuG4RY> [Accessed 5 July 2013].
- 2009. *HVAC 101 evacuating AC unitand adding refrigerant* [Video online] Available at: < https://www.youtube.com/watch?v=W6mzdUfdSNM> [Accessed 5 July 2013].
- 2010. *LED Mobile Lighting System* [Video online] Available at: <https://www.youtube.com/watch?v=3CiOw04ZNT8> [Accessed 5 July 2013].
- 2011. *Compressed Air System Basics*, [Video online] Available at: <https://www.youtube.com/watch?v=2KKCwfvqoNs> [Accessed 5 July 2013].
- 2011. *Fans and Blowers* [Video online] Available at: <https://www.youtube.com/watch?v=M0ZmidNA520> [Accessed 5 July 2013].
- 2011. *System Head Curves:How to have a successful pumping system* [Video online] Available at: < https://www.youtube.com/watch?v=okKKZiRqrPI> [Accessed 5 July 2013].
- *2011.Electrical Systems* [Video online] Available at: < https://www.youtube.com/watch?v=ffP8t7F3l_I> [Accessed 5 July 2013].
- 2012. *Build an Electric Motor* [Video online] Available at: < https://www.youtube.com/watch?v=elFUJNodXps> [Accessed 5 July 2013].
- 2012. *Compressed Air System* [Video online] Available at: < https://www.youtube.com/watch?v=HUcHHIrm9CI> [Accessed 5 July 2013].
- 2012. *Diesel Electric Set-Non Functional Mock up* [Video online] Available at: < https://www.youtube.com/watch?v=NwTKhe9iztE> [Accessed 5 July 2013].
- 2012. *How a Cooling Tower Works?* [Video online] Available at: < https://www.youtube.com/watch?v=z9-cVGrR9OE> [Accessed 5 July 2013].
- 2012. *Progressing Cavity Pumping System* [Video online] Available at: < https://www.youtube.com/watch?v=v5VnnBtXtlc> [Accessed 5 July 2013].
- 2012. *What are Cooling Towers?*[Video online] Available at: < https://www.youtube.com/watch?v=KbxHk7go7UU> [Accessed 5 July 2013].
- *2012.Electrical Systems-Part 1* [Video online] Available at: <https://www.youtube.com/watch?v=tUul6kB9slo> [Accessed 5 July 2013].
- 2013. *Smart LED Lighting System* [Video online] Available at: <https://www.youtube.com/watch?v=YHBaVmpcdso> [Accessed 5 July 2013].
- *Assembly of Diesel Generator Set* [Pdf] Available at: < www.dcmsme.gov.in/publications/pmryprof/electrical/ch2.pdf> [Accessed 5 July 2013].
- Bleier, F., 1997. *Fan Handbook: Selection, Application, and Design*, 1st ed., McGraw-Hill Professional Publication.

- Brady, R. N. & Dagel. J. F., *Diesel Engine and Fuel System Repair*, 5th ed., Prentice Hall Publication.
- *Chapter 6 Energy Efficient Electrical Systems* [Pdf] Available at: <www.teriin.org/ResUpdate/reep/ch_6.pdf> [Accessed 5 July 2013].
- *Chapter 6 Introduction to Pumping Systems* [Pdf] Available at: < dec.alaska.gov/water/opcert/Docs/Chapter6.pdf> [Accessed 5 July 2013].
- Chen, K.,1999. *Energy Management in Illuminating Systems*,1st ed., CRC Press Publication.
- *Compressed Air System* [Pdf] Available at: < http://www.energymanagertraining.com/GuideBooks/3Ch3.pdf> [Accessed 5 July 2013].
- *Compressed Air System Study Guidelines* [Pdf] Available at: <http://www.vectren.com/cms/assets/pdfs/conservation/compressed-air-guidelines.pdf> [Accessed 5 July 2013].
- *Cooling Tower* [Pdf] Available at: < www.beeindia.in/energy_managers_auditors/documents/.../3Ch7.pdf> [Accessed 5 July 2013].
- *Cooling Tower Fundamentals- SPX Cooling Technologies* [Pdf] Available at: < spxcooling.com/pdf/Cooling-Tower-Fundamentals.pdf> [Accessed 5 July 2013].
- *DG Set System* [Pdf] Available at: < www.beeindia.in/energy_managers_auditors/documents/.../3Ch9.pdf> [Accessed 5 July 2013].
- Dunlop, C., 2003. *Electrical Systems*, Dearborn Financial Publishing, Inc.
- *Electrical System* [Pdf] Available at: <http://www.enercon.gov.pk/images/pdf/3ch1.pdf> [Accessed 5 July 2013].
- Elliott, B., 2006. *Compressed Air Operations Manual*, 1st ed., McGraw-Hill Professional publication.
- *Energy Efficient Technologies in Electrical Systems* [Pdf] Available at: <beeindia.in/energy_managers_auditors/documents/guide.../3Ch10.pdf> [Accessed 5 July 2013].
- *Fans and Blowers* [Pdf] Available at: <http://www.enercon.gov.pk/images/pdf/3ch5.pdf> [Accessed 5 July 2013].
- Frayne, C., 1999. *Cooling water treatment: Principles and practice*, Chemical Pub. Co publication.
- Gilbert, M., 2004. *Renewable and Efficient Electric Power Systems,* Wiley-IEEE Press publication.
- Giridharan, M.K., *Electrical Systems Design:Data Handbook*, I.K.International Pvt. Ltd.
- *How to Select a Fan or Blower* [Pdf] Available at: <http://www.cincinnatifan.com/manuals/HowToSelectAFanOrBlower.pdf> [Accessed 5 July 2013].
- Hughes, A. & Drury. B., 2013. *Electric Motors and Drives: Fundamentals, Types and Applications*, 4rth ed., Elsevier Ltd.
- *hvac and refrigeration system* [Pdf] Available at: < http://www.beeindia.in/energy_managers_auditors/documents/guide_books/3Ch4.pdf> [Accessed 5 July 2013].
- *Introduction to Electrical Design Systems* [Pdf] Available at: < http://www.ecs.umass.edu/ece/hollot/ECE497DS06/ESD_1.pdf> [Accessed 5 July 2013].
- Kroger, D., 2004. *Air-cooled Heat Exchangers And Cooling Towers: Thermal-flower Performance Evaluation and Design*, Volume 2. Pennwell Books Publication.
- Levermore, G., 2000. *Building Energy Management Systems: An Application to Heating, Natural Ventilation, Lighting and Occupant Satisfaction*, 2nd ed., Spon Press Publication.
- *Lighting System* [Pdf] Available at: <www.beeindia.in/energy_managers_auditors/documents/.../3Ch8.pdf> [Accessed 5 July 2013].
- *Lighting Systems Made Easy* [Pdf] Available at: <www.leprecon.com/catalogs/280075BLightingMadeEasy.pdf> [Accessed 5 July 2013].
- Mahon, L. L. J., 1992. *Diesel Generator Handbook*, Newnes publication.
- Menon, E. S., 2009. *Working Guide to Pump and Pumping Stations: Calculations and Simulations*,1st ed., Gulf Professional Publishing.

- Moczola, H., 1998. *Small Electrical Motors*, The Institution of Electrical Engineers.
- Moyer, E. J. & Chicago, U., 2010.*Basics on electric motors* [Pdf] Available at: <http://geosci.uchicago.edu/~moyer/GEOS24705/Readings/ElecReadingII_Motors.pdf> [Accessed 5 July 2013].
- *Pumps and Pumping System* [Pdf] Available at: < http://www.beeindia.in/energy_managers_auditors/documents/guide_books/3Ch6.pdf> [Accessed 5 July 2013].
- Randolph, J. & Gilbert, M. *Energy for Sustainability: Technology, Planning, Policy*, 1st ed., Island Press Publication.
- *Refrigeration System Accessories* [Pdf] Available at: < http://www.mavcc.org/pdffiles/ACRUnit14SG.pdf> [Accessed 5 July 2013].
- Rishel, J., Durkin, T. & Kincaid, B., 2006. *HVAC Pump Handbook*, 2nd ed., McGraw-Hill Professional publication.
- Simons, T., 1914. *Compressed air: a treatise on the production, transmission and use of compressed air*, McGraw-Hill Book Co. Publication.
- Stoecker, W., 1998. *Industrial Refrigeration Handbook*, 1st ed., McGraw-Hill Professional Publication.
- *Types of Electric Motors* [Pdf] Available at: <http://www.ece.uah.edu/courses/material/EE410-Wms2/Electric%20motors.pdf> [Accessed 5 July 2013].
- Wang, S., 2000. *Handbook of Air Conditioning and Refrigeration*, 2nd ed., McGraw-Hill Professional publication.
- Yahya, S. M., 2005. *Turbines compressors and fans*, 3rd ed., Tata McGraw-Hill Publication.

Recommended Readings

- 2004. *Variable Speed Pumping: A Guide to Successful Applications*, Elsevier Ltd.
- Abbi, Y. P. & Jain, S., 2006. *Handbook on Energy Audit and Environment Management*, TERI Press.
- Abdulqadar, M., 2006. *Diesel Generator Auxillary Systems and Instruments*, Lulu.com Publication.
- Beggs, C., 2009. *Energy: Management, Supply and Conservation*, 2nd ed., Butterworth-Heinemann publication.
- Bertoldi, P. & Parasiliti F., *Energy Efficiency in Motor Driven Systems,* Springer.
- Casazza, J. & Delea. F.,2003. *Understanding electric power systems an overview of the technology and the marketplace*. (Volume 13). Wiley-IEEE Publication.
- Chapman, S., 2001. *Electric Machinery and Power System Fundamentals*, 1st ed., McGraw-Hill Science/Engineering/Math Publication.
- Crocker, F. B., 2009. *Electric Motors: Their Action, Control and Application*, 2nd ed., BiblioBazaar, LLC, Publication.
- Doty, S. & Turner, W. C., 2009. *Energy management handbook*, 7th ed., The Fairmont Press.
- Gurney, J. D. & Cotter, I. A., 1966. Cooling towers, McMillan & sons.
- Heumann, W. L., 1997. *Industrial air pollution control systems*. McGraw-Hill Professional publication.
- Hughes, A., 2006. *Electric motors and drives: fundamentals, types and applications*, 3rd ed., Newnes publication.
- Kaltschmitt, M., Streicher, W. & Wiese, A., 2009. *Renewable energy: technology, economics, and environment*. Springer publication.
- Khartchenko, N., 1997. *Advanced Energy Systems* (Energy Technology Series), 1st ed., Taylor & Francis Publication.
- Lindsey, J. L., 1997. *Applied illumination engineering*, 2nd ed., The Fairmont Press, Inc.Publication.
- Mackay, R. C., 2004. *The Practical Pumping Handbook*, Elsevier Science publication.
- McCoy, J. W., 1983. *The Chemical Treatment of Cooling Water*, 2nd ed., Chemical Publishing Company Publication

- McDowall, R., 2007. *Fundamentals of HVAC systems*. Academic Press Publication.
- Meade, N. G.,1908. *Electric motors: their installation, control, operation and maintenance*, McGraw publishing company.
- Meier, A., 2006. *Electric Power Systems: A Conceptual Introduction* (Wiley Survival Guides in Engineering and Science). Wiley-IEEE Press publication.
- Nourbakhsh, A., Jaumotte, A., Hirsch, C. & Parizi, H. B., 2007. *Turbopumps and Pumping Systems,* 1st ed., Springer Publication.
- Patterson, E. G., 2001. Lighting Systems: Advanced Course, Thomson Learning.
- Ramli, Y., 2010. *Introduction to Compressed Air Systems*.
- Rosaler, R. C., 1998. *HVAC maintenance and operations handbook*. McGraw-Hill Professional publication.
- Rustebakke, H. M., 1983. *Electric Utility Systems and Practices*, 4rth ed., Wiley-Interscience Publication.
- Smith, R. E., *Electricity for Refrigeration*, 8th ed., CengageBrain.com.
- Srinivasulu, P. & Vaidyanathan, C. V., 1977. *Handbook of machine foundations*. Tata McGraw-Hill Publication.
- Stanford, H. W., 2003. HVAC *Water Chillers and Cooling Towers: Fundamentals, Application, and Operation* (Dekker Mechanical Engineering),1st ed., CRC Press publication.
- Talbott, E. M., 1993. *Compressed air systems: a guidebook on energy and cost savings*, 2nd ed. The Fairmont Press, Inc.
- Wharton, J., 2006. *Diesel Engines*, Butterworth-Heinemann.

Self Assessment Answers

Chapter I

1. c
2. d
3. a
4. b
5. c
6. a
7. b
8. d
9. c
10. a

Chapter II

1. a
2. c
3. d
4. a
5. b
6. d
7. d
8. b
9. a
10. c

Chapter III

1. a
2. b
3. c
4. d
5. d
6. a
7. c
8. b
9. b
10. c

Chapter IV

1. a
2. d
3. b
4. c
5. d
6. c
7. a
8. b
9. d
10. b

Chapter V

1. a
2. c
3. b
4. a
5. a
6. b
7. a
8. d
9. c
10. b

Chapter VI

1. c
2. b
3. a
4. b
5. d
6. b
7. c
8. d
9. a
10. c

Chpater VII

1. d
2. d
3. a
4. a
5. b
6. b
7. d
8. c
9. d
10. a

Chapter VIII

1. d
2. d
3. c
4. b
5. c
6. b
7. c
8. c
9. c
10. c

Chapter IX

1. a
2. c
3. b
4. d
5. c
6. a
7. b
8. d
9. a
10. d

Chapter X

1. c
2. b
3. b
4. b
5. d
6. c
7. a
8. c
9. c
10. d