Energy Efficiency in Electrical Utilities

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Abbreviations

AC	-	Alternating Current
ACSR	-	Aluminium Conductor with Steel Reinforcement
AHU	-	Air Handling Units
ANSI	-	American National Standards Institute
AS	-	Australian Standard
ASME	-	American Society of Mechanical Engineers
BEE	-	Bureau of Energy Efficiency
BEP	-	Best Efficiency Point
BHP	-	Brake Horsepower
BIS	-	Bureau of Indian Standards
CFC	-	Chlorinated Fluorocarbon
CFL	-	Compact Fluorescent Lamps
CMD	-	Contracted Maximum Demand
COC	-	Cycles of Concentration
COP	-	Coefficient of Performance
DC	-	Direct Current
DG	-	Diesel Generating
EEM	-	Energy Efficient Motors
FAD	-	Free Air Delivery
FCU	-	Fan Coil Units
FD	-	The Forced Draft
FIFO	-	First in First Out
FILO	-	First in Last Out
FTL	-	Fluorescent Tube Lamps
GLS	-	General Lighting Service
GRP	-	Glass Reinforced Plastic
HCFC	-	Hydrochloro Fluorocarbon
HFC	-	Hydro Fluorocarbon
HP	-	Horsepower
HPMV	-	High Pressure Mercury
HPSV	-	High Pressure Sodium Vapour
HT	-	High Tension
HVAC	-	Heating, Ventilation, and Air Conditioning
ID	-	Induced Draft
IE	-	Indian Electricity
IEC	-	International Electro Technical Commission
IEEE	-	Institute of Electrical and Electronics Engineers
IGBTs	-	Insulated Gate Bi Polar Transistors
IPFC	-	Intelligent Power Factor Controller
IPLV	-	Integrated Part Load Value
IS	-	Indian Standard
kV	-	Kilovolt
KVA	-	Kilo Volts-Amperes
kVAr	-	Kilo Volt-Amperes Reactive
kW	-	Kilo Watts
LEDs	-	Light Emitting Diodes
LPSV	-	Low Pressure Sodium
lx	-	Lux
MCC	-	Motor Control Centre
MD	-	Maximum Demand
MERC	-	Maharashtra State Electricity Regulatory Commission

MT	-	Metric Ton
NEMA	-	National Electrical Manufacturers Association
NPSH	-	Net Positive Suction Head
NPSHA	-	Net Positive Suction Head Available
NPSHR	-	Net Positive Suction Head Required
OLTC	-	On Load Tap Changer
PA	-	Primary Air
PCC	-	Power Control Centre
PF	-	Power Factor
PID	-	Proportional Integral Differential (PID)
PLC	-	Programmable Logic Controller
R	-	Resistance
RH	-	Relative Humidity
RI	-	Colour Rendering Index
RMS	-	Root Mean Square
RVSS	-	Reduced Voltage Soft Starters
SLD	-	Single Line Diagram
SP	-	Static Pressure
TOD	-	Time of the Day
TR	-	Tons of Refrigeration
V	-	Voltage
VAR	-	Vapour Absorption Refrigeration
VCR	-	Vapour Compression Refrigeration
VFDs	-	Variable Frequency Drives
VSDs	-	Variable Speed Drives
W	-	Watt
WBT	-	Wet Bulb Temperature
WHR	-	Waster Heat Recovery

Chapter I

Electrical System

Aim

The aim of this chapter is to:

- define the concept of generation, transmission and distribution of energy
- explain the important electrical equipments
- explicate the electrical symbols and SLD

Objectives

The objectives of this chapter are to:

- explain the concept of generation, transmission and distribution of energy
- explicate important electrical equipments, electrical symbols and SLD
- elucidate the factor improvement and transformer distribution

Learning outcome

At the end of this chapter students will be able to:

- define and identify the concept of generation, transmission and distribution of energy
- understand the concept of power factor improvement and its benefit
- comprehend the importance of distribution and transformer losses

1.1 Introduction

- Electricity (from the New Latin ēlectricus, meaning "amber-like", from the Greek ήλεκτρον [(electron) meaning amber] is a general term encompassing a variety of phenomena resulting from the presence and flow of electric charge. These include many easily recognisable phenomena, such as lightening and static electricity, but in addition, less familiar concepts, such as the electromagnetic field and electromagnetic induction.
- Electric Power Supply System is an aggregate of equipments used to transmit and distribute electricity from sources to consumers. General-purpose power supply systems transmit and distribute approximately 98% of the total electricity generated. They link electric power plants with consumers of electricity within electric power systems and interconnect individual systems by overhead or cable power transmission lines. Electric power supply systems ensure reliable, centralised power supply with the required quality and excellent economy to widely dispersed locations of consumption. Some electric power supply systems are self-contained and are not connected to transmission lines, for example, the systems used in aircraft, ships, and automobiles.
- Electric power supply systems may be classified according to several characteristics. Depending on their purpose, they may be classified as feeder systems:
    - used to transmit electric power
    - used to transmit distribution systems, which distribute power from central substations to consumers (urban, industrial, agricultural, and other users)

Classification by voltage divides systems into two groups:
- those carrying voltages up to 1 kilovolt (kV)
- those carrying voltages of more than 1 kV

Electric power supply systems may also be classified as:
- by type of current (direct and alternating)
- by plant location (overhead and cable)
- by layout (circular and radial)
- by normal operating mode (open and closed)

- In addition to transmission lines, electric power supply systems also have power substations, which are used for the conversion and distribution of electric power and for controlling operation of the system.
- Electric power supply system in a country comprises of the following:
    - generating units that produce electricity
    - high voltage transmission lines that transport electricity over long distances
    - distribution lines that deliver the electricity to consumers
    - substations that connect the pieces to each other
    - energy control centres to coordinate the operation of the components
- Today electricity is the most widely used form of energy mainly because;
    - it is easy to generate, transmit and distribute
    - it is easy to control
    - it can be easily converted to other forms of energy like mechanical motion, heating etc. with very accurate controls required for processes
    - it is the cleanest form of energy
- Because of these four reasons, we find that electricity is a more preferrable form of energy almost everywhere whether it is household, commercial, shop, hospital, hotel, small or large industry or railway traction.
- The Figure 1.1 shows a simple electric supply system with transmission and distribution networks and linkages from electricity sources to end-user.

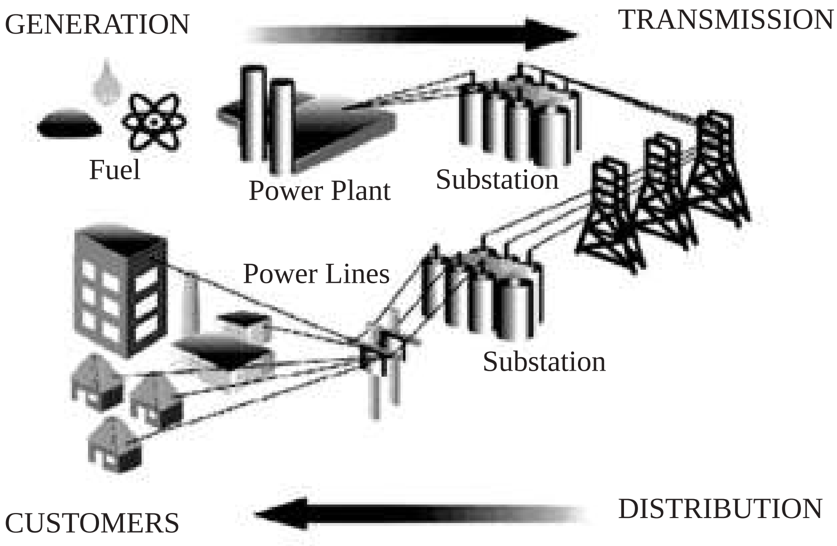

Fig. 1.1 Typical electric power supply systems

1.2 Generation, Transmission and Distribution of Electricity

The fundamental principles of electricity generation were discovered during the 1820s and early 1830s by the British scientist, Michael Faraday. His basic method is still used; i.e. electricity is generated by the movement of a loop of wire or disc of copper between the poles of a magnet. For electric utilities, it is the first process in the delivery of electricity to consumers. The other processes, electricity transmission, distribution, and electrical power storage and recovery using pumped storage methods are normally carried out by the electrical power industry.

Electricity generation

Electricity is generated in a number of ways, the most prominent of all are thermal power plants, hydroelectric power plants, nuclear power plants, etc. There are other ways of producing electricity which are called Non-Conventional Energy sources; which include windmill, solar systems, tidal energy etc. The electricity thus generated is needed to be sent to a place where it can be utilized; such a place could be a household consumer using electricity for his microwave oven or it could be an industry manufacturing cement, paper, etc. The process of sending electricity for utilization is called transmission.

Electricity transmission

The term transmission is used for the process of transporting electricity at a very high voltage and the transmission is in bulk amount. Normally this is done at different voltages. In addition to transmission lines, electric power supply systems also have power substations, which are used for the conversion and distribution of electric power and for controlling operations of the system (raising and lowering voltages, converting three-phase alternating current to direct current and vice versa, and providing a number of outgoing lines that differ from incoming lines).

Voltage is usually lowered or raised in several steps. For each step, there is a separate network of transmission lines and substations through which the electricity is fed to the network operated at the next voltage step. The resulting multistage system consists of several interconnected networks carrying different voltages. Transmission is a link between Generation and Distribution.

Electricity distribution

Distribution of electricity denotes sending electricity from substations where it is transmitted and received followed by its distribution to various points of utilisation. The substation could be a small place in a village receiving electricity and then distributing it to nearby consumers or a place where bulk power is received by an industry like aluminium, steel processing, etc.

1.3 IE (Indian Electricity) Rules

- Indian Electricity Rules 1956 are the guidelines for electrical standards followed in our country. They classify various voltages into different grades. These are classified as follows:
  - Low: the voltage need not exceed 250V
  - Medium: the voltage need not exceed 650V
  - High: the voltage need not exceed 33000V (33KV)
  - Extra High: the voltage exceeds 33000V (33KV)
- It is important to know why there are different voltages for different stages. Generation at power plants is generally at 11KV. This 11KV is then converted into 132KV, 220KV or 400 KV using various transformers. Again when power is to be utilized at the user end, the voltages are reduced to the required voltages first at 33KV, 22KV or 11 KV for distribution and then finally to 415V three phases or 230V single phase. Generation is at 11KV because that is considered optimum based on its cost. If one tries to go to a higher voltage, the cost of insulation is high and if he tries to go below, the current rating increases, thus demanding a higher size of conductor in generator winding, thereby also increasing the cost. Hence 11KV is considered the most optimum voltage level for generation.
- On the other hand, transmission is done at voltage levels of 132KV and above. Here the obvious advantage is the use of air as an insulator and the negligible cost of insulation of the conductor. The conductor size reduces drastically because; current value comes down for the same power handled. Again if one tries to reduce voltage for transmission, the conductor cost will go up. Hence transmission is always preferred at extra high voltage.
- Distribution voltages of course again have to be brought down because the voltage has to match the voltage of utilizing equipment like motors, furnaces, etc. Since a majority of the equipment is rated for medium and low voltages, these voltages have to be brought down.

1.4 Important Equipments

One can classify the equipment used in electrical systems into the following categories:

Equipment	Function
Generator	This equipment converts mechanical energy of rotation to electrical energy.
Cables	These are insulated conductors used to provide a flow path to electricity.
Breaker	Breaker is protects electrical circuits under any abnormal conditions like faults, accidents, etc.
Transformer	This equipment converts the voltage of one level to another level, also changing the current level simultaneously. If the voltage is increased, it is called a Step Up Transformer. If the voltage is reduced, it is called a Step Down Transformer.
CT/PT	CT stands for Current Transformer and PT stands for Potential Transformer. This equipment is used for measurement and protection in the electrical circuits.
Motor	This equipment converts electrical energy into mechanical energy. There are various types of motors depending on the type of application. This equipment is most widely used in electrical circuits.
ACSR conductor	ACSR stands for Aluminium Conductor with Steel Reinforcement. This is used as overhead conductor in transmission and distribution.
Transmission Tower	This equipment is used as a mechanical supporting structure for the ACSR conductor used for the transmission of electrical energy.

Table1.1 List important electrical equipment

1.5 Electrical Symbols and SLD

- Electrical engineers use standard symbols for various equipments to represent them in a drawing. The most important drawing is called the Single Line Diagram (SLD), which represents the power flow in a system along with various protection equipment, cable sizes, and relevant details.
- There are several national and international standards for graphical symbols in circuit diagrams, in particular the following ones:
  - International Electro technical Commission[IEC 60617] (also known as British Standard BS 3939)
  - American National Standards Institute[ANSI standard Y32] (also known as IEEE Std 315)
  - Australian Standard [AS 1102]
- The symbols are covered in IS 12032 entitled "Graphical Symbols for Diagrams in the Field of Electro technology". A typical page from the standard is shown below:

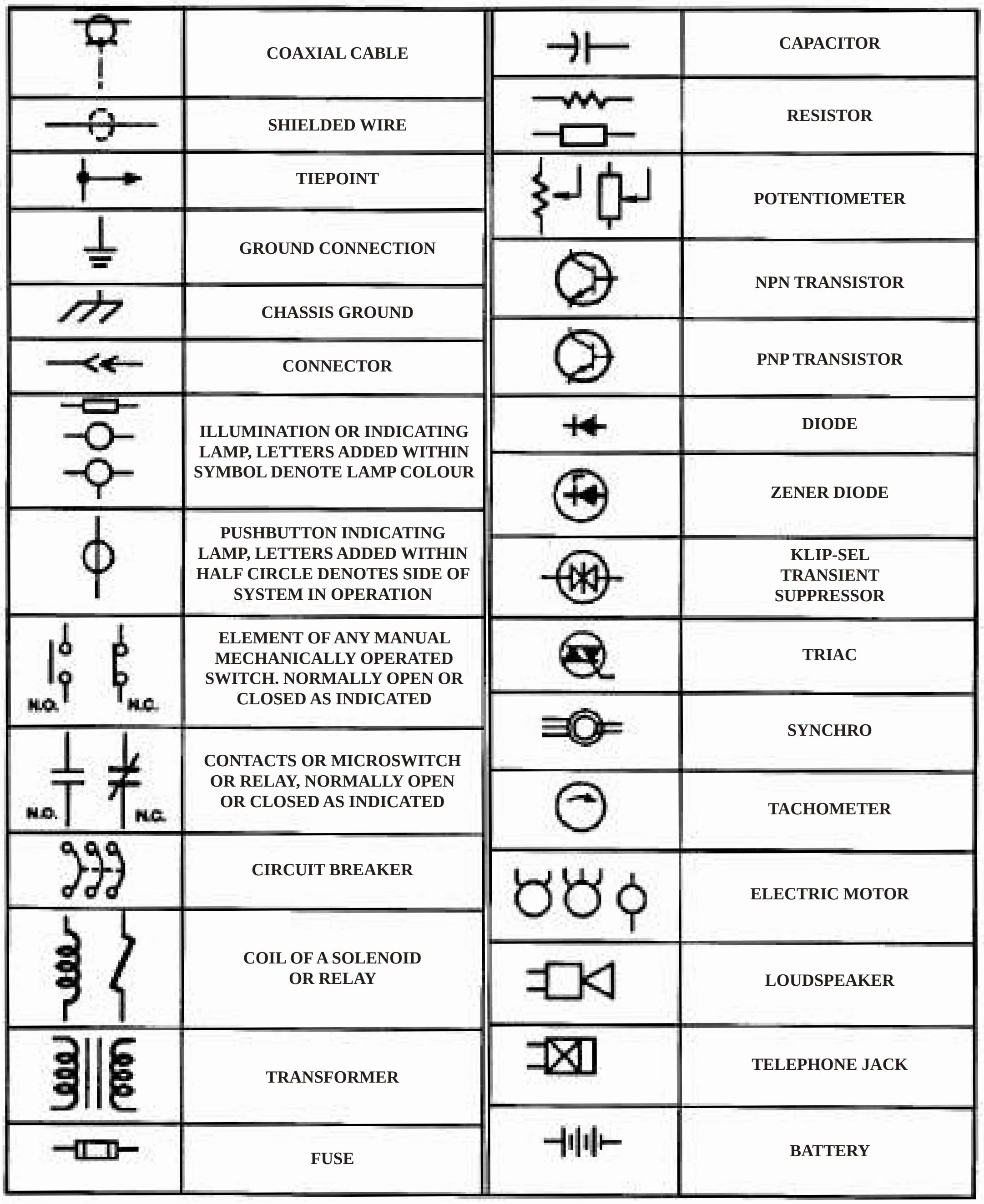

Fig. 1.2 Graphical symbols for diagrams

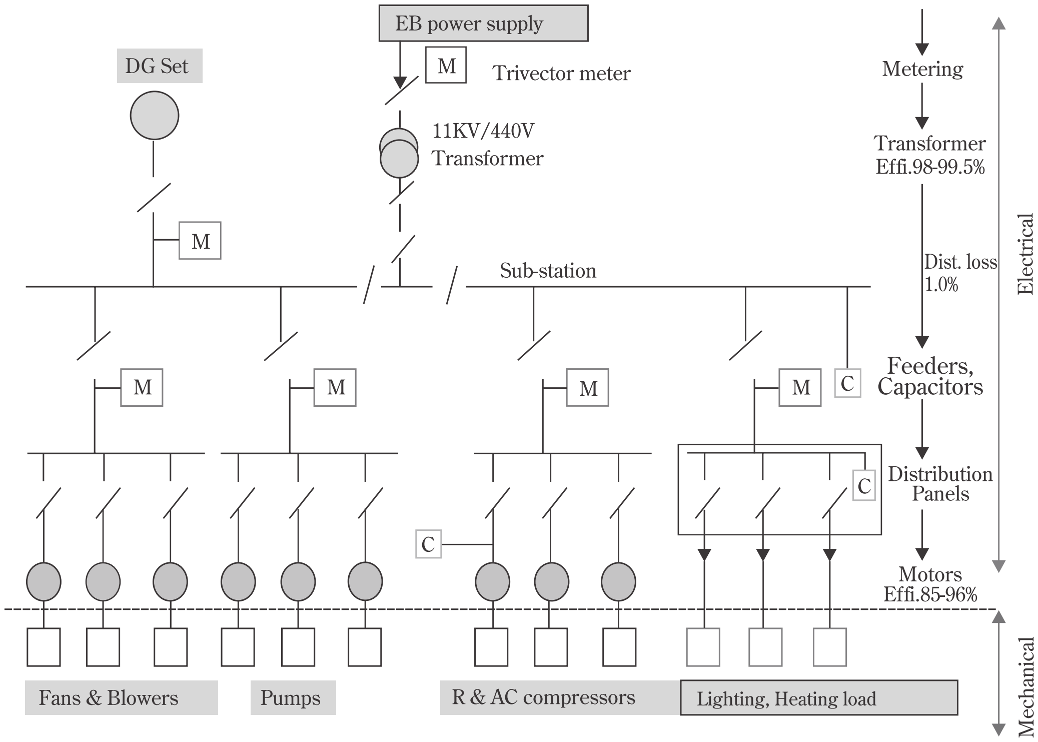

Fig. 1.3 Typical single line diagram

1.6 Electricity Billing

Electricity Billing varies from State to State. Till the enactment and implementation of the Electricity Act 2003, the State Electricity Boards had the monopoly for supplying Electricity to consumers and their own formats for electricity billing. With the implementation of this act, each state has to have a number of distribution companies. In order to bring uniformity amongst all the distribution companies, the task of Standardizing has been entrusted to the respective State Electricity Regulatory Commissions. Recently the state of Maharashtra MERC (Maharashtra State Electricity Regulatory Commission) has brought out a standard format of the bill applicable to the state. It states as follows:

- The bill to the consumer shall include all charges, deposits, taxes and duties due and payable by the consumer to the Distribution Licensee for the period billed, in accordance with the provisions of the Act. These regulations and the schedule of charges are as approved by the Commission under Regulation 18.
- The Distribution Licensee shall, upon request by the consumer, explain the detailed basis of computation of the consumer's bill.
- Unless otherwise agreed between the distribution licensee and the consumer, the bill shall be in Marathi and / or in the English language.
- The bill shall include, inter alia (among other things), the following information
    - Consumer No., name and address
    - Name of office of the distribution licensee having jurisdiction over the supply
    - (i) Type of supply (i.e. single phase, three-phase, LT or HT)
- Contract demand / Sanctioned Load
    - Category of the consumer (i.e. domestic, commercial etc.)
    - Meter No
    - Billing period (dates to be mentioned)
    - Previous meter reading of the billing period / cycle with date
    - Present meter reading of the billing period / cycle with date
    - Multiplying factor of the meter

- Number of units (e.g. Kwh, kVArh, kVAh, etc.) consumed during the billing period and, where relevant determination of charges, during different time slots in the billing period
- Maximum demands during the billing period
- Average power factor during the billing period
- Last six months consumption
- Date of the bill and due date of payment
- Billing details- Details for the current month demand and arrears shall be furnished in the bills
- Security deposit details
- Table showing the various components of applicable tariff
- Details of subsidy, if any, under Section 65 of the Act
- Mode of payment and collection facilities
- Telephone number and address of the Customer Service Centre where the consumer can make a bill-related complaint
- Telephone numbers and address of the Forum constituted in accordance with the Grievance Redressal Regulations
- In case of cheques and bank drafts, the receiving authority in whose favour the amount should be drawn

Similarly for other states, one can find out details from the websites of the respective electricity regulatory commissions.

1.7 Electrical Load Management and Maximum Demand Control

- In the utilisation of electrical energy, there are three fundamental parameters which one has to understand. They are:
  - Load Factor
  - Diversity Factor
  - Utilisation Factor
- Normally for low voltage consumers, only energy consumed is measured. But for a bulk electricity consumer with a high voltage connection, the meter used is called a trivector meter. This meter measures the maximum demand (kva), energy consumed (kwh), and total apparent energy consumed (kvah). from these measurements, one can calculate the average power factor as (kWh/kVAH).
- Previously, these meters were electromagnetic, but with advancements in electronics, new meters have been developed. They are called TOD (Time of the Day) meters. These meters not only record all the above mentioned quantities but they also record the time these quantities were measured.

1.8 Maximum Demand

Maximum Demand is kVAH measured during a prefixed time duration of either 15 minutes or 30 minutes and then multiplied by either four or two respectively to give KVAH per hour i.e. KVA. Thus, at the end of each time cycle, the timer is reset and fresh measurement starts. Such measurement also ensures that an instantaneous load like starting of the motor does not affect the MD measurement.

Normally a 15 minute timer is used for CMD exceeding 5 MVA whereas a 30 minute timer is used for CMD less than 5 MVA. This provision was applicable till recently but as the per latest regulations by MERC for the state of Maharashtra, all the consumers are covered by 30 minute timers. Similarly this provision varies from state to state.

As example, in an industry, if the drawl over a recording cycle of 30 minutes is:

- 2500 kVA for 4 minutes
- 3600 kVA for 12 minutes
- 4100 kVA for 6 minutes
- 3800 kVA for 8 minutes

The MD recorder will be computing MD as:

$$\frac{(2500x4) + (3600 \times 12) + (4100 \times 6) + (3800 \times 8)}{30} = 3606.7 \text{ kVA}$$

1.9 Contracted Maximum Demand (CMD)

- Contracted maximum demand (CMD) is the demand mutually agreed between the supply company and the consumer by way of a signed contract.
- This demand forms the basis for working out of various capacities for the supply company and the consumer. Thus the supply company makes arrangements to supply the required demand and expects the consumer to restrict his demand within that limit.
- If a consumer exceeds that demand, the supply company charges him a penalty. If the consumer draws less than 80% of CMD the supply company charges him for 80% of CMD called Billing Demand. Thus the billing demand is the higher of the two:
    - 80% of CMD
    - Actual maximum demand established by the meter
- This figure of 80% may again vary from state to state but the principle remains same.

1.10 Connected Load

- Connected load is the sum of the nameplate ratings of all the equipments utilising electricity inside the consumer installation. Normally, when the figure is worked out, standby equipments is not considered since only one of them is running at a time. Also the figure is based on end utilising equipment and intermediate equipment like distribution transformers, motor control centres, etc. are not considered.

- Average load is energy consumption recorded divided by the operating hours of the plant.
    - Load Factor = (Average Load)/ (Maximum Demand) always less than 1.
    - Diversity Factor = (Connected Load)/ (Maximum Demand) always more than 1.
    - Utilisation Factor=(Average Load)/(Connected Load) always less than 1.
    - Utilisation Factor = (Load Factor) / (Diversity Factor)
    - Utilisation factor can easily be derived by multiplying both the numerator and the denominator by maximum demand.

- It is important to note here that all the quantities must be worked out on the same unit basis of KW or KVA. Example, if maximum demand is measured in KVA, then using a power factor, it should be converted to KW. Similarly in a connected load, if the rating of any particular equipment is given in KVA, then using its rated power factor it should be converted to KW.

- From the above it will be amply clear that by reducing maximum demand one can save lot of money and hence the control of maximum demand forms an essential part of the energy conservation programme. Similarly achieving a load factor as close to unity as possible ensures that demand is uniform and energy is uniformly and well utilised. This also ensures that distribution losses are reduced.

- There are various methods of controlling maximum demand. They can be:
  - Shift non essential loads to off peak hours: For example, if one is working in a bottling plant working in two shifts, then loads like the water treatment plant, the effluent treatment plant can be made during the third shift alone.
  - Better co-ordination amongst departments: For example, in a cement plant where mines work only from sunrise to sunset, the colony water pumps, water treatment plants, etc. can be run only during sunset to sunrise.
  - Improvement of the power factor gives a great relief to MD. This is because for the given kW, the unity power factor records the same kVA. But a 0.5 power factor records double the kVA. Since billing is done on the basis of kVA, a better power factor helps in controlling maximum demand.
- The above methods indicated are dependent on manual systems and hence are not reliable. The most modern method is to provide an automatic maximum demand controller. This is a microprocessor - based instrument which monitors the Maximum Demand by iterative projections and cuts off automatically nonessential loads as per priorities decided earlier.

1.11 Power Factor

- In case of pure resistive loads, the voltage(V),current (I), resistance (R)relations are linearly related, i.e. $V = I \times R$ and Power (kW) = $V \times I$
- Active power is measured in kW (Kilo Watts). Reactive power is measured in kVAr (Kilo Volt-Amperes Reactive)
- The vector sum of the active power and reactive power make up the total (or apparent) power used. This is the power generated by the SEBs for the user to perform a given amount of work. Total Power is measured in KVA (Kilo Volts-Amperes)
- Power Factor is a ratio of kW to KVA which is always less than or equal to unity. This is represented by a famous triangular relation as shown below:

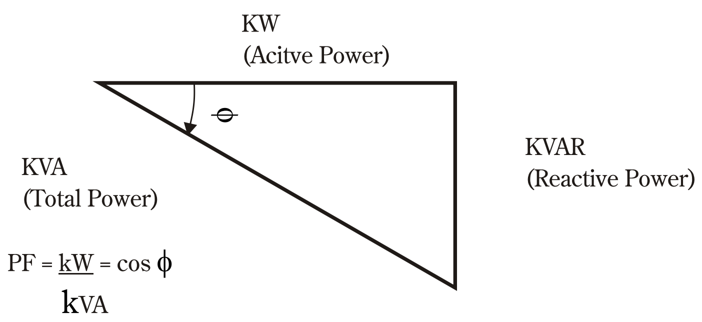

Fig.1.4 Power factor triangle

- The active power (shaft power required or true power required) in kW and the reactive power required (kVAr) are 900 apart vectorically in a pure inductive circuit i.e., reactive power kVAr lagging the active kW. The vector sum of the two is called the apparent power or kVA, as illustrated above and the kVA reflects the actual electrical load on distribution system.

1.12 Selection of Power Factor Correction Capacitors

- From the triangle of KW, KVA and kVAr, it is seen that capacitor rating in kVAr should be equal to the kVArR causing the power factor to deviate from Unity. This will ensure that the power factor is properly compensated. But in practice where automatic power factor correction is used extensively now-a-days, these are selected in steps of eight or ten and brought in the circuit as and when required through cutting in and cutting out devices.

- Example

A chemical industry had installed a 1500 kVA transformer. The initial demand of the plant was 1160 kVA with power factor of 0.70. The % loading of transformer was about 78% (116□0/1500 = 77.3%). To improve the power factor and to avoid the penalty, the unit had added about 410 kVAr in motor load end. This improved the power factor to 0.89, and reduced the required kVA to 913, which is the vector sum of kW and kVAr (see Fig. 1.5).

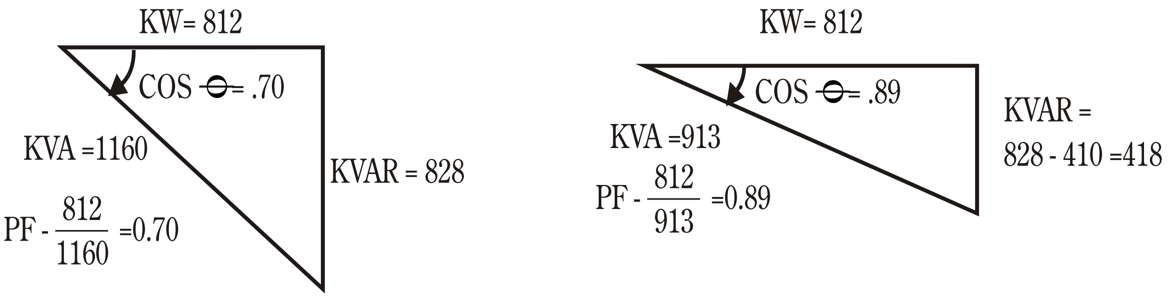

Fig. 1.5 Power factor before and after improvement

Figure 1.5 Effect of power factor improvement for a typical plant where active load is 812 kW and the power factor is improved from 0.7 to 0.89 by the addition of the 418 kVAr capacitor, the obvious advantage is reduction in the kVA demand from 1160 kVA to 913 kVA.

- After improvement the plant had avoided penalty and the 1500 kVA transformer now loaded only to 60% of capacity. This will allow the addition of more load in the future to be supplied by the transformer.
- If the power factor of an installation is improved from PF_1 to PF_2, percentage distribution losses will come down as shown by the formula:

  [1 – (PF1/PF2)2] X 100
- Direct relation for capacitor sizing;

  kVAr Rating = kW [tan φ1 – tan φ2] where,
  - kVAr rating is the size of the capacitor needed,
  - kW is the average power drawn,
  - tan φ1 is the trigonometric ratio for the present power factor, and
  - tan φ2 is the trigonometric ratio for the desired PF.
  - φ1 = Existing (Cos-1 PF_1) and
  - φ2 = Improved (Cos-1 PF_2)
- Alternatively the Table 1.2 can be used for capacitor sizing.
- The figures given in table are the multiplication factors which are to be multiplied with the input power (kW) to give the kVAr of capacitance required to improve present power factor to a new desired power factor.
- Example: The utility bill shows an average power factor of 0.72 with an average KW of 627. How much kVAr is required to improve the power factor to 0.95?

  Using formula;
  Cos Φ1 = 0.72, tan Φ1 = 0.963
  Cos Φ2 = 0.95, tan Φ2 = 0.329
  kVAr required = P (tanφ1 - tanφ2) = 627 (0.964 – 0.329)
  = 398 kVAr
  Using table (see Table 1.2);
  - Locate 0.72 (original power factor) in column (1).
  - Read across desired power factor to 0.95 column. We find 0.635 multiplier
  - Multiply 627 (average kW) by 0.635 = 398 kVAr.
  - Install 400 kVAr to improve power factor to 95%.

- The advantages of PF improvement by capacitor addition are as follows:
  - Reactive component of the network is reduced and so also the total current in the system from the source end.
  - I2R power losses are reduced in the system because of reduction in current.
  - Voltage level at the load end is increased.
  - kVA loading on the source generators as also on the transformers and lines upto the capacitors reduces giving capacity relief. A high power factor can help in utilising the full capacity of your electrical system.

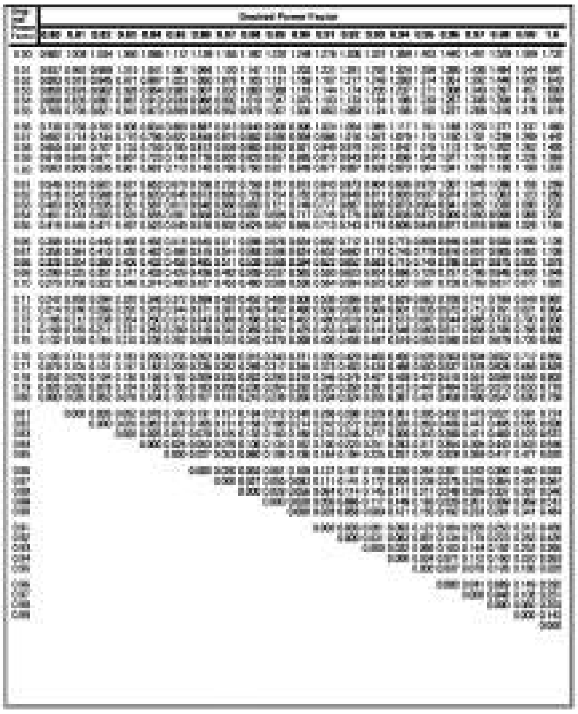

Table 1.2 Multipliers to determine capacitor kVAr requirements for power factor correction

1.13 Leading and Lagging Power Factor

Leading Power Factor	Lagging Power Factor
When the Current in an AC Circuit is leading the voltage in waveform, the power factor is called the leading power factor.	When the Current in an AC Circuit is lagging the voltage in waveform, the power factor is called the lagging power factor.
The leading power factor is caused when the net load is capacitive in nature.	The lagging power factor is caused when the net load is inductive in nature.

- The inductive and capacitive loads cancel each other while responding to an electric supply. Since a majority of the loads by nature are inductive, the best way to improve the power factor is to add capacitors.
- The obvious advantages of improving the power factor are:
  - Reduction in distribution losses.
  - Improvement in voltage.

1.14 Position of Power Factor Correction Capacitors

- The ideal location for capacitors is to provide them as close to the point of utilisation as possible.

- Locations C1A, C1B and C1C of Figure 1.6 indicate three different arrangements at the load. Note that in all three locations extra switches are not required, since the capacitor is either switched with the motor starter or the breaker before the starter. Case C1A is recommended for new installation, since the maximum benefit is derived and the size of the motor thermal protector is reduced. In Case C1B, as in Case C1A, the capacitor is energized only when the motor is in operation. Case C1B is recommended in cases where the installation already exists and the thermal protector does not need to be re-sized. In position C1C, the capacitor is permanently connected to the circuit but does not require a separate switch, since capacitor can be disconnected by the breaker before the starter.

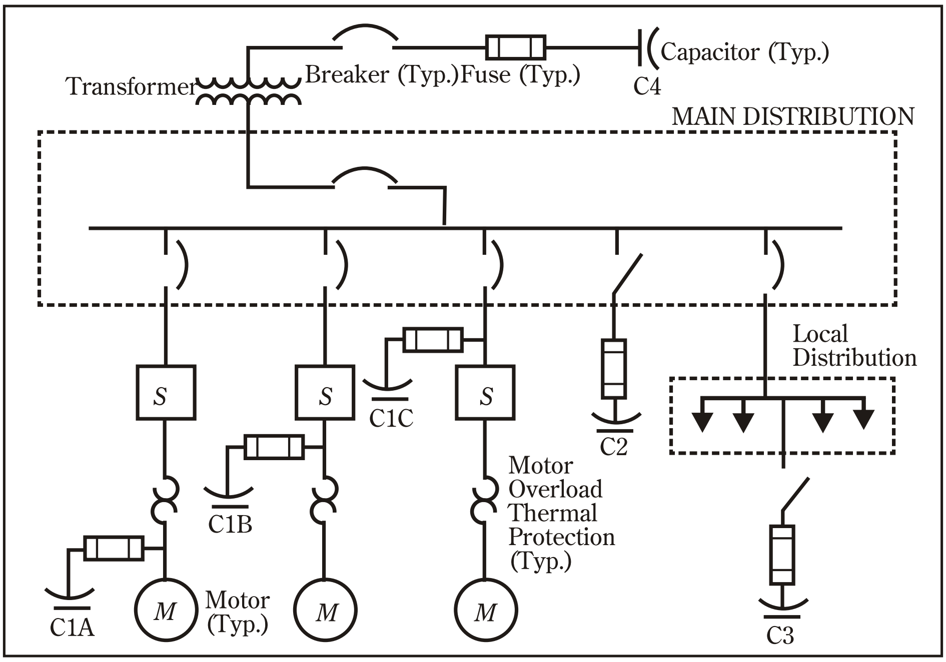

Fig. 1.6 Power distribution diagram illustrating capacitor locations

- But there are certain practical difficulties.
  - Introduction of capacitors demands a cutting out device which will disconnect them from the live circuit as soon as the main equipment is switched off. In short, if one is using a power factor correction capacitor for a furnace, as soon as the furnace is switched off, the capacitor also should be switched off.
  - If not done, this may result in either the power factor going to the leading side but less than unity again. Moreover it may also result in voltage surges which may damage the installation.
  - Hence installing capacitors for each individual equipment becomes expensive and may work out to be uneconomical.
- On the other hand, installing capacitors right at the receiving point will benefit only in reducing Maximum Demand and the distribution losses down the line will not be reduced. Hence, one has to judiciously work out a cost benefit analysis for each location of the capacitors and take an appropriate decision.

1.15 Performance Assessment of Power Factor Correction Capacitors

- Once the power factor capacitors are installed, they continuously need to be monitored for their performance. Their performance depends on voltage as well as ambient temperature. They too have an internal loss called Tan Delta loss.
- The capacitor before failing totally, gives a number of indications showing the deterioration of their performance. This can be monitored by recording the daily reading or hourly reading of the consumption and power factor by the user. However specialised testing can be done by the manufacturer to know the exact reason for the failure.

1.16 Transformer

- The transformer is one of the most widely used electrical equipment. The main function of the transformer is to either increase voltage or to reduce voltage. The Indian Standard IS 2026 (part-1) of 1997 covers transformers in detail. There are a few parameters of a transformer which need to be understood. The voltage ratio is the ratio of Output Voltage/Input Voltage. This is also called Secondary Voltage/Primary Voltage. When voltage is reduced, the current output increases with the same ratio. Alternatively when voltage is increased, the current output decreases with the same ratio.
- A typical transformer is shown below.

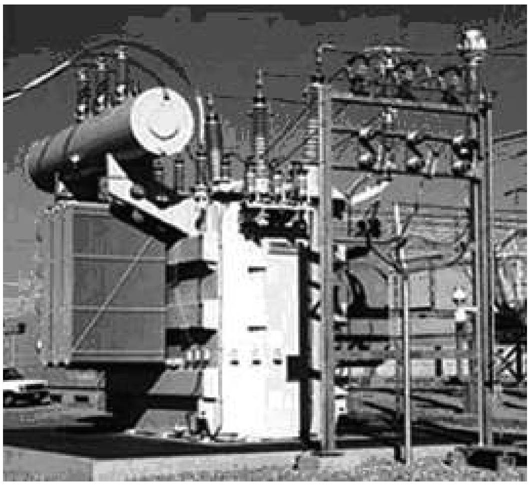

Fig. 1.7 View of a transformer

- A transformer requires cooling which is either by using oil or air. The following types of cooling are generally indicated on transformer nameplates.
  - ONAN: Means oil is cooled by natural convection and air cooling is also cooled by natural convection.
  - ONAF: Means oil is cooled by natural convection and air cooling is by forced circulation.
  - OFAF : Means both oil and air cooling are by forced circulation.
- Transformer performance depends on losses it suffers during no load operation and full load operation.
- Transformers are classified in two categories:
- Power transformers are used in the transmission network for higher voltages, deployed for step-up and step-down transformer applications (400 kV, 200 kV, 110 kV, 66 kV, 33kV).
  - Distribution transformers are used for lower voltage distribution networks as a means to end user connectivity (11kV, 6.6 kV, 3.3 kV, 440V, 230V).

1.17 Rating and Location of the Transformer

Rating of the transformer:

Rating of the transformer is calculated based on the connected load and applying the diversity factor on the connected load, applicable to the particular industry and arriving at the kVA rating of the Transformer. The diversity factor is defined as the ratio of overall maximum demand of the plant to the sum of individual maximum demand of various equipments.

- The diversity factor varies from industry to industry and depends on various factors such as individual loads, load factor and future expansion needs of the plant. The diversity factor should always be less than one.

Location of the Transformer:

Location of the transformer is very important as far as distribution losses are concerned. A transformer receives HT voltage from the grid and steps it down to the required voltage. Transformers should be placed close to the load centre, considering other features like optimisation needs for centralised control, operational flexibility, etc. This brings down distribution losses in cables.

1.18 Losses and Efficiency of a Transformer

- The efficiency varies anywhere between 96 to 99 percent. The efficiency of transformers not only depends on the design, but also, on the effective operating load.
- Transformer losses consist of two parts:
  - No-load loss
  - Load loss
- No-load loss (also called core loss) is the power consumed to sustain the magnetic field in the transformer's steel core. Core loss occurs whenever the transformer is energised; core loss does not vary with load. Core losses are caused by two factors: hysteresis and eddy current losses. Hysteresis loss is that energy lost by reversing the magnetic field in the core as the magnetising AC rises and falls and reverses direction. Eddy current loss is a result of induced currents circulating in the core.
- Load loss (also called copper loss) is associated with a full-load current flow in the transformer windings. Copper loss is power lost in the primary and secondary windings of a transformer due to the ohmic resistance of the windings. Copper loss varies with the square of the load current (P=I2R).
- Transformer losses as a percentage of load are given below:

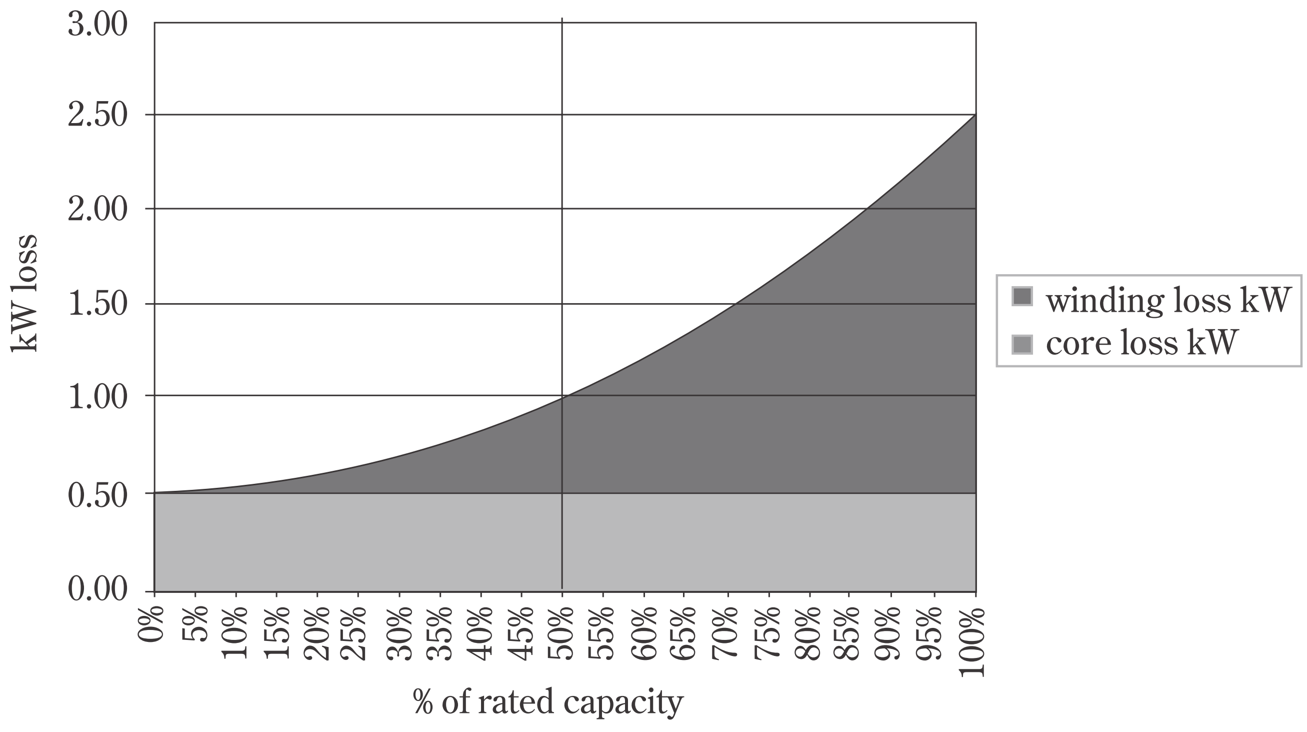

Fig. 1.8 Losses in a transformer

- For a given transformer, the manufacturer can supply values for no-load loss, PNO-LOAD, and load loss, PLOAD. The total transformer loss, P TOTAL , at any load level can then be calculated from:
- PTOTAL = P NO-LOAD + (%Load/100)2 x PLOAD
- Where transformer loading is known, the actual transformer loss at a given load can be computed as;
- No Load Loss + kVALoad/Rated kVA)2 x (Full Load Loss)

1.19 Control Used for Voltage Fluctuation

- The control of voltage in a transformer is important due to frequent changes in the supply voltage level. Whenever the supply voltage is less than the optimal value, there is a chance of nuisance tripping of voltage sensitive devices. Voltage regulation in transformers is done by altering the voltage transformation ratio with the help of tapping.

- There are two types of tap changing facility available:
  - the Off-circuit tap changer
  - the On-load tap changer
- The Off-circuit tap changer:

It is a device fitted in the transformer, used to vary the voltage transformation ratio. Here the voltage levels can be varied only after isolating the primary voltage of the transformer.

- The On-load tap changer (OLTC)
  - Voltage levels can be varied without isolating the connected load to the transformer. To minimise the magnetisation losses and to reduce the nuisance tripping of the plant, the main transformer (the transformer that receives supply from the grid) should be provided with an On-load Tap Changing facility at the design stage.
- Down stream distribution transformers can be provided with an off-circuit tap changer.
- The On-load gear can be put on the auto mode or the manual, depending on the requirement. The OLTC can be arranged for transformers of size 250 kVA onwards. However, the necessity for an OLTC below 1000 kVA can be considered after calculating the cost economics.

1.20 The Parallel Operation of Transformers

- The design of the Power Control Centre (PCC) and the Motor Control Centre (MCC) of any new plant should have the provision for operating two or more transformers in parallel. Additional switchgears and bus couplers should be provided at the design stage.
- Whenever two transformers are operating in parallel, both should be technically identical in all aspects and more importantly should have the same impedance level. This minimises the circulating current between transformers.
- Where the load is fluctuating in nature, it is preferable to have more than one transformer running in parallel, so that the load can be optimised by sharing it between transformers. The transformers can be operated close to the maximum efficiency range by this operation.

Summary

- Electricity is generated from various sources such as thermal power stations, hydroelectric power stations, nuclear power stations and renewable sources. The performance of a Thermal Power station is measured in terms of the specific heat ratio kCal per kWH generated. Lower the ratio better is the performance of the plant.
- Electricity is the most popular form of energy because it can be easily transmitted, controlled, measured and utilised. It is also the cleanest form of energy.
- The different equipment used in electricity generation are turbines, alternators, etc. The transmission equipment used is Step up Transformers, Transmission Towers, Overhead Conductors, Insulators, Circuit Breakers and other protective equipment, etc. Distribution equipment includes Distribution Transformers, Circuit breakers, Overhead wires and Cables, etc.
- Electrical engineers use a graphical representation to express power flow and various equipments used to indicate the complete electrical installation. This is represented by one line though most of the circuits are three phase. These diagrams are called single line diagrams.
- The power factor represents the utilisation rate of power transferred from one place to the other. The power transferred is measured in terms of kVA whereas utilisation is measured in terms of kW. The ratio of kW to kVA is given as power factor. Most of the transmission equipments such as transformer, circuit breakers are designated by the kVA capacity whereas utilisation equipment such as motors, etc. is designated by kW. The unity power factor represents that utilization is at the maximum with its best performance and hence the power factor should be as close to unity as possible.
- Capacitors improve the power factor, but their location has to be very judicious. The transformer is electrical equipment which helps to either increase voltage or to reduce voltage. The Indian Standard IS 2026 (part-1) of 1997 covers transformers in detail
- The voltage control in a transformer is important due to frequent changes in the supply voltage level. Voltage regulation in transformers is done by altering the voltage transformation ratio with the help of tapping.
- The last part of the chapter talks about the parallel operation of transformers. Whenever two transformers are operating in parallel, both should be technically identical in all aspects and more importantly should have the same impedance level. This minimises the circulating current between transformers.

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Self assessment

1. _______________is the sum of the nameplate ratings of all the equipments utilising electricity inside the consumer installation
   a. Associated load
   b. Coupled load
   c. Connected load
   d. Reconnected load

2. Electrical engineers use a graphical representation to express power flow and various equipment used to indicate the complete electrical installation. This is represented by one line though most of the circuits are three phase. These diagrams are called ___________.
   a. block diagrams
   b. flat diagrams
   c. bold line diagrams
   d. single line diagrams

3. Which of the following sentences is false?
   a. Capacitors improve the power factor, but their location has to be very judicious.
   b. Capacitors degenerates the power factor, but their location has to be very judicious.
   c. Capacitors deteriorates the power factor, but their location has to be very reckless.
   d. Capacitors worsen the power factor, but their location has to be very inattentive.

4. The electrical equipment which helps to either increase voltage or to reduce voltage is called ________.
   a. a capacitor
   b. a transformer
   c. an alarm
   d. a meter

5. The maximum demand of an industry, if trivector motor records 3600 kVA for 15 minutes and 3000 kVA for next 15 minutes over a recording cycle of 30 minutes is__________.
   a. 3600 kVA
   b. 3000 kVA
   c. 3300 kVA
   d. 600 kVA

6. ___________is a term used for sending electricity from substations where it is transmitted and is received and then distributed to various points of utilisation.
   a. Distribution
   b. Generation
   c. Transmission
   d. Production

7. The demand mutually agreed between the supply company and the consumer by way of a signed contract is called _____________.
    a. Contracted Minimum Demand (CMD)
    b. Contracted Maximum Demand (CMD)
    c. Convention Maximum Demand (CMD)
    d. Convention Minimum Demand (CMD)

8. Power Factor is a ratio of _________.
    a. reactive power to total power
    b. active power to total power
    c. total power to reactive power
    d. active power to total power

9. Match the following

1. Leading power	A. The net load is inductive in nature
2. Power factor	B. The net load is capacitive in nature
3. Transformer	C. Always less than or equal to unity
4. Lagging power	D. Used to either increase voltage or to reduce voltage

    a. 1-A, 2-B, 3-C, 4-D
    b. 1-C, 2-D, 3-A, 4-B
    c. 1-B, 2-C, 3-D, 4-A
    d. 1-D, 2-A, 3-B, 4-C

10. The equipment used as a mechanical supporting structure for the ACSR conductor used for the transmission of electrical energy is known as _________.
    a. transmission tower
    b. CT/PT
    c. transformer
    d. breaker

Chapter II

Electric Motors

Aim

The aim of this chapter :

- enlist the types of electric motors
- explain the losses in induction motor
- explicate motor efficiency

Objectives

The objectives of the chapter are:

- explain the losses in motor efficiency
- enlist the factors affecting motor performance, rewinding and motor replacement issues
- explicate energy saving opportunities with energy efficient motors

Learning outcome

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

- define the types of electric motors
- understand the concept of rewinding and motor replacement issues
- comprehend the importance of energy saving opportunities with energy efficient motors

2.1 Introduction

Motors convert electrical energy into mechanical energy by the interaction between the magnetic fields set up in the stator and rotor windings. Electric motors are undoubtedly the largest prime movers used. Industrial electric motors can be broadly classified as:

- induction motors
- direct current motors
- synchronous motors

All motor types have the same four operating components which are:

- stator (stationary windings)
- rotor (rotating windings)
- bearings
- frame (enclosure)

2.2 Types of Motors

There are various types of motors depending on types of construction. Due to difference in construction and their design their applications also vary from process to process. There is a continuous technological development in the motor technology and hence many types get outdated too.
As we have seen there are two types of electric supply. Similarly to suit each of them there are two types of motors:

- DC Motors
- AC Motors

Industrial electric motors are generally classified as:

- direct current motors (DC motors)
- synchronous motors (AC motors)
- induction motors (induced magnetic field)

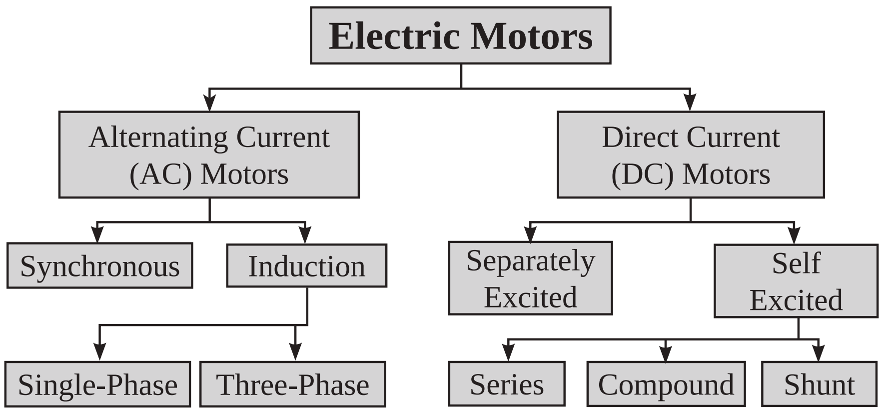


Fig. 2.1 Classification of the main types of electric motors

2.2.1 Direct Current Motors (DC Motors)

DC motors were the first to be developed. They have a stationary field winding housed in a stator and rotating armature called rotor. The rotor winding rotate in front of alternating rotor poles, north and south poles. This tries to reverse the current in the winding. To overcome this problem, a commutator and brush arrangement is provided. Depending on the field and armature connections, the motors are classified into different categories:

- Separately Excited Motor
- Self excited motor

- Series Motor
- Compound motor
- Shunt Motor

Since these motors give different torque and speed characteristics, they are used for different applications. Example, series motors are invariably used in DC traction systems. Separately excited motors are used for applications where a high starting torque is required and also where jamming is likely to take place and sudden torque requirement is likely to go up to 250% of full load torque. The speed control of DC Motors is quite linear and accurate. The torque offered is uniform over the entire speed range. Because of these characteristics, they are still preferred in some of the applications.

The main advantage of DC motors is speed control, which does not affect the quality of power supply. It can be controlled by adjusting:

- The armature voltage – increasing the armature voltage will increase the speed
- The field current – reducing the field current will increase the speed

The disadvantages of these motors are mainly their initial cost and maintenance of brushes and the commutator. Moreover they require a separate cooling arrangement.

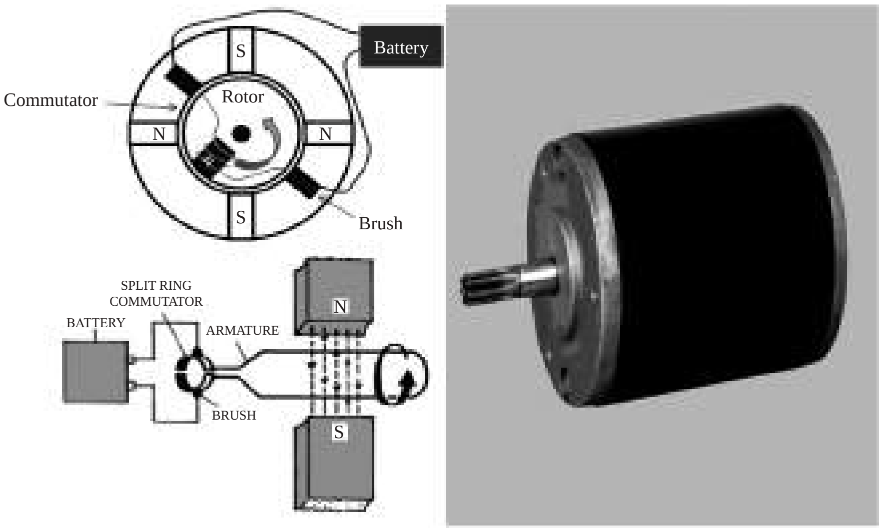


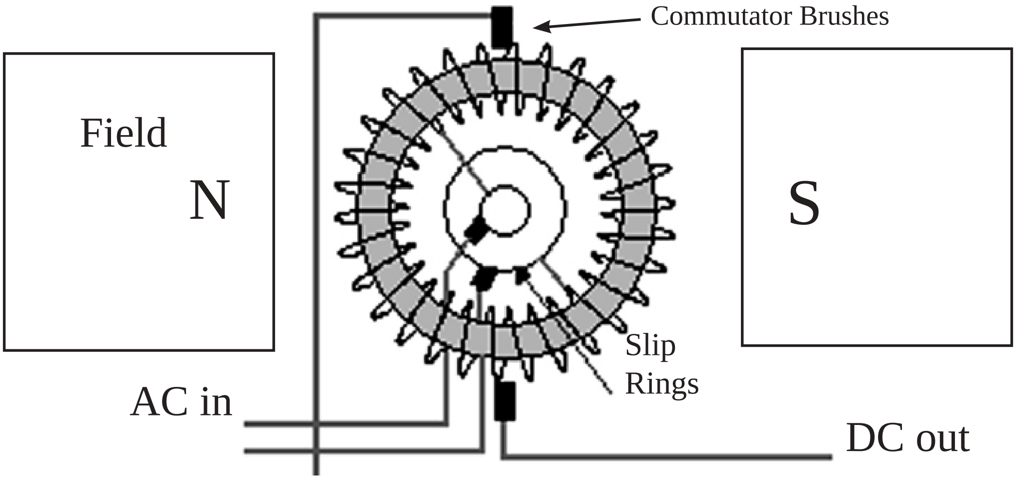
Fig. 2.2 Direct current motors (DC motors)

2.2.2 Synchronous Motors

- In these motors, the stator is given a three phase A.C. supply. The Rotor is given a DC supply through brushes and slip rings. The stator produces a rotating magnetic field and the rotor field is locked into the synchronism of the rotating magnetic field.
- The speed of rotation is equal to:

  Synchronous Speed (RPM) = (120 x Frequency) ÷ No. of poles

- The synchronous motor is not a self-starting motor. It has to be prepared to a speed near the synchronous speed so that the rotor gets locked with the stator rotator magnetic field. At one point of time in the history of technology, this motor was quite popular.
- The main advantage of this motor was that by controlling the rotor excitation, the power factor of the motor could be controlled and the motor could be made to operate with a leading power factor. Hence in the olden days when a combination of the induction motor and the static capacitor was not available, one big synchronous motor was provided to control the power factor of the entire electrical installation. They were even referred to as synchronous condensers rather than motors.
- The evident disadvantages of this motor were:
  - the slip ring and brush maintenance and provision for the prime mover
  - the initial cost of these motors also was high. But these days nobody opts to use these motors.



Single-phase synchronous converter

Fig.2.3 Synchronous motors

2.2.3 Induction Motors

- Induction motors are the most commonly used prime mover for various equipments in industrial applications. In induction motors, the induced magnetic field of the stator winding induces a current in the rotor. This induced rotor current produces a second magnetic field, which tries to oppose the stator magnetic field, and this causes the rotor to rotate.
- There are two types of Induction Motors.
    - the Slip Ring Induction Motor
    - the Squirrel Cage Induction Motor

The slip ring induction motor

- In this motor, the stator is given a three phase A.C. supply. The rotor is shorted outside through slip rings and brushes. Since the rotor connection is brought outside, an initial resistance for the higher starting torque can be introduced and as the motor picks up speed, the resistance is slowly reduced and eventually shorted to make it zero.
- This arrangement ensures that a starting torque of as much as 250% of full load torque can be obtained. This type of an arrangement is very common for loads like ball mill, hammer mills, etc.
- The disadvantage of this motor is the slip ring and brush maintenance.

The squirrel cage induction motor

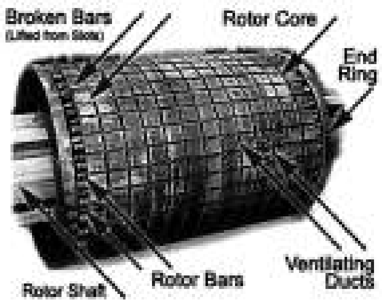
- A squirrel cage rotor is the rotating part used in the most common form of AC induction motor. An electric motor with a squirrel cage rotor is termed a squirrel cage motor. By far, this type of motor has the largest population in industry.
- In overall shape, it is a cylinder mounted on a shaft. Internally it contains longitudinal conductive bars (usually made of aluminium or copper) set into grooves and connected together at both ends by shorting rings forming a cage-like shape. The name is derived from the similarity between this rings-and-bars winding and a squirrel cage.
- In this motor the stator is given a three phase A.C. supply. The rotor is shorted inside through copper rings at either ends. When the stator is given a supply, it produces a rotating magnetic field which rotates at synchronous speed. The rotor then starts rotating; trying to achieve the synchronous speed but it can never achieve it. The difference between actual speed and the synchronous speed is called slip. The slip, when represented in terms of percentage with respect to synchronous speed is called percent slip.

The formula is as follows:

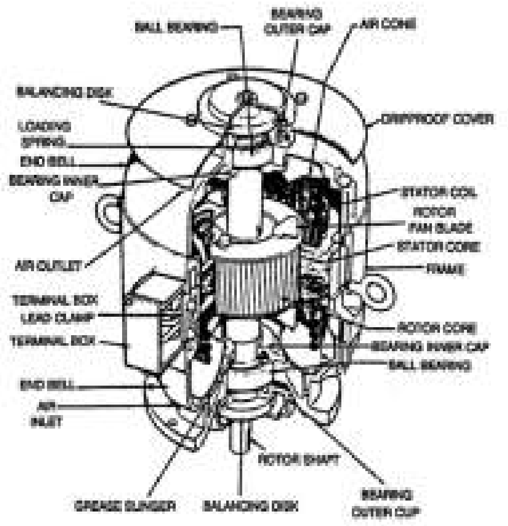
$$\textbf{Slip (\%)} = \frac{\textbf{Synchronous speed - Full load rated speed} \times 100}{\textbf{Synchronous speed}}$$

From the above points, one must remember the following facts:

- the number of poles available in a machine will be 2,4,6,8, and so on.
- since the Indian Standard for frequency is 50 Hz, the synchronous speeds available are 3000, 1500, 1000,750 RPM.
- if a 4 Pole Induction Motor is running at 1470 RPM, the slip will be 30 and percent slip will be 2%.
- the advantages of these motors are simple construction, wide variety in application, practically no maintenance.



Squirrel Cage Induction motor



Squirrel Cage Induction motor

Slip Ring induction motors

Fig.2.4 Types of induction motors.

- Squirrel cage induction; (b) Slip ring induction motor

2.3 The Power Factor

- The power factor of the motor is given as:

$$\textbf{Power factor} = \textbf{Cos}\varphi = \textbf{kW/kVA}$$

- As the load on the motor comes down, the magnitude of the active current reduces. However, there is no corresponding reduction in the magnetizing current, which is proportional to supply voltage with the result that the motor power factor reduces, with a reduction in applied load. Induction motors, especially those operating below their rated capacity, are the main reason for low power factor in electric systems.

2.4 Name Plate

- Every motor leaves the factory with a specific nameplate. The nameplate contains information about the motor.

- The parameters mentioned which are useful to understand the performance of the motor are:
  - rated voltage
  - rated current
  - rated power output
  - rated speed
  - number of poles
  - connection
  - rated power factor
  - rated efficiency
- Since each parameter is measured at a different point, one has to understand the nameplate well. The following Table 2.1 will be quite helpful.

Parameter	Point
Rated Voltage	Stator Input Supply
Rated Current	Stator Input Supply Current. This will occur when the motor is loaded fully to its rated output and rated supply voltage is applied
Rated Power Output	This is shaft power. This will occur when the full mechanical load is applied to the shaft
Rated Speed	This is shaft speed and will occur when the motor is fully loaded.
Number of Poles	This will decide synchronous speed
Connection	Star or Delta. This will decide the stator winding connections.
Rated Power Factor	This will occur when the motor is loaded fully and will occur at the stator input
Rated Efficiency	This will occur when the motor is loaded fully and will indicate Mechanical Output Power at Shaft / Input Electrical Power

Table 2.1 Name plate parameters of a motor

- Since it is not possible to load every motor at all times to operate at its rated capacity, most of the motors operate at partial loading and hence it becomes necessary to study motor performances when they are partially loaded.
- It is at this stage of partial load that the performance of the induction motor is highly unpredictable and needs proper analysis to come to a definite conclusion so that energy can be saved.

2.5 Motor Load

- Because the efficiency of a motor is difficult to assess under normal operating conditions, the motor load can be measured as an indicator of the motor's efficiency. As loading increases, the power factor and the motor efficiency increase to an optimum value at around full load.

The following equation is used to determine the load:

Load = $Pi \times \eta / HP \times 0.7457$

Where,

- η = Motor operating efficiency in %
- HP = Nameplate rated horse power
- Load = Output power as a % of rated power
- Pi = Three phase power in kW

The load is measured in three steps:

- Step 1. Determine the input power using the following equation:

$$Pi = \frac{V \times I \times PF \times \sqrt{3}}{1000}$$

Where,

- Pi = Three phase power in kW
- V = RMS (root mean square) voltage, mean line to line of 3 phases
- I = RMS current, mean of 3 phases
- PF = Power factor as a decimal

It is noted that power analysers give the power value directly. Industries that do not have a power analyser can use multi-meters or tong-testers to measure voltage, current and power factor separately to calculate the input power.

- Step 2. Determine the rated power by taking the nameplate value or by using the following equation:

$$\mathbf{Pr = (hp \times 0.7457)/n_r}$$

  - Where,
  - Pr = Input power at full-rated load in kW
  - HP = Nameplate rated horse power
  - ηr = Efficiency at full-rated load (nameplate value or from motor efficiency tables)

- Step 3. Determine the percentage load using the following equation:

$$\mathbf{Load = (Pi / Pr) \times 100\%}$$

Where,

- Load = Output power as a % of rated power
- Pi = Measured three phase power in kW
- Pr = Input power at full-rated load in kW

2.6 Motor Efficiency and its Losses

- Electrical Motor Efficiency when Shaft Output is measured in Watt is given as;

If power output is measured in Watt (W), efficiency can be expressed as:

$\eta m = Pout / Pin$

Where

- ηm = motor efficiency
- Pout = shaft power out (Watt, W)
- Pin = electric power in to the motor (Watt, W)

- Thus, if one can concentrate on assessing losses and trying to reduce them, then too efficiency can be increased. Hence it is pertinent to study what losses do occur in a motor.
- The losses can be generally classified into two categories:
  - Fixed losses
  - Variable losses
- Fixed losses are those which occur in the motor irrespective of the quantum of load. These are also called no load losses.
- Variable losses are those which are dependent on the quantum of the load. Since the current drawn by the motor is a function of the load, both stator and rotor copper losses are variable losses. They occur by way of heat loss equal to I2R where I represent the current and R represents the resistance. Hence they are dependent on stator and rotor resistance. The value of stator resistance in turn is dependent on temperature.

- The variation of resistance with respect to temperature is governed by the relation:

$$\frac{R_1}{R_2} = \frac{235 + t_2}{235 + t_1}$$

Where,
t_1 = ambient temperature in °C
t_2 =operating temperature in °C

- The ambient temperature can be measured by an accurate multimeter or Wheatstone bridge. There are two important tests carried out on the motor, based on which its performance at partial load can be calculated with the help of a circle diagram.
- No Load Test : This test gives the fixed losses of the motor. The motor is run in a decoupled condition by applying the rated voltage and parameters like current and wattage are measured.
- Blocked Rotor Test:
  - For this test, the rotor is blocked and with reduced voltage a full load rated current is circulated through the stator. At this time, voltage applied is measured along with the power drawn i.e. wattage. These parameters are extrapolated for full load voltage and based on the extrapolated parameters; a diagram is drawn called the Circle Diagram.
  - Once the circle diagram is drawn, the performance of the motor at any partial load can be assessed. But this method is used in the design office or at the test bed and is rarely used at site.
  - The mechanical losses such as friction and windage losses are fixed losses dependent on bearings and aerodynamic losses associated with the ventilation fan and other rotating parts.
  - Stray load losses are difficult to measure and are taken as a thumb rule based on certain standards.

2.7 Factors Affecting Motor Performance

- Motor performance depends on:
  - Partial load operation
  - Correct Application of the drive to suit the application
  - Application of rated voltage and frequency
- The performance of an induction motor on partial load can be seen from the following graph. It will be observed that the best performance of the motor is nearer the rated output. The power factor is also improved as the load approaches the rated load. Hence the performance of the motor depends very much on the load on the motor. Thus loading a 10 HP motor with 9 HP load is far superior than loading a 15 HP motor with 9HP load.
- In that case, it is worthwhile to replace a 15 HP motor with a 10 HP Motor. The economics of replacement will always be in favour of replacement which will ensure near rated load operations.

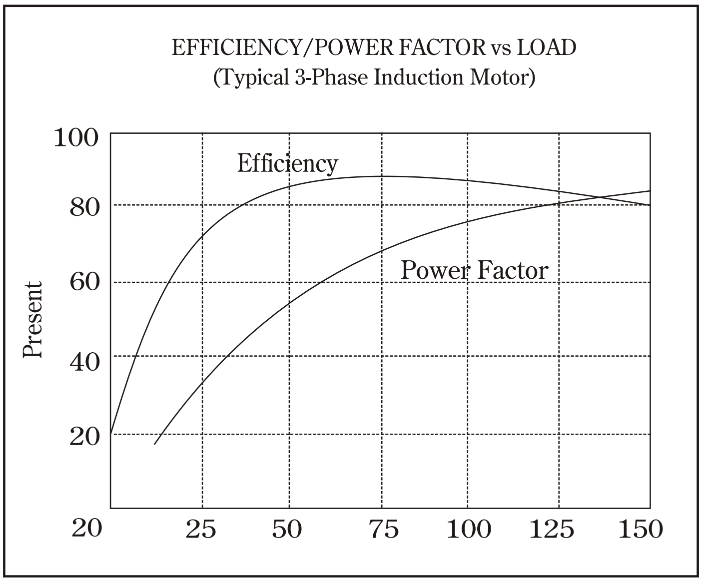


Fig.2.5 Efficiency and power factor vs. percent load

2.8 Rewinding and Motor Replacement Issues

- It is a general exercise in industry to rewind burnt-out motors. Many a times during the maintenance of motors, one has to encounter rewinding of motors. The rewound motors seldom give the same performance as original motors. This is mainly because:
  - The gauge of the wire used for rewinding is rarely the same
  - The characteristics do not remain the same after rewinding
  - No load motor and full load current also undergo change
- Due to this every time a motor is rewound, its useful life is affected and the next rewinding is advanced. Hence a stage comes when replacement is more economical that rewinding. Hence motors rewound must be checked thoroughly before loading them to the original loading pattern.
- One standard method is to measure the stator winding resistance before and after rewinding. It is also a good practice to keep a record of the no. load current prior to and after rewinding. These two parameters do speak about the condition of the rewound motor. Infact in many factories, the payment of the rewinding contractor is linked with these two parameters and the motor is rejected after rewinding if the no load current exceeds the predefined value.

2.9 Energy Saving Opportunities with Energy Efficient Motors

- Energy-efficient motors (EEM) are the ones in which, design improvements are incorporated specifically to increase operating efficiency over motors of standard design. It is important to know what an EEM is, as it takes care of the shortfall in efficiency. Energy Efficient Motors were defined by National Electrical manufacturers association (NEMA) in the U.S.A, first under the Energy Policy Act and then the trend was followed by other countries.
- Bureau of Indian Standards (BIS) defines EEM as those which operate without loss of efficiency from 75% load to 100% load. Moreover the mounting and overall dimensions are designed as per IS 1231, making it easier to replace the standard performance motors with EEM.
- While selecting a motor for any application, an engineer should keep a margin of about 20% in motor rating. EEM automatically takes care of this shortfall in efficiency. Many a times economics has proved that even an existing running standard performance motor can be replaced with an EEM with a payback period of as low as 18 months.

- The figure below shows the comparison of EE and SP motors:

EFFICIENCY/POWER FACTOR vs LOAD
(Typical 3-Phase Induction motor)

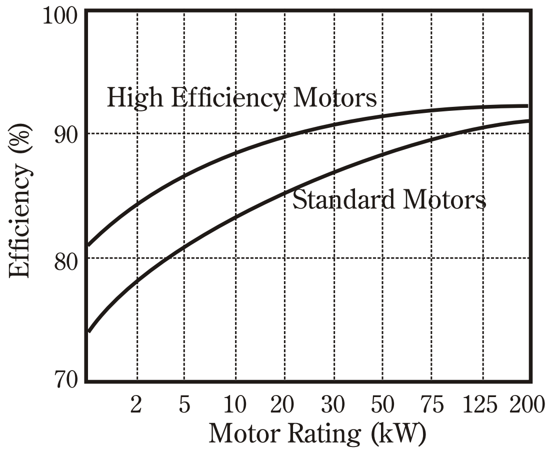


Fig.2.6 Comparison of efficiency - high efficiency motor vs. standard motor

- It is important to know how EEM are different from SP motors. As we have seen, efficiency can be improved by reducing standard losses. Thus EEM are designed so that these losses are reduced.
- Table 2.2 describes the improvement opportunities that are often used in the design of energy efficient motors.

Power Loss Area	Efficiency Improvement
Stator and Rotor Copper Losses	These losses are reduced by using copper instead of aluminium wherever possible.
Magnetic Losses of the Stator	are reduced by reducing the air gap
Core losses	Reduced by using thinner material. Also low loss silicon steel is adopted.
Friction and Windage losses	Reduced by using better bearings and better cooling fans.
Stray losses	Reduced by better designing geometry of the motor

Table 2.2 Efficiency improvement areas used in EEM (source BEE india, 2004)

Summary

- Motors convert electrical energy into mechanical energy by the interaction between the magnetic fields set up in the stator and rotor windings.
- DC Motors were the first to be developed. They have a stationary field winding housed in a stator and rotating armature called rotor.
- DC motors are classified into different categories: Separately Excited Motor and Self excited motor. Self excited motors are of three types.
- The synchronous motor is not a self-starting motor. It has to be prepared to a speed near the synchronous speed so that the rotor gets locked with the stator rotator magnetic field. At one point of time in the history of technology, this motor was quite popular.
- Induction motors are the most commonly used prime mover for various acquirements in industrial applications.
- The Slip Ring Induction motor, the stator is given a three phase A.C. supply. The rotor is shorted outside through slip rings and brushes. A squirrel cage rotor is the rotating part used in the most common form of AC induction motor. An electric motor with a squirrel cage rotor is termed a squirrel cage motor. By far, this type of motor has the largest population in industry.
- The difference between actual speed and the synchronous speed is called slip. The slip, when represented in terms of percentage with respect to synchronous speed is called percent slip.
- Every motor leaves the factory with a specific nameplate. The nameplate contains information about the motor.
- Because the efficiency of a motor is difficult to assess under normal operating conditions, the motor load can be measured as an indicator of the motor’s efficiency. As loading increases, the power factor and the motor efficiency increase to an optimum value at around full load.
- The losses can be generally classified into two categories; fixed losses and Variable losses.
- Fixed losses are those which occur in the motor irrespective of the quantum of load. These are also called no load losses.
- It is a general exercise in industry to rewind burnt-out motors. Many a times during the maintenance of motors, one has to encounter rewinding of motors. The rewound motors seldom give the same performance as original motors.
- Energy-efficient motors (EEM) are the ones in which, design improvements are incorporated specifically to increase operating efficiency over motors of standard design. It is important to know what an EEM is, as it takes care of the shortfall in efficiency.

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Self Assessment

1. Which motors have the disadvantages of their initial cost and maintenance of brushes and the commutator?
   a. DC motors
   b. AC motors
   c. Induction motors
   d. Magnetic motors

2. ___________convert electrical energy into mechanical energy by the interaction between the magnetic fields set up in the stator and rotor windings.
   a. Compressors
   b. Transistors
   c. Motors
   d. Circuits

3. The difference between actual speed and the synchronous speed is called a _________.
   a. slide
   b. glide
   c. trip
   d. slip

4. ____________are the ones in which, design improvements are incorporated specifically to increase operating efficiency over motors of standard design.
   a. Energy-efficient motors
   b. Bureau of Indian Standards
   c. National Electrical manufacturers association
   d. Partial load operation

5. The synchronous speed of a motor with 6 poles and operating at 50 Hz frequency is _______.
   a. 1500
   b. 1000
   c. 3000
   d. 750

6. The motor load can be measured as an indicator of the __________.
   a. motor’s competence
   b. motor’s proficiency
   c. motor’s ability
   d. motor’s efficiency

7. Which of the following statements is true?
   a. No Load Test gives the fixed gain of the motor
   b. Load Test gives the fixed losses of the motor
   c. No Load Test gives the variable losses of the motor
   d. No Load Test gives the fixed losses of the motor

8. Motor performance does not depend on which of the following factor
    a. Correct Application of the drive to suit the application
    b. Erroneous Application of the drive to suit the application
    c. Application of rated voltage and frequency
    d. Partial load operation

9. Fixed losses are those which occur in the motor irrespective of the ________.
    a. quantum of load
    b. resistance of load
    c. maintenance of load
    d. efficiency of load

10. It is a general exercise in industry to ___________burnt-out motors.
    a. generate
    b. produce
    c. rewind
    d. redraw

Chapter III

Compressed Air System

Aim

The aim of this chapter are:

- explain compressed air systems
- enlist the types of air compressors
- explicate compressor efficiency and its components

Objectives

The objectives of the chapter are:

- define compressed air systems
- explicate efficient compressor operation, capacity assessment and leakage test
- enlist factors affecting performance and efficiency

Learning outcome

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

- identify a compressed air systems
- define the types of air compressors
- understand the concept of efficient compressor operation, capacity assessment and leakage test

3.1 Introduction

- Air compressors account for significant amount of electricity used in Indian industries. Compressed air is an essential but costly utility and its use must be made wisely. Compressed air is generated from compressors which are largely driven by electricity. If efficiency is calculated, only 10% useful energy reaches the end point through compressed air. Thus there is a vast scope for energy saving through proper understanding of the functions of this utility and avoiding its wastage.
- The applications of compressed air are plenty. A few of them can be listed as:
  - operation of solenoid valves plunger
  - operation of pneumatic cylinders
  - instrumentation
  - pneumatic tool
- In the olden days, vast areas of instrumentation including modulating actuators, etc. were operated using compressed air especially 3-15 PSI standards. But slowly, these are being replaced by electronic and electrical drives mainly because of their accuracy, repeatability, maintainability and cost.
- However, there are certain hazardous areas, like the petroleum industry, the mining industry, etc. where even small electrical sparks are not permissible. In such areas it is compulsory to use pneumatic devices.

3.2 Category of Compressors

- Compressors are broadly classified as:
  - Positive Displacement Compressors
  - Dynamic (Centrifugal) Compressors
- The flow and pressure requirements of a given request determine the suitability of a particular type of compressor. These are further classified as:

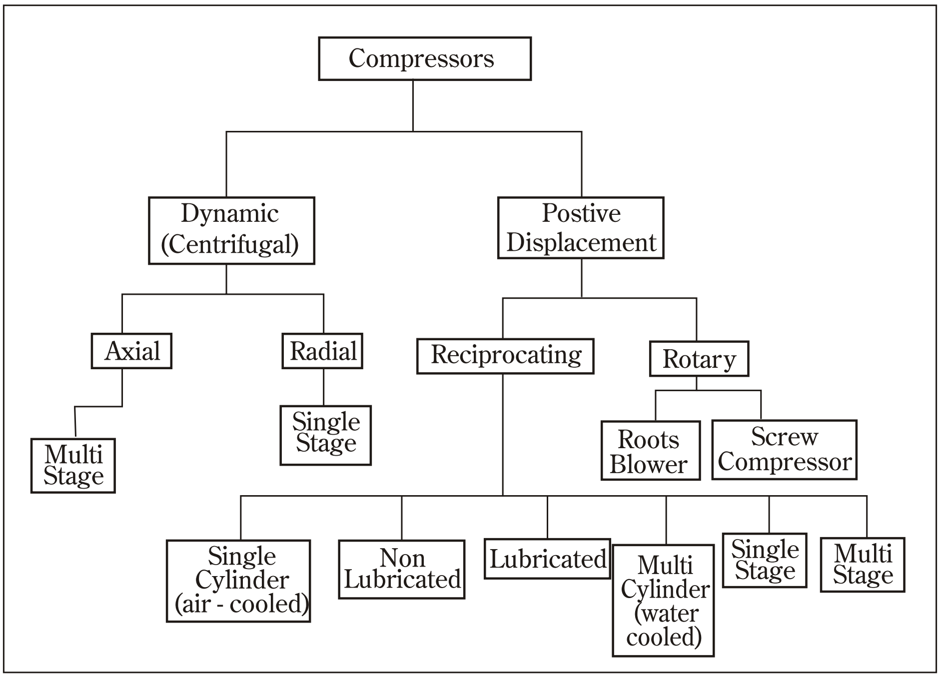

Fig. 3.1 Types of compressors

Positive displacement compressors

The compressors which increase the pressure of the gas by reducing the volume are called positive displacement compressors. These compressors are further classified into:

- reciprocating compressors
- rotary compressors

Reciprocating compressors

Reciprocating compressors are the most widely used compressors. They operate on the cylinder and piston principle. Their flow output remains constant over a wide range of discharge pressures. The capacity is directly proportional to the speed of the prime mover. The output however, is pulsating since in one cycle, air is allowed to enter and in the other it is compressed and discharged. To make this output smooth, a receiver is invariably used. Reciprocating compressors come in variety of types; such as: lubricated and non lubricated, single or multiple cylinder, water or air cooled, single or multi stage reciprocating compressors.

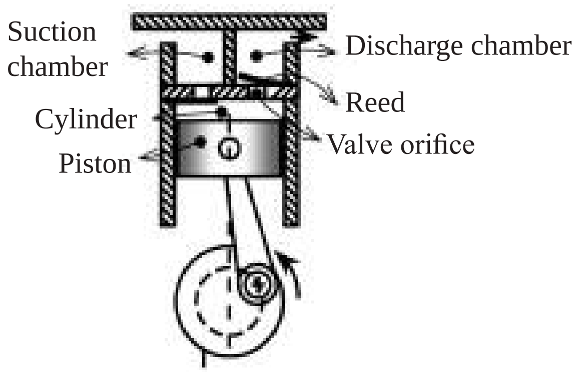

Fig. 3.2 A Typical reciprocating compressor

Rotary compressors

Rotary compressors unlike reciprocating compressors give a uniform flow. They are directly coupled to the prime mover and need less starting torque. Their outputs are higher compared to reciprocating compressors. Mechanically, reciprocating compressors give an imbalance, a thrust and vibrations, hence need heavy foundation. On the other hand, rotary compressors need a simple foundation. These compressors can give a discharge pressure upto 10 bar.

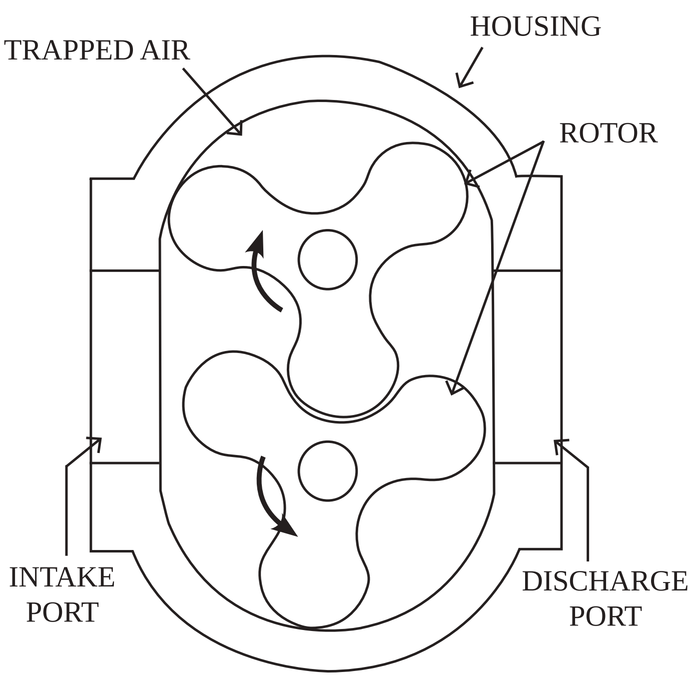

Fig. 3.3 A typical rotary compressor

Dynamic compressors

Dynamic compressors increase the air velocity, which is then converted to increased pressure at the outlet. They are basically centrifugal compressors and are further divided into:

- radial type
- axial flow types

Dynamic compressors operate on similar principles as centrifugal pumps. But one fundamental principle is to be understood. Pumps deal with liquid which is an incompressible fluid. Hence if you throttle output, the discharge is reduced. For air, if you throttle output, the pressure goes up because it gets compressed. This is how a centrifugal compressor operates. Hence these are typically suitable for outputs above 12000 CFM.

Compressors should be selected on the basis of individual requirements but as a general guideline, the given table may be used.

Type of Compressor	Capacity (m3/h)		Pressure (bar)	
	From	**To**	**From**	**To**
Roots blower compressor single stage	100	30,000	0.1	1
Reciprocating				
- Single / Two stage	100	12,000	0.8	12
- Multi stage	100	1,200	12	700
Screw				
- Single stage	100	2,400	0.8	13
- Two stage	100	2,400	0.8	24
Centrifugal	600	30,000	0.1	450

Table 3.1 Compressor selection chart

3.3 Efficiency of a Compressor

Compressor capacity:

Capacity of a compressor is the full rated volume of flow of gas compressed and delivered at conditions of total temperature, total pressure, and composition existing at the compressor inlet. It sometimes means actual flow rate, rather than rated volume of flow. This is also termed as Free Air Delivery (FAD) i.e. air at atmospheric conditions at any specific location. Because the altitude, barometer, and temperature may vary at different localities and at different times, it follows that this term does not mean air under identical or standard conditions.

Compressor efficiency :

Several different measures of compressor efficiency are commonly used: volumetric efficiency, adiabatic efficiency, isothermal efficiency and mechanical efficiency.

- Before going on to the formulae, one must understand that air behaves as per the gas equation:

$PV = mRT$

Where;

P = Pressure
V = Volume
m = Specific Mass
R = Constant
T = Absolute Temperature

Also, there are many thermodynamic processes like the isothermal, the adiabatic, the polytrophic, etc.

- Adiabatic and isothermal efficiencies are computed as the isothermal or adiabatic power divided by the actual power consumption. The figure obtained indicates the overall efficiency of compressor and drive motor.

- As air is compressed, its temperature at the outlet tends to increase. If this temperature is accounted, the calculations become complex and hence for simplicity, efficiency is calculated assuming the temperature remains constant. This efficiency is called Isothermal Efficiency.
- Isothermal power is calculated using the following:

$$\textbf{Isothermal power (kW)} = P_1 \times Q_1 \times \log_e r/36.7$$

Where,
P_1 = Absolute intake pressure kg/ cm^2
Q_1 = Free air delivered m^3/hr.
r = Pressure ratio P_2/P_1

- Since Actual Power can be measured on the electrical side, the Isothermal Efficiency is calculated as:

Isothermal Efficiency= Actual measured input power/Isothermal Power
Normally,manufacturers give the isothermal efficiency.

- Volumetric Efficiency:

Volumetric efficiency = Free air delivered (m^3/min)/Compressor displacement

Compressor Displacement = $\frac{\pi}{4} \times D^2 \times L \times S \times \chi \times n$
Where,
D = Cylinder bore (metre)
L = Cylinder stroke (metre)
S = Compressor speed in rpm
χ = 1 for single acting and 2 for double acting cylinders
n = No. of cylinders

- For practical purposes, the most effective guide in comparing compressor efficiencies is the specific power consumption i.e. kW per volume flow rate , for different compressors.

3.4 Compressed Air System Components

- Apart from the compressor proper, there are certain system components in the compressed air system which also should be understood properly. The most important of these are as follows:
- Intake air filters:

They prevent dust from entering the compressor and are normally specified in terms of microns (indicating the size below which dust cannot be prevented). Example, a 5-micron filter can prevent dust particles above 5 microns size where as cannot stop dust particles lower than 5 microns. Hence before choosing a filter, it is worthwhile to assess the dust conditions in the surroundings.

- Interstage coolers:

During compression the temperature of air increases, especially when multistage compressors are used, each stage needs cooling. Hence coolers are required and they are mostly water-cooled. They need specific attention as per the manufacturer's recommendations.

  - After Coolers: These are used to remove moisture.
  - Air Dryers:

These are used to remove the rest of the moisture which may be left at various locations in the pipelines.

- Moisture Drain Traps:

These are used at the end of piping sections to remove moisture in compressed air. Various types of moisture drain traps are available like manual drain cocks, timer based / automatic drain valves etc.

- Receivers:

Air receivers are provided to be storage and smoothening vital air output - reducing pressure variations from the compressor.

- Each of the components mentioned above, needs to be well-maintained for an overall good performance of the system. See Fig.3.4 for a typical compressed air system components and network.

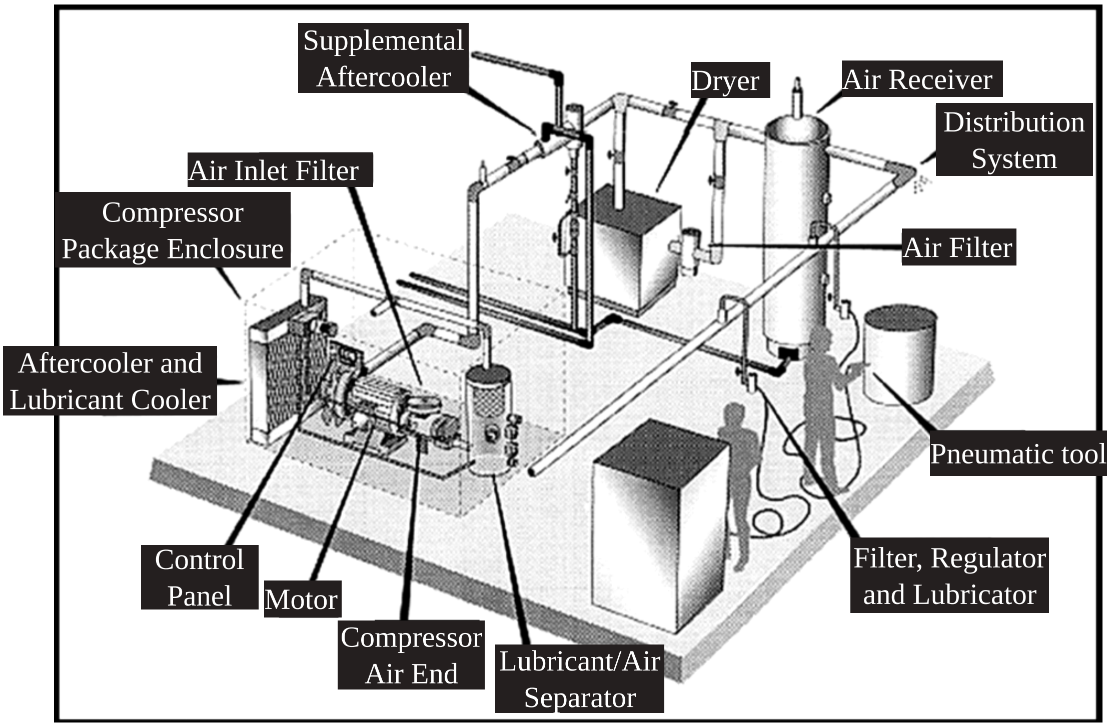

Fig. 3.4 A typical compressed air system components and network

3.5 Efficient Operation of Compressor

- There are a number of issues to be must be considered right at the stage of project planning and also during operation. This will ensure the efficient operation of the compressor. One important issue is the centralised compressor house or distribution system.
- A typical case (example, a cement plant) would explain the situation. In a cement plant, compressed air is required at various places. Apart from this, there is a vehicle workshop at the mines for vehicle maintenance. There is no point in running a compressed air pipeline from a centralised compressor house to the mines workshop. It is worth to provide an independent compressor for the mine vehicle maintenance workshop. Thus, locating a compressor at the proper location is most important since compressors once located cannot be shifted very easily.
- Cool Air Intake: Statistics show that every 40C rise in intake air results in additional 1% power consumption. Hence cool ambient temperature must be provided as intake air. There should be no heat source like a Kiln, Furnace, etc. near the compressor house.
- Dust free air intake is most essential for a compressor. The dust accumulated in the filter should be removed regularly and eventually, the filters must be replaced. There are manometers or pressure switches which will warn about the differential pressure across the filters so that their performance can be watched.
- Dry Air is equally important. Moisture in the air can get converted into water during compressor operations and damage compressor parts.
- The compressor must be operated within the altitude recommended by the manufacturer else its performance will be affected.
- The cooling water circuit should be properly maintained. As explained above, compression results in a rise in temperature and many compressors require intercoolers. The intercoolers are water cooled. They need to be maintained well. Especially the quality and quantity of water should be as per the manufacturer's recommendations.
- Optimum pressure settings should be set for load and unload operations.

3.6 Capacity Assessment of A Compressor

- Unlike electricity, compressed air is not a continuous flowing energy. Example, in a plant if there is no operation of any pneumatic device for one hour the compressed air supplied will only cater to leakages. If there are no leakages during this time, then the compressor will run without compressing air. This operation is called unload.
- During unload operations, the prime mover is running the compressor, but it does not compress air. Thus, it meets only no load losses. The measurement of timings of load and unload operations and power consumption readings will give an idea about the efficiency of operation.
- The ideal method of compressor capacity assessment is through a nozzle test wherein a calibrated nozzle is used as a load, to vent out the generated compressed air. Flow is assessed, based on the air temperature, stabilization pressure, and orifice constant.
- Actual Free air discharge (Q)

$$\mathbf{Q} = \frac{P_2 - P_1}{P_0} \times \frac{V}{T}\ \mathbf{Nm^3/Minute}$$

Where,
P_2 = Final pressure after filling (kg/cm2 a)
P_1 = Initial pressure (kg/cm2a) after bleeding
P_0 = Atmospheric Pressure (kg/cm2 a)
V = Storage volume in m3 which includes receiver, after cooler, and delivery piping
T = Time take to build up pressure to P2 in minutes

- The above equation is relevant where the compressed air temperature is same as the ambient air temperature, i.e., perfect isothermal compression. In case the compressed air temperature at discharge, say $t2^0C$ is higher than ambient air temperature say $t1^0C$ (as is usual case), the compressor free air delivery test (FAD) is to be corrected by a factor (273 + t1) / (273 + t2).

Leakage test

If the compressor has prolonged load operations, one can come to the conclusion that there are a lot of leakages. This means apart from the pneumatic devices, there are certain places where air is continuously being drained. The best way is to attend to the leakage and find out the reduction in load time.

- The Specific Power Consumption of a Compressor can be calculated in the following method:
  - If a compressor of capacity Qm3 FAD per minute is being operated with the following consumption, the specific energy consumption can be worked out.

Load Cycle P1kW for t1 minutes and Unload P2kW for t2 minutes, then specific energy consumption =
Air Delivered = Q x t_1 minutes

$$\textbf{Energy Consumed} = \frac{(P_1 \times t_1) + (P_2 \times t_2)}{60\ \text{kWh}}$$

Hence,

$$\textbf{Specific Energy Consumption} = \frac{(P_1 \times t_1) + (P_2 \times t_2)}{60 \times Q \times t_1}\ \mathbf{kWh/m^3\ of\ FAD}$$

- Note the sub-sequent time taken for 'load' and 'unload' cycles of the compressors. For accuracy, take ON & OFF times for 8 – 10 cycles continuously. Then calculate total 'ON' Time (T) and Total 'OFF' time (t).
- The system leakage is calculated as:

% leakage = T × 100 / (T + t)
(Or)
System leakage (m^3/minute) = Q × T / (T + t)

Where,
Q = Actual free air being supplied during trial, in cubic meters per minute (cmm)
T = Time on load in minutes
t = Time on unload in minutes

- Example

In the leakage test in a process industry, following results were observed-
Compressor capacity (m3/minute) = 35
Cut in pressure, kg/cm2 = 6.8
Cut out pressure, kg/cm2 = 7.5
Load kW drawn = 188 kW
Unload kW drawn = 54 kW
Average ‘Load’ time = 1.5 minutes
Average ‘Unload’ time = 10.5 minutes
Comment on leakage quantity and avoidable loss of power due to air leakages.

$$\textbf{Leakage quantity (m3/minute)} = \frac{(1.5)}{(1.5)+(10.5)} \times 35$$

$$= 4.375$$

Leakage per day, (m3/day) = 6300

$$\textbf{Specific power for compressed air generation} = \frac{188\text{kWh}}{(35 \times 60)\ \text{m}^3/\text{day}}$$

$$= 0.0895 \text{ kWh/m3}$$

Energy lost due to leakages/day = 564 kWh

3.7 Factors Affecting Performance and Efficiency

- One of the most important factors affecting efficiency is lack of general awareness amongst the plant personnel that compressed air is the costliest utility and the prevention of small leakages and misuse can result in great economical benefits.
- Example, let us take a simple case where a worker uses a compressed air pipe in the plant to fill air into his bicycle tyre. Normally the pressure required by a bicycle tyre is 0.3-0.5 bar. For this, he wastes the compressed air which is worth Rs.5/-. The same job can be done in 50 paise or less outside the plant. The management can also afford free air filling well outside the plant from a roadside shop rather than allowing the utility air to be misused for this purpose.
- Another case is the wrong application and extensions of existing pipelines.
- Example, if a new area is being added to the plant, a proper study is not undertaken to revise options on whether to install a dedicated compressor or to extend the existing line. Many a times, the existing compressed air pipelines are extended. Then it is found that the pressure is not sufficient. Then the discharge pressure of the compressor is increased and the existing system components fail more frequently due to increased pressure, thus adding to leakages. Hence proper needs must always be assessed before undertaking such works.
- Also, proper choice should be exercised between a centralised and a distributed system.
- Many a time’s compressed air is required for aeration. At such places blowers can do the job of compressors. Hence pressure requirements of each application should be done from the point of view of energy savings.
- Another consideration is pneumatic conveying. In the 70's and 80's this process was quite popular because it does not involve mechanical maintenance. But now again with energy costs rising, economic viability is in favour of bucket elevators, etc.

3.8 Load Unload Versus On/Off Control

- In earlier days starting and stopping large motors was not easy. They used to create a lot of stress on the motor and starting devices. Hence it was worthwhile to operate compressors with the Load/Unload Control where the motor continues to run but the compressor does not compress air. During these operations, motors will have no load losses and compared to the cost of stress on the motor and starting devices, this was affordable.
- But now-a-days, excellent electronic devices are available to give a smooth soft start to the motor. This avoids stress on the motor and starting devices. Their cost is much less compared to the savings achieved in avoiding no load losses of the motor. So now a days most of the compressors are operated with the On/Off controls rather than Load/Unload Control.

Summary

- Compressed air is generated from compressors which are largely driven by electricity. If efficiency is calculated, only 10% useful energy reaches the end point through compressed air. Pneumatic tool and instrumentation are few of the applications of compressed air.
- Compressors are broadly classified as Positive Displacement Compressors and Dynamic (Centrifugal) Compressors.
- The compressors which increase the pressure of the gas by reducing the volume are called positive displacement compressors. These compressors are further classified as reciprocating compressors and rotary compressors.
- Dynamic compressors increase the air velocity, which is then converted to increased pressure at the outlet. These are basically centrifugal compressors and are further divided into radial type and axial flow types.
- Capacity of a compressor is the full rated volume of flow of gas compressed and delivered at conditions of total temperature, total pressure, and composition existing at the compressor inlet. Sometimes, it means actual flow rate rather than rated volume of flow. This is also termed as Free Air Delivery (FAD) i.e. air at atmospheric conditions at any specific location.
- The most commonly used compressor efficiency are volumetric efficiency, adiabatic efficiency, isothermal efficiency and mechanical efficiency.
- The compressed air system is composed of certain system components like intake air filters, interstage coolers, after coolers, air dryers, moisture drain traps and receivers.
- If there are no leakages at this time, the compressor will run without compressing air. This operation is called unload.
- The ideal method of compressor capacity assessment is done through a nozzle test wherein a calibrated nozzle is used as a load to vent out the generated compressed air. Flow is assessed, based on the air temperature, stabilization pressure and orifice constant.
- Factors affecting performance and efficiency include the lack of general awareness among the plant personnel that compressed air is the costliest utility and the prevention of small leakages and misuse can result in great economical benefits. Also the wrong application and extensions of existing pipelines and proper choice should be exercised between a centralised and a distributed system.
- These days most of the compressors are operated with the On/Off controls rather than Load/Unload Control.

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Self Assessment

1. The ratio of actual measured input power of a compressor to isothermal power is known as_______.
    a. Isothermal efficiency
    b. Volumetric Efficiency
    c. Barometric efficiency
    d. Mechanical efficiency

2. The compressor capacity of a reciprocating compressor is directly proportional to ______.
    a. pressure
    b. speed
    c. volume
    d. time

3. Reciprocating compressors are based on which principle?
    a. Pyramid and piston principle
    b. Triangle and piston principle
    c. Cylinder and piston principle
    d. Circular and piston principle

4. Dynamic compressors increase the air velocity, which is then converted to increased pressure at the outlet. They are basically______.
    a. pressure compressors
    b. volume compressors
    c. density compressors
    d. centrifugal compressors

5. ______ prevent dust from entering the compressor.
    a. After coolers
    b. Receivers
    c. Interstage coolers
    d. Intake air filters

6. For every 40C rise in air intake, the power consumption in turn increase by ____.
    a. 1%
    b. 2%
    c. 3%
    d. 4%

7. Which of the following statements is true?
    a. Dryness in the air can get converted into water during compressor operations and damage compressor parts.
    b. The dust accumulated in the filter should be removed regularly and eventually the filters must never be replaced.
    c. Cool ambient temperature must be provided as intake air.
    d. Most terrible pressure settings should be set for load and unload operations.

8. The ideal method of compressor capacity assessment is through a ______.
    a. needle test
    b. nozzle test
    c. puzzle test
    d. riddle test

9. Now a days most of the compressors are operated with the ________.
    a. in/out control
    b. on/off control
    c. left/right control
    d. up/down control

10. The compressors which increase the pressure of the gas by reducing the volume are called _______.
    a. Dynamic compressors
    b. Centrifugal compressors
    c. Positive displacement compressors
    d. Negative displacement compressors

Chapter IV

HVAC and Refrigeration System

Aim

The aim of this chapter is:

- explain HVAC and refrigeration systems
- elucidate vapour compression refrigeration cycle
- explicate refrigerants, coefficient of performance and capacity

Objectives

The objectives of the chapter are:

- explain the factors affecting refrigeration
- explain air conditioning system performance, savings opportunities and potential
- enlist types and comparisons with vapour compression system

Learning outcome

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

- identify a HVAC and refrigeration systems
- understand the concept of vapour absorption refrigeration system and working principle
- enlist the types of refrigeration system

4.1 Introduction

- The Heating, Ventilation, and Air Conditioning (HVAC) and refrigeration system transfer heat energy from one atmosphere to the other. One of them is a closed environment, while the other is the open atmosphere of the Earth.
- HVAC includes the bi-directional flow of heat, in the sense that when earth's atmospheric temperature is too low, then the requirements of a closed atmosphere are to be maintained. Heat is injected into the closed atmosphere.
- Refrigeration on the other hand, has a unidirectional flow of heat. It always extracts heat from the closed atmosphere with the help of a low boiling point refrigerant and dispels it into the open atmosphere of the earth.

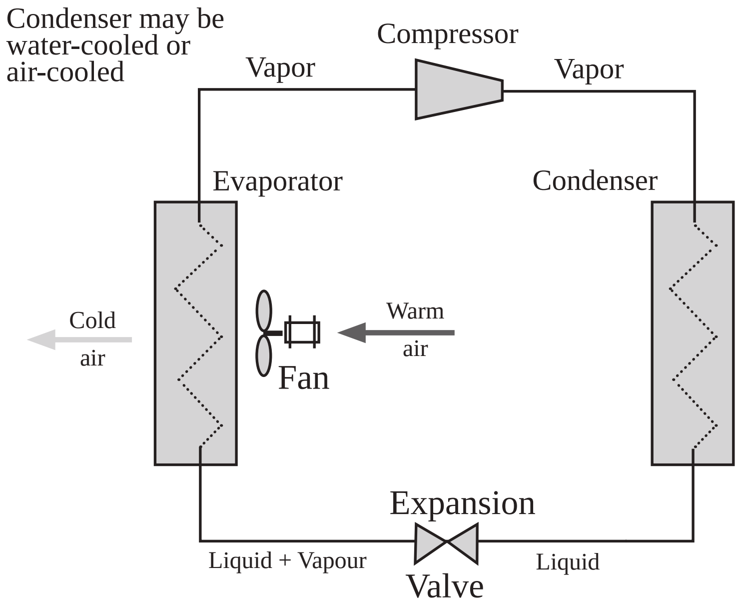


Fig. 4.1 Schematic representation of refrigeration system

- According to thermodynamic laws, heat cannot flow from a cold object to a hot object unless external work is done. The external work is done by the equipment used in HVAC/Refrigeration using electricity as the energy source.
- There are several heat transfer loops in the refrigeration system as described below. In Fig. 4.2, thermal energy moves from the left to the right as it is extracted from the space and expelled to the outdoors through five loops of heat transfer:

Indoor air loop

- In the leftmost loop, indoor air is driven by the supply air fan through a cooling coil, where it transfers its heat to chilled water. The cool air then cools the building space.

Chilled water loop

- Driven by the chilled water pump, water returns from the cooling coil to the chillers' evaporator to be re-cooled.

Refrigerant loop

- Using a phase-change refrigerant, the chillers' compressor pumps heat from the chilled water to the condenser water.

Condenser water loop

- Water absorbs heat from the chillers' condenser, and the condenser water pump sends it to the cooling tower.

Cooling tower loop

- The cooling tower fan drives air across an open flow of the hot condenser water, transferring the heat to the outdoors.

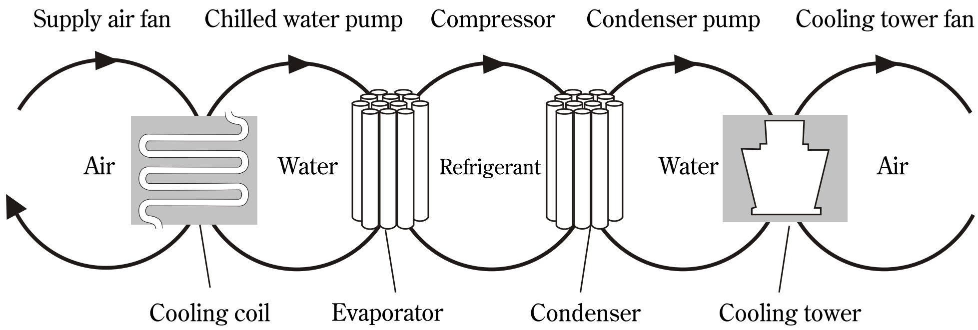


Fig. 4.2 Heat transfer loops in refrigeration system

4.1.1 Air-Conditioning System

Depending on applications, there are several options / combinations, which are available for use as given below:

- Air Conditioning (for comfort / machine)
- Split air conditioners
- Fan coil units in a larger system
- Air handling units in a larger system

4.1.2 Refrigeration Systems (for processes)

- Small capacity modular units of direct expansion type similar to domestic refrigerators, small capacity refrigeration units.
- Centralised chilled water plants with chilled water as a secondary coolant for temperature range over 50˚C typically. They can also be used for ice bank formation.
- Brine plants, which use brines as lower temperature, secondary coolant, for typically sub zero temperature applications, which come as modular unit capacities as well as large centralised plant capacities.
- The plant capacities upto 50 TR are usually considered as small capacity, 50 – 250 TR as medium capacity and over 250 TR as large capacity units.
- A large industry may have a bank of such units, often with common chilled water pumps, condenser water pumps, cooling towers, as an off site utility.

The same industry may also have two or three levels of refrigeration & air conditioning such as:

- Comfort air conditioning (200 – 250^{0}C)
- Chilled water system (80 – 100^{0}C)
- Brine system (sub-zero applications)
- Two principle types of refrigeration plants found in industrial use are: Vapour Compression Refrigeration (VCR) and Vapour Absorption Refrigeration (VAR). VCR uses mechanical energy as the driving force for refrigeration, while VAR uses thermal energy as the driving force for refrigeration.

4.1.3 Capacity Measurement

The capacity of household refrigerators is measured in litres of volume of the enclosed chamber which is cooled. The capacity of the air conditioning system is measured in terms of TR. The term 1 TR means the rate at which heat is extracted. 1 ton signifies that amount of heat required to melt one ton of ice in 24 hours. This can be derived as given below.

1 Ton = 907 Kg. Please note Ton means 1 metric ton (MT).

The latent heat of Ice = 80 kCal/kg.
Hence the rate of extraction of heat equivalent to 1 TR will be:
(907 x 80)/24 = 3024 kCal/hr = (3024/0.252) BTU per hour = 12000 BTU/hr
In terms of kW, it will be 3.5169988 kW.
Since this is an ideal conversion assuming no losses, the operating efficiency criterion of any HVAC/Refrigeration system will be judged from kW/TR.

4.2 Types of Refrigeration System

The two principle types of refrigeration plants found in industry include:

- Vapour Compression Refrigeration (VCR) and
- Vapour Absorption Refrigeration (VAR)

VCR uses mechanical energy as the driving force for refrigeration, while VAR uses thermal energy as the driving force for refrigeration.

4.2.1 Vapour Compression Refrigeration

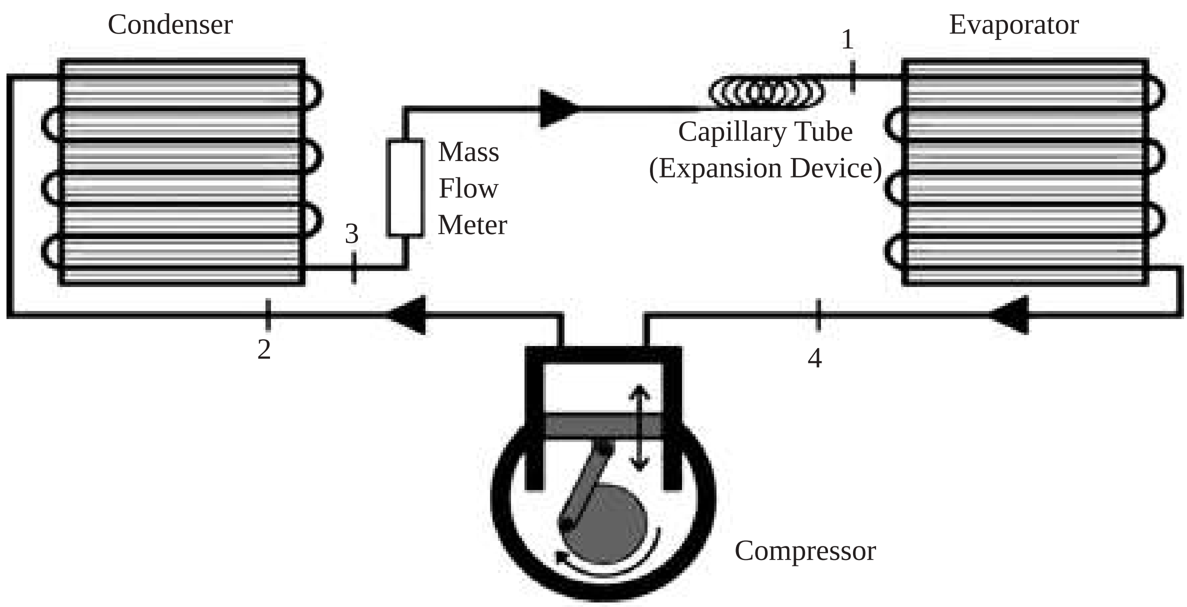


Fig. 4.3 Schematic representation of the vapour compression refrigeration cycle

- Heat flows naturally from a hotter to colder body. In refrigeration system, the opposite must occur i.e. heat flows from a colder to hotter body. This is achieved by using a substance called a refrigerant, which absorbs heat and hence boils or evaporates at a low pressure to form a gas. This gas is then compressed to a higher pressure, such that it transfers the heat it has gained to ambient air or water and turns back (condenses) into a liquid. In this way, heat is absorbed or removed from a low temperature source and transferred to a higher temperature source.
- The refrigeration cycle can be broken down into the following stages (see Figure 4.4):
    - 1–2 - Low pressure liquid refrigerant in the evaporator absorbs heat from its surroundings, usually air, water or some other process liquid. During this process it changes its state from a liquid to a gas, and at the evaporator exit is slightly superheated.
    - 2–3 - the superheated vapour enters the compressor where its pressure is raised. There will also be a big increase in temperature because a proportion of the energy input into the compression process is transferred to the refrigerant.
    - 3–4 - the high pressure superheated gas passes from the compressor into the condenser. The initial part of the cooling process (3–3a) desuperheats the gas before it is then turned back into liquid (3a–3b). The cooling

for this process is usually achieved by using air or water. A further reduction in temperature happens in the pipe work and liquid receiver (3b–4) so that the refrigerant liquid is sub-cooled as it enters the expansion device.

- 4–1 - The high-pressure sub-cooled liquid passes through the expansion device, which both reduces its pressure and controls the flow into the evaporator.
- It can be seen that the condenser has to be capable of rejecting the combined heat inputs of the evaporator and the compressor; i.e. (1–2) + (2–3) has to be the same as (3–4). There is no heat loss or gain through the expansion device.

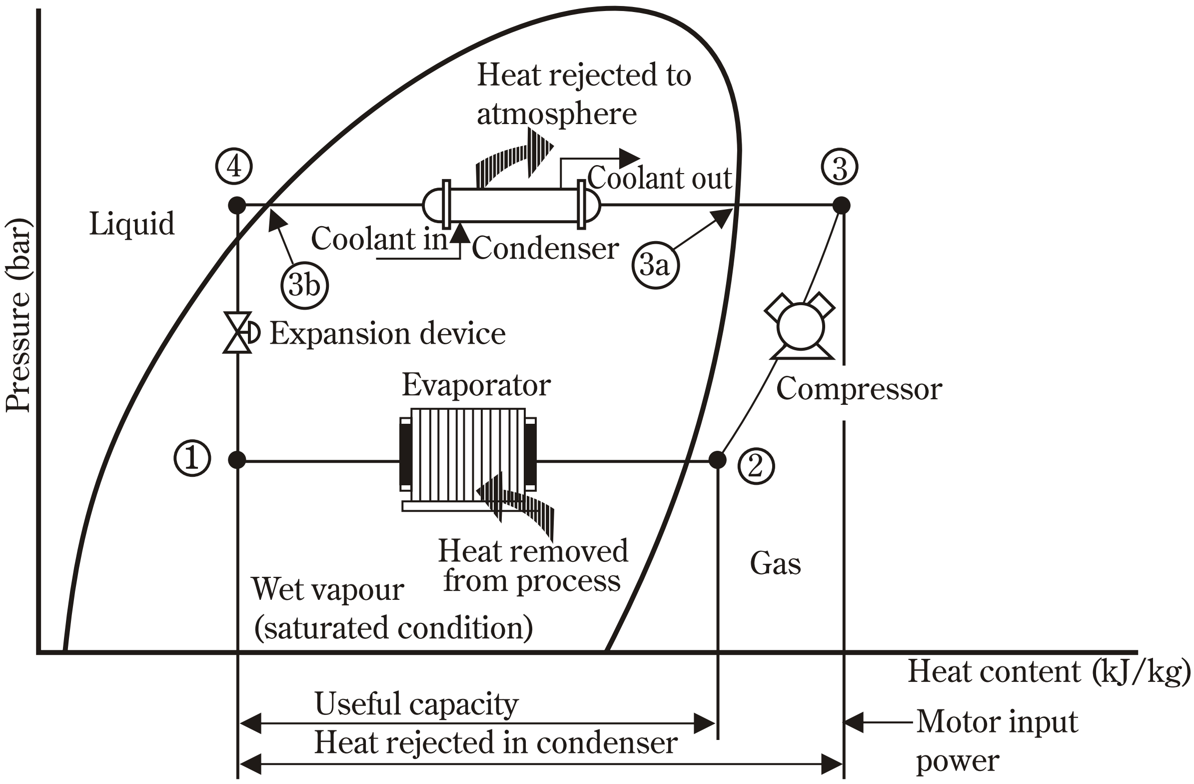


Fig. 4.4 Schematic diagram of a basic vapour compression refrigeration system

4.2.2 Alternative Refrigerants for Vapour Compression Systems

- The use of CFCs is now beginning to be phased out due to their damaging impact on the protective ozone layer present in the troposphere around the earth.
- The Montreal Protocol of 1987 and the subsequent Copenhagen agreement of 1992 mandated a reduction in the production of ozone depleting Chlorinated Fluorocarbon (CFC) refrigerants in a phased manner, with an eventual stop to all production by the year 1996.
- In response, the refrigeration industry has developed two alternative refrigerants;
  - based on Hydrochloro Fluorocarbon (HCFC)
  - another based on Hydro Fluorocarbon (HFC)
- The HCFCs have a 2–10% ozone depleting potential as compared to CFCs and also have an atmospheric lifetime between 2–25 years as compared to 100 or more years for CFCs (Brandt, 1992). However, even HCFCs are mandated to be phased out by 2005, and only the chlorine free (zero ozone depletion) HFCs would be acceptable.
- Until now, only one HFC based refrigerant, HFC 134a, has been developed. HCFCs are comparatively simpler to produce and the three refrigerants 22, 123, and 124 have been developed. The use of HFCs and HCFCs results in slightly lower efficiencies as compared to CFCs, but this may change with increasing efforts being made to replace CFCs.

4.2.3 Absorption Refrigeration

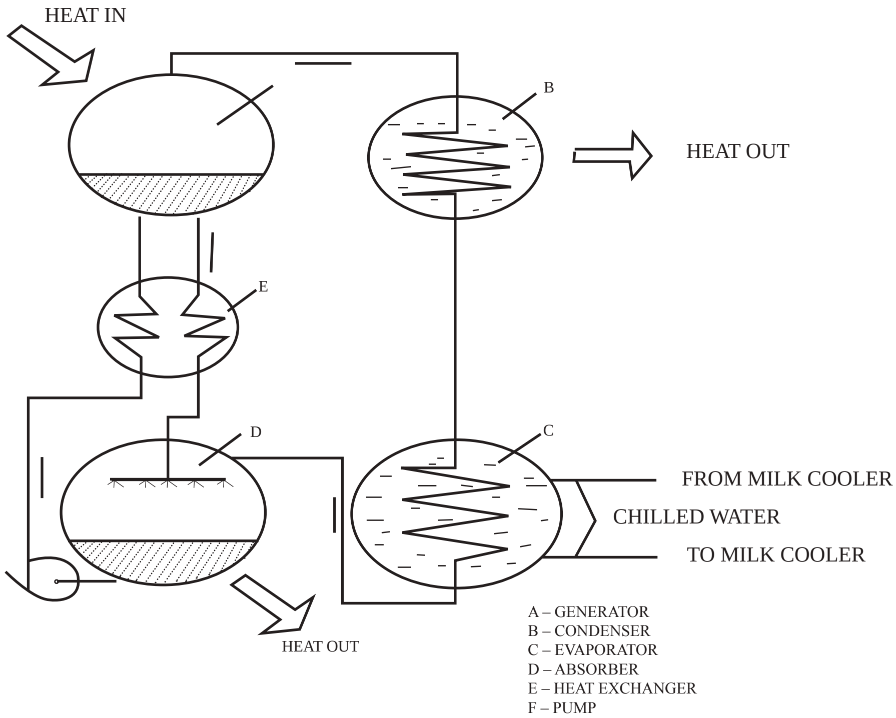


Fig. 4.5 Schematic diagram absorption refrigeration system

The absorption chiller is a machine which produces chilled water by using heat such as steam, hot water, gas, oil etc. Chilled water is produced by the principle that a liquid (refrigerant), which evaporates at low temperature, absorbs heat from the surroundings when it evaporates. Pure water is used as refrigerant and lithium bromide solution is used as the absorbent

Heat for the vapour absorption refrigeration system can be provided by waste heat extracted from process, diesel generator sets, etc. Absorption systems require electricity only to run pumps. Depending on the temperature required and the power cost, it may even be economical to generate heat/steam to operate the absorption system.
A description of the absorption refrigeration concept is given in Table 4.1

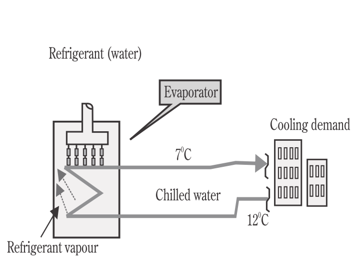
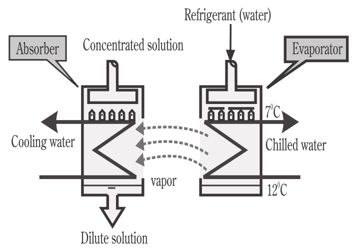
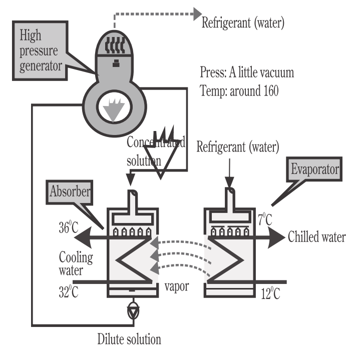
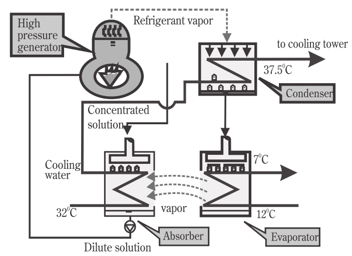
	**Evaporator** • The refrigerant (water) evaporates at around 40^0C under a high vacuum condition of 754mmHg in the evaporator. • Chilled water goes through heat exchanger tubes in the evaporator and transfers heat to the evaporated refrigerant. • The evaporated refrigerant (vapour) turns into liquid again, while the latent heat from this vaporization process cools the chilled water (in the diagram from 12^0C to 7^0C). The chilled water is then used for cooling purposes.
	**Absorber** • In order to keep evaporating, the refrigerant vapour must be discharged from the evaporator and refrigerant (water) must be supplied. • The refrigerant vapour is absorbed into lithium bromide solution, which is convenient to absorb the refrigerant vapour in the absorber. • The heat generated in the absorption process is continuously removed from the system by cooling water. • The absorption also maintains the vacuum inside the evaporator.
	**High Pressure Generator** • As lithium bromide solution is diluted, the ability to absorb the refrigerant vapour reduces. • In order to keep the absorption process going, the diluted lithium bromide solution must be concentrated again. • An absorption chiller is provided with a solution concentrating system, called a generator. Heating media such as steam, hot water, gas or oil perform the function of concentrating solutions. • The concentrated solution is returned to the absorber to absorb refrigerant vapour again.
	**Condenser** • To complete the refrigeration cycle, and thereby ensuring the refrigeration takes place continuously, the following two functions are required, • To concentrate and liquefy the evaporated refrigerant vapour, which is generated in the high pressure generator. • To supply the condensed water to the evaporator as refrigerant (water). • For these two functions a condenser is installed.

Table 4.1 Typical schematic representation of the absorption refrigeration concept

Absorption refrigeration systems that use Li-Br-water as a refrigerant have a Coefficient of Performance (COP) in the range of 0.65–0.70 and can provide chilled water at 6.7^0C with a cooling water temperature of 30^0C. Systems capable of providing chilled water at 30^0C are also available. Ammonia based systems operate at above atmospheric pressures and are capable of low temperature operation (below 0^oC). Absorption machines are available with capacities in the range of 10-1500 tons. Although the initial cost of an absorption system is higher than that of a compression system, operational costs are much lower if waste heat is used.

4.2.4 Evaporative Cooling

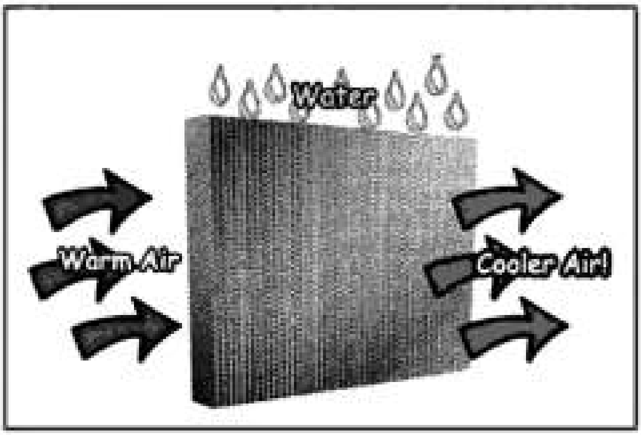


Fig. 4.6 An Evaporative cooling unit

There are occasions where air conditioning, which stipulates control of humidity up to 50 % for human comfort or for process, can be replaced by a much cheaper and less energy intensive evaporative cooling.

The concept is very simple and is the same as that used in a cooling tower. Air is brought in close contact with water to cool it to a temperature close to the wet bulb temperature. The cool air can be used for comfort or process cooling. The disadvantage is that the air is rich in moisture. Nevertheless, it is an extremely efficient means of cooling at a very low cost. Large commercial systems employ cellulose filled pads over which water is sprayed. The temperature can be controlled by controlling the airflow and the water circulation rate. The possibility of evaporative cooling is especially attractive for comfort cooling in dry regions. This principle is practiced in textile industries for certain processes.

4.3 Common Refrigerants and their Properties

A variety of refrigerants are used in vapour compression systems. The choice of the fluid is determined largely by the cooling temperature required. Commonly used refrigerants are in the family of chlorinated fluorocarbons (CFCs, also called Freons), R-11, R-12, R-21, R-22 and R-502. The properties of these refrigerants are summarised in Table 4.2 and the performance of these refrigerants is given in Table 4.3.

Refrigerant	Boiling Point** (^{0}C)	Freezing Point (^{0}C)	Vapour Pressure* (kPa)	Vapour Volume* (m^3/kg)	Enthalpy*	
					Liquid (kJ/kg)	Vapour (kJ/kg)
R 11	-23.82	-111.0	25.73	0.61170	191.40	385.43
R 12	-29.79	-158.0	219.28	0.07702	190.72	347.96
R 22	-40.76	-160.0	354.74	0.06513	188.55	400.83
R 502	-45.40		414.30	0.04234	188.87	342.31
R 7 (Ammonia)	-33.30	-77.7	289.93	0.41949	808.71	487.76

Table 4.2 Properties of commonly used refrigerants

* At 10^{0}C

** At Standard Atmospheric Pressure (101.325 kPa)

Refrigerant	Evaporating Press (kPa)	Condensing Press (kPa)	Pressure Ratio	Vapour Enthalpy (kJ/kg)	COP**Carnot
R 11	20.4	125.5	6.15	155.4	5.03
R 12	182.7	744.6	4.08	116.3	4.70
R 22	295.8	1192.1	4.03	162.8	4.66
R 502	349.6	1308.6	3.74	106.2	4.37
R 717	236.5	1166.5	4.93	103.4	4.78

Table 4.3 Performance of commonly used refrigerants*

* At -15^{0}C Evaporator Temperature, and 30^{0}C Condenser Temperature

****COP = Coefficient of Performance =** $\frac{Temp._{Evap}}{Temp._{cond} - Temp._{Evap}}$

The choice of the refrigerant and the required cooling temperature and load determine the choice of the compressor, as well as the design of the condenser, evaporator, and other auxiliaries. Additional factors, such as ease of maintenance, physical space requirements and the availability of utilities for auxiliaries (water, power, etc.) also influence component selection.

4.4 Types of Compressor and Their Applications

For industrial use, open type systems (compressor and motor as separate units) are normally used, though hermetic systems (motor and compressor in a sealed unit) also find service in some low capacity applications. Hermetic systems are used in refrigerators, air conditioners, and other low capacity applications. Industrial applications largely employ reciprocating, centrifugal and more recently, screw compressors, and scroll compressors. Water-cooled systems are more efficient than air-cooled alternatives because the temperatures produced by refrigerant condensation are lower with water than with air.

4.4.1 Centrifugal Compressors

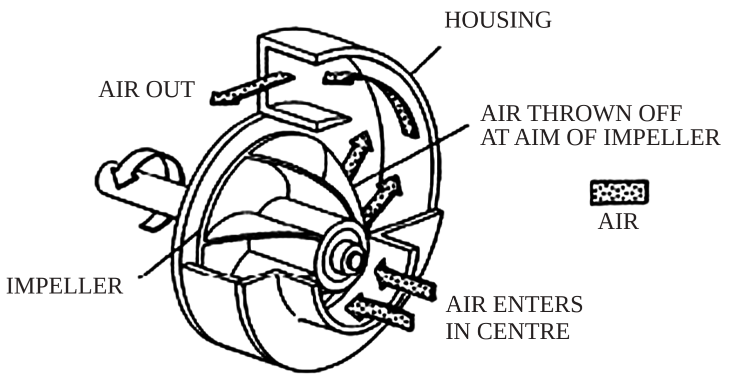


Fig. 4.7 Centrifugal compressor

- Centrifugal compressors are the most efficient types (see Figure 4.7), when they operate near full load. Their efficiency advantage is the greatest in large sizes and they offer considerable economy of scale, so they dominate the market for large chillers. They are able to use a wide range of refrigerants efficiently, so they will probably continue to be the dominant types in large sizes.
- Centrifugal compressors have a single major moving part -an impeller that compresses the refrigerant gas by the centrifugal force. The gas is given kinetic energy as it flows through the impeller. This kinetic energy is not useful in itself, so it must be converted to pressure energy. This is done by allowing the gas to slow down smoothly in a stationary diffuser surrounding the impeller.

- To minimise efficiency loss at reduced loads, centrifugal compressors typically throttle output with inlet guide vanes located at the inlet to the impeller(s). This method is efficient down to about 50% load, but the efficiency of this method decreases rapidly below 50% load.
- The older centrifugal machines are unable to reduce load much below 50%. This is because of “surge” in the impeller. As the flow through the impeller is choked off, the gas does not acquire enough energy to overcome the discharge pressure. Flow drops abruptly at this point and an oscillation begins as the gas flutters back and forth in the impeller. Efficiency drops abruptly, and the resulting vibration can damage the machine. Many older centrifugal machines deal with low loads by creating a false load on the system, such as by using hot gas bypass. This wastes the portion of the cooling output that is not required.
- Another approach is to use variable speed drives in combination with inlet guide vanes. This may allow the compressor to throttle down to about 20% of full load, or less, without false loading. Changing the impeller speed causes a departure from optimum performance, so efficiency still declines badly at low loads.
- A compressor that uses a variable-speed drive reduces its output in the range between full load and approximately half load by slowing the impeller speed.
- At lower loads, the impeller cannot be slowed further, because the discharge pressure would become too low to condense the refrigerant. Below the minimum load provided by the variable-speed drive, inlet guide vanes are used to provide further capacity reduction.

4.4.2 Reciprocating Compressors

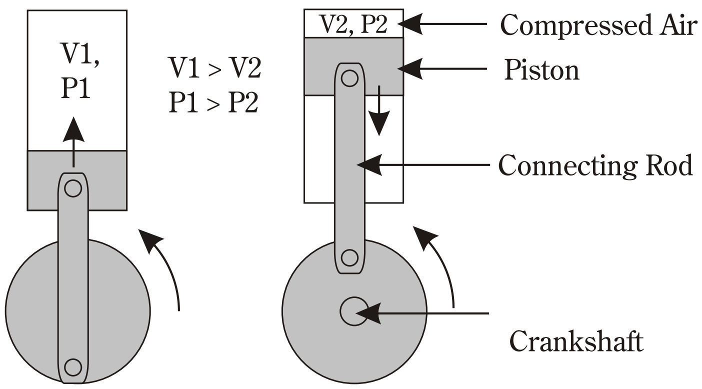


Fig. 4.8 Schematic diagram of reciprocating compressors

- The maximum efficiency of reciprocating compressors (see Fig. 4.8) is lower than that of centrifugal and screw compressors. Efficiency is reduced by the clearance volume (the compressed gas volume that is left at the top of the piston stroke), throttling losses at the intake and discharge valves, abrupt changes in gas flow, and friction. Lower efficiency also results from the smaller sizes of reciprocating units, because motor losses and friction account for a larger fraction of energy input in smaller systems.
- Reciprocating compressors suffer less efficiency loss at partial loads than other types, and they may actually have a higher absolute efficiency at low loads than the other types. Smaller reciprocating compressors control output by turning on and off. This eliminates all part-load losses, except for a short period of inefficient operation when the machine starts.
- Larger multi-cylinder reciprocating compressors commonly reduce output by disabling (“unloading”) individual cylinders. When the load falls to the point that even one cylinder provides too much capacity, the machine turns off. Several methods of cylinder unloading are used, and they differ in efficiency. The most common is holding open the intake valves of the unloaded cylinders. This eliminates most of the work of compression, but a small amount of power is still wasted in pumping refrigerant gas to-and-fro through the unloaded cylinders. Another method is blocking gas flow to the unloaded cylinders, which is called “suction cut-off.”
- Variable-speed drives can be used with reciprocating compressors, eliminating the complications of cylinder unloading. This method is gaining popularity with the drastic reduction in costs of variable speed drives.

4.4.3 Screw Compressors

Fig. 4.9 Screw compressor

- Screw compressors, sometimes called "helical rotary" compressors, compress the refrigerant by trapping it in the "threads" of a rotating screw-shaped rotor (see Figure 4.7). Screw compressors have increasingly taken over from reciprocating compressors of medium sizes and large sizes, and they have even entered the size domain of centrifugal machines. Screw compressors are applicable to refrigerants that, such as HCFC-22 and ammonia.
- They are especially compact. A variety of methods are used to control the output of screw compressors. There are major efficiency differences among the different methods. The most common is a slide valve that forms a portion of the housing that surrounds the screws.
- Using a variable-speed drive is another method of capacity control. It is limited to oil-injected compressors, because slowing the speed of a dry compressor would allow excessive internal leakage. There are other methods of reducing capacity, such as suction throttling that are inherently less efficient than the previous two.

4.4.4 Scroll Compressors

Fig. 4.10 Scroll compressor

- The scroll compressor is an old invention that has finally come to the market. The gas is compressed between two scroll-shaped vanes. One of the vanes is fixed, and the other moves within it. The moving vane does not rotate, but its centre revolves with respect to the centre of the fixed vane, as shown in Fig. 4.10.
- This motion squeezes the refrigerant gas along a spiral path, from the boundaries of the vanes toward the centre, where the discharge port is located. The compressor has only two moving parts, the moving vane and a shaft with an off-centre crank to drive the moving vane.
- Scroll compressors have only recently become practical, because close machining tolerances are needed to prevent leakage between the vanes, and between the vanes and the casing.

4.5 Selection of a Suitable Refrigeration System

- A clear understanding of the cooling load to be met is the first and most important part of designing/selecting the components of a refrigeration system. Important factors to be considered in quantifying the load are the actual cooling need, heat (cool) leaks, and internal heat sources (from all heat generating equipment).
- Consideration should also be given to process changes and/or changes in ambient conditions that might affect the load in the future. Reducing the load, e.g. through better insulation, maintaining as high a cooling temperature as practical, etc. is the first step towards minimising electrical power required to meet refrigeration needs.
- With a quantitative understanding of the required temperatures and the maximum, minimum, and average expected cooling demands, selection of the appropriate refrigeration system (single-stage/multi-stage, economised

Sl. No	Parameters	Vapour Compression Chillers			Vapour Absorption Chiller			
					LiBr			
		Recipro-cating	Centri-fugal	Screw	Single Effect	Double Effect	Half Effect	Triple Effect
1	Refrigeration Temp. Range (Brine / Water)	+7 to -30°C	+7 to - 0°C	+7 to - 25°C	Above 60°C			
2	Energy Input	Electricity	Electr-icity	Electricity	Heat (Steam / Hot Water / Hot Oil/Direct Fired)	Heat (Steam / Hot Water / Hot Oil/ Direct Fired)	Heat (Hot Water)	Heat (Steam /Hot Oil /Direct Fired)
3	Heat Input Temp. Range -Maximum -Minimum				Minimum 85°C	Minimum 130°C	Minimum 55°C	Minimum 190°C
4	Typical Energy to TR Ratio							
	Air Conditioning Temp. Range	0.7-0.9 kW/ TR	0.63kW/TR	0.65 kW/TR	5000 kcal/TR	2575 kcal/TR	7500 kcal/ TR	2000 kcal/TR
	Subzero Temp. Range	1.25 to 2.5 kW/TR		1.25 to 2.5 kW/TR	-----------	-------------	--------	---------
5	Refrigerant	R11, R123, R134a Ammonia	R22, R12	R22, R134a Ammonia	Pure Water	Pure Water	Pure Water	Pure Water
6	Absorbent	-----------	--------	----------	Water-LiBr solution	Water-LiBr solution	Water-LiBr solution	Water-LiBr solution
7	Typical single unit capacity range							
8	Air Condition temp. range	1-150 TR	300 TR & above	50-200 TR	30 TR & above	30 TR & above	30 TR & above	50 TR & above
9	Subzero temp. range	10-50 TR	------	50-200 TR	-----	-----	-----	-----
10	Typical COP at Part Load upto 50%	Reduces at part load	Reduces at part load	Improves by 15-20%	Marginal Improvement at Part Load			

11	Typical Internal Pressure Levels -Low -High Typical Internal Temp. Levels	0.15-0.40 bar a 1.20-1.50 bar a -25 to 50°C	2.5-3.5 bar a 11-12 bar -5 to 50°C	2-5.5 bar 18-20 bar -25 to 50°C	5-6 mm Hg (abs) 60-70 mm Hg (abs) +4 to 75°C	5-6 mm Hg (abs) 370-390 mm Hg (abs) +4 to +130°C	5-6 mm Hg (abs) 60-70 mm Hg (abs) +4 to 130°C	5-6 mm Hg (abs) 2 kg/ cm2 (a) +4 to 160°C
12	Typical Cooling tower capacity range per 100 TR of chillers Air- conditioning Temperature Range- Subzero temp. range	130 190	120 -----	120 160	260 ---	200 ---	370 ---	170 ---
13	Typical Make-up	672 983	620 ---	620 830	1345 ---	1035 ---	1914 ---	880 ---
14	water quantity range in Ltrs/ Hr. -Air Conditioning temperature range -Subzero temp. range							
15	Material of construction-Generator							Cu-Ni or Stainless Steel
16	Absorber							Cu-Ni
17	-Evaporator							Cu-Ni
18	-Condenser							Cu-Ni
19	-Solution Heat Exchange							Carbon Steel
20	-Solution Pump							
21	-Refrigerant pump							
22	Expected Life							

23	Normally Expected Repairs / Maintenance	Periodic Compressor Overhaul Tube Replacement after 1-12 years	Tube Replacement due to Corrosion	Practically no repairs				
24	Factory Assembled	Factory Assembled						
25	packaged Or Site Assembled							
26	Beneficial Energy Sources	Low cost Electricity	Low cost Electricity	Low cost Electricity	a) Waste Heat b) Low cost steam / Low cost fuels			
27	Critical Parameters	Electricity supply	-Lubrication System -Compressor Operation & Maintenance -Electrical Power Panel Maintenance	—	a) Vacuum in Chiller b) Purge System for Vacuum c) Corrosion Inhibitors in Absorbent d) Surfactants in Absorbent e) Cooling Water Treatment f) Cooling Water Temperature g) Heat Source Temperature	Sudden Power failure for 45-60 min. or more can disturb the distillation column for continuous operation. Needs D.G.set if there is frequent power failure for periods longer than 30 min.		

Table. 4.4 Comparison of different types of refrigeration plants
(Source: Ashrae & Vendor Information)

compression, compound/cascade operation, direct cooling/secondary coolants) and equipment (type of refrigerant, compressor, evaporator, condenser, etc.) can be undertaken.

4.6 Performance Assessment of Refrigeration Plants

The cooling effect produced is quantified as tons of refrigeration (TR).
1 TR of refrigeration = 3024 kCal/hr heat rejected.
The refrigeration TR is assessed as

$$TR = \frac{Q \times Cp \times (T_i T_o)}{3024}$$

Where,

Q = mass flow rate of coolant in kg/hr
C_p = coolant specific heat in kCal/kg^{0}C
T_i = inlet temperature of coolant to evaporator (chiller) in ^{0}C
T_0 = outlet temperature of coolant from evaporator (chiller) in ^{0}C
The above TR is also called as chiller tonnage

- Specific power consumption kW/TR is a useful indicator of the performance of a refrigeration system. By measuring the refrigeration duty performed in TR and the kiloWatt inputs, kW/TR is used as a reference energy performance indicator.
- In a centralised chilled water system, apart from the compressor unit, power is also consumed by the chilled water (secondary) coolant pump as well as condenser water (for heat rejection to cooling tower) pump and cooling tower fan in the cooling tower. Effectively, the overall energy consumption would be towards:
  - Compressor kW
  - Chilled water pump kW
  - Condenser water pump kW
  - Cooling tower fan kW, for induced / forced draft towers

- The specific power consumption for certain TR output would therefore have to include:
  - Compressor kW/TR
  - Chilled water pump kW/TR
  - Condenser water pump kW/TR
  - Cooling tower fan kW/TR

The overall kW/TR is the sum of the above.

The theoretical Coefficient of Performance (Carnot),
COPCarnot -a standard measure of refrigeration efficiency of an ideal refrigeration system- depends on two key system temperatures namely;

- the evaporator temperature Te
- the condenser temperature Tc

With COP being given as:

$$COPCarnot = \frac{Te}{(T_c - T_e)}$$

This expression also indicates that a higher COPCarnot is achieved with higher evaporator temperature and lower condenser temperature. But COPCarnot is only a ratio of temperatures, and hence does not take into account the type of compressor. Hence the COP normally used in the industry is given by

$$COP = \frac{\text{Cooling effect (kW)}}{\text{Power input to compressor (kW)}}$$

where, the cooling effect is the difference in enthalpy across the evaporator and expressed as kW. The effect of evaporating and condensing temperatures are given in Figure 4.11 and Figure 4.12 below:

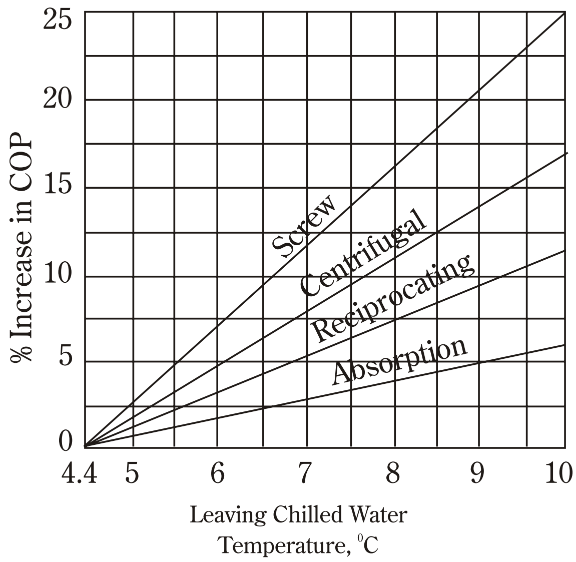


Fig. 4.11 Effect of evaporator temperature on chiller COP

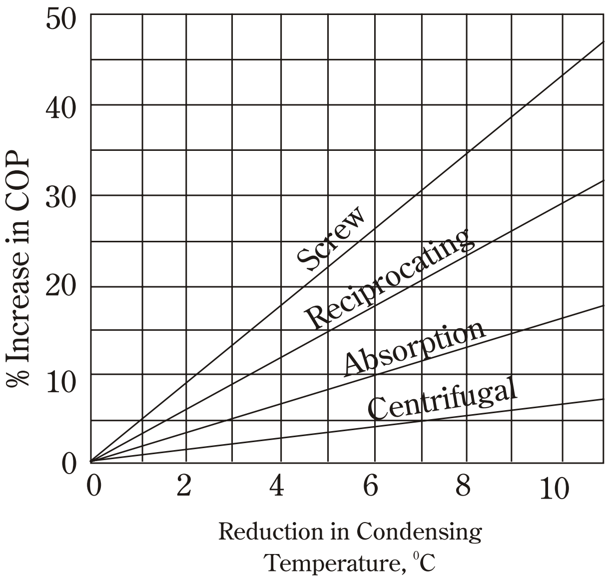


Fig. 4.12 Effect of condensing temperature on chiller COP

- In field performance assessment, accurate instruments for inlet and outlet chilled water temperature and condenser water temperature measurement are required, preferably with a least count of 0.1 C. Flow measurements of chilled water can be made by an ultrasonic flow meter directly or inferred from pump duty parameters. An adequacy check of chilled water is needed often and most units are designed for a typical 0.68 m^3/hr per TR (3gpm/TR) chilled water flow. Condenser water flow measurements can also be made by a non-contact flow meter directly or inferred from pump duty parameters. An adequacy check of condenser water is also often needed, and most units are designed for a typical 0.91 m3/hr per TR (4 gpm/TR) condenser water flow.
- In case of air conditioning units, the airflow at the Fan Coil Units (FCU) or the Air Handling Units (AHU) can be measured with an anemometer. Dry bulb and wet bulb temperatures are measured at the inlet and outlet of the AHU or the FCU and the refrigeration load in TR is assessed as:

$$TR = \frac{Q \times \rho \times (h_{in} - h_{out})}{3024}$$

Where,

Q = the air flow in m^3/h

ρ = density of air kg/m^3

h_{in} = enthalpy of inlet air kCal/kg

h_{out} = enthalpy of outlet air kCal/kg

- Use of psychometric charts can help to calculate h and h in out from dry bulb, wet bulb temperature values which are, in-turn measured during trials, by a whirling psychrometer.
- Power measurements at, compressor, pumps, AHU fans, cooling tower fans can be accomplished by a portable load analyser.
- Estimation of the air conditioning load is also possible by calculating various heat loads, sensible and latent based on inlet and outlet air parameters, air ingress factors, air flow, number of people and the type of materials stored.

An indicative TR load profile for air conditioning is presented as follows:

- Small office cabins = 0.1TR/m^2
- Medium size office i.e., 10–30 people = 0.06TR/m^2 occupancy with central A/C
- Large multi-storeyed office = 0.04TR/m^2 complexes with central A/C

4.6.1 Integrated Part Load Value (IPLV)

- Although the kW/ TR can serve to be an initial reference, it should not be taken as an absolute since this value is derived from 100% of the equipment's capacity level and is based on design conditions that are considered the most critical.
- These conditions occur may be, example, during only 1% of the total time the equipment is in operation throughout the year. Consequently, it is essential to have data that reflects how the equipment operates with partial loads or in conditions that demand less than 100% of its capacity.
- To overcome this, an average of kW/TR with partial loads i.e. Integrated Part Load Value (IPLV) have to be formulated. The IPLV is the most appropriate reference, although not considered the best, because it only captures four points within the operational cycle: 100%, 75%, 50% and 25%.
- Furthermore, it assigns the same weight to each value, and most equipment usually operates at between 50 % and 75% of its capacity. This is why it is so important to prepare specific analysis for each case that addresses the four points already mentioned, as well as developing a profile of the heat exchanger's operations during the year.

4.7 Factors Affecting Performance and Energy Efficiency of Refrigeration Plants

The various factors which affect the performance and energy efficiency of refrigeration plants are as follows:

4.7.1 The Design of Process Heat Exchangers

- There is a tendency of the process group to operate with high safety margins which influences the compressor suction pressure/evaporator set point. For instance, a process cooling requirement of 15^0C would need chilled water at a lower temperature, but the range can vary from 6^0C to say 10^0C. At 10^0C chilled water temperature, the refrigerant side temperature has to be lower, say 5^0C to $+5^0$C.
- The refrigerant temperature again sets the corresponding suction pressure of the refrigerant which decides the inlet duty conditions for the work of compression of the refrigerant compressor.
- Having an optimum/ minimum driving force (temperature difference) can, thus, help to achieve the highest possible suction pressure at the compressor, thereby leading to less energy requirement.
- This requires proper sizing of heat transfer areas of process heat exchangers and evaporators as well as rationalising the temperature requirement to the highest possible value. A 1^0C raise in evaporator temperature can help save almost 3% on power consumption. The TR capacity of the same machine will also increase with the evaporator temperature, as given in Table 4.4.

Evaporator Temperature(^{0}C)	Refrigeration Capacity* (tons)	Specific Power Consumption	Increase in kW/ton (%)
5.0	67.58	0.81	-
0.0	56.07	0.94	16.0
-5.0	45.98	1.08	33.0
-10.0	37.20	1.25	54.0
-20.0	23.12	1.67	106.0

Table 4.5 Effect of variation in evaporator temperature on compressor power consumption

* Condenser temperature 40^{0}C
Towards rationalising the heat transfer areas, the heat transfer coefficient on the refrigerant side can be considered to range from 1400–2800 watts/m^{2}K.The refrigerant side heat transfer areas provided are of the order of 0.5 Sqm./TR and above in evaporators.

- Condensers in a refrigeration plant are critical equipment that influence the TR capacity and power consumption demands. Given a refrigerant, the condensing temperature and the corresponding condenser pressure depend upon
  - the heat transfer area provided
  - effectiveness of heat exchange
  - the type of cooling chosen
- A lower condensing temperature, pressure, in the best of combinations would mean that the compressor has to work between a lower pressure differential as the discharge pressure is fixed by the design and the performance of the condenser.
- The choices of condensers in practice range from air cooled, air cooled with water spray, and heat exchanger cooled. Generously sized shell and tube heat exchangers as condensers, with good cooling tower operations help to operate with low discharge pressure values and the TR capacity of the refrigeration plant also improves.
- With the same refrigerant, R22, a discharge pressure of 15 kg/cm^2 with a water cooled shell and tube condenser and 20kg/cm^2 with an air cooled condenser indicate the kind of additional work of compression duty and almost 30% additional energy consumption required by the plant.
- One of the best options at the design stage would be to select generously sized (0.65m^2/TR and above) shell and tube condensers with water-cooling as against cheaper alternatives like air cooled condensers or water spray atmospheric condenser units.

The effect of condenser temperature on refrigeration plant energy requirements is given in Table 4.5.

Condensing Temperature(0C)	Refrigeration Capacity (tons)	Specific Power Consumption (kW/TR)	Increase in kW/TR (%)
26.7	31.5	1.17	-
35.0	21.4	1.27	8.5
40.0	20.0	1.41	20.5

Table 4.6 Effects of variations in condenser temperature on compressor power consumption

* Reciprocating compressor using R-22 refrigerant. Evaporator temperature-10^{0}C

4.7.2 Maintenance of Heat Exchanger Surfaces

- After ensuring procurement, effective maintenance holds the key to optimising power consumption.
- Heat transfer can also be improved by ensuring proper separation of the lubricating oil and the refrigerant, timely defrosting of coils, and increasing the velocity of the secondary coolant (air, water, etc.).
- However, increased velocity results in larger pressure drops in the distribution system and higher power consumption in pumps/fans. Therefore, careful analysis is required to determine the most effective and efficient option.
- Fouled condenser tubes force the compressor to work harder to attain the desired capacity. For example, a 0.8mm scale build-up on condenser tubes can increase energy consumption by as much as 35%. Similarly, fouled evaporators (due to residual lubricating oil or infiltration of air) result in increased power consumption. Equally important is proper selection, sizing, and maintenance of cooling towers. A reduction of 0.550C temperature in water returning from the cooling tower reduces the compressor power consumption by 3.0% (see Table 4.6).
-

Condition	Evap. Temp (^{0}C)	Cond. Temp (^{0}C)	Refrigeration Capacity* (tons) kW/Ton	Specific Power Consumption	Increase in (kW/ton) (%)
Normal	7.2	40.5	17.0	0.69	-
Dirty condenser	7.2	46.1	15.6	0.84	20.4
Dirty evaporator	1.7	40.5	13.8	0.82	18.3
Dirty condenser and evaporator	1.7	46.1	12.7	0.96	38.7

Table 4.7 Effect of poor maintenance on compressor power consumption

*15 ton reciprocating compressor based system.

- The power consumption is lower than that for systems typically available in India. However, the percentage change in power consumption is indicative of the effect of poor maintenance.

4.7.3 Multi-staging for Efficiency

- Efficient compressor operation requires that the compression ratio be kept low to reduce discharge pressure and temperature. For low temperature applications involving high compression ratios, and for wide temperature requirements, it is preferable (due to equipment design limitations) and often economical to employ multi-stage reciprocating machines or centrifugal / screw compressors.
- Multi-staging systems are of two-types:
    - compound
    - cascade

They are applicable to all types of compressors.

- With reciprocating or rotary compressors, two-stage compressors are preferable for load temperatures from 20–58^{0}C, and with centrifugal machines for temperatures around 43^{0}C.
- In multi-stage operation, a first-stage compressor, sized to meet the cooling load, feeds into the suction of a second-stage compressor after inter-cooling of the gas. A part of the high-pressure liquid from the condenser is flashed and used for liquid sub-cooling. The second compressor, therefore, has to meet the load of the evaporator and the flash gas.

- A single refrigerant is used in the system, and the work of compression is shared equally by the two compressors. Therefore, two compressors with low compression ratios can in combination provide a high compression ratio.
- For temperatures in the range of 46–101^{0}C, cascaded systems are preferable. In this system, two separate systems using different refrigerants are connected such that one provides the means of heat rejection to the other.
- The chief advantage of this system is that a low temperature refrigerant which has a high suction temperature and low specific volume can be selected for the low-stage to meet very low temperature requirements.

4.7.4 Matching Capacity to System Load

- During part-load operation, the evaporator temperature rises and the condenser temperature falls, effectively increasing the COP. But at the same time, deviation from the design operation point and the fact that mechanical losses form a greater proportion of the total power negate the effect of improved in COP, resulting in lower part-load efficiency.
- Therefore, consideration of part-load operation is important, because most refrigeration applications have varying loads. The load may vary due to variations in temperature and process cooling needs.
- Matching refrigeration capacity to the load is a difficult exercise, requiring knowledge of compressor performance, and variations in ambient conditions, and detailed knowledge of the cooling load.

4.7.5 Capacity Control and Energy Efficiency

- The capacity of compressors is controlled in a number of ways. Capacity control of reciprocating compressors through cylinder unloading results in incremental (step-by-step) modulation as against continuous capacity modulation of centrifugal through vane control and screw compressors through sliding valves. Therefore, temperature control requires a careful system design.
- Usually, when using reciprocating compressors in applications with widely varying loads, it is desirable to control the compressor by monitoring the return water (or other secondary coolant) temperature rather than the temperature of the water leaving the chiller. This prevents excessive on-off cycling or unnecessary loading/unloading of the compressor.
- However, if load fluctuations are not high, the temperature of the water leaving the chiller should be monitored. This has the advantage of preventing operation at very low water temperatures, especially when flow reduces at low loads. The leaving water temperature should be monitored for centrifugal and screw chillers.
- Capacity regulation through speed control is the most efficient option. However, when employing speed control for reciprocating compressors, it should be ensured that the lubrication system is not affected. In the case of centrifugal compressors, it is usually desirable to restrict speed control to about 50% of the capacity to prevent surging. Below 50%, vane control or hot gas bypass can be used for capacity modulation.
- The efficiency of screw compressors operating at part load is generally higher than either centrifugal compressors or reciprocating compressors, which may make them attractive in situations where part-load operation is common.
- Screw compressor performance can be optimised by changing the volume ratio. In some cases, this may result in higher full-load efficiencies as compared to reciprocating and centrifugal compressors. Also, the ability of screw compressors to tolerate oil and liquid refrigerant slugs makes them preferred in some situations.

4.7.6 Multi-level Refrigeration for Plant Needs

- The selection of refrigeration systems also depends on the range of temperatures required in the plant. For diverse applications requiring a wide range of temperatures, it is generally more economical to provide several packaged units (several units distributed throughout the plant) instead of one large central plant.
- Another advantage would be the flexibility and reliability accorded. The selection of packaged units could also be made depending on the distance at which cooling loads need to be met. Packaged units at load centres reduce distribution losses in the system.

- Despite the advantages of packaged units, central plants generally have lower power consumption since at reduced loads; power consumption can reduce significantly due to the large condenser and evaporator surfaces.
- Many industries use a bank of compressors at a central location to meet the load. Usually chillers feed into a common header from which branch lines are taken to different locations in the plant. In such situations, operation at part-load requires extreme care.
- For efficient operation, the cooling load, and the load on each chiller must be monitored closely. It is more efficient to operate a single chiller at full load than to operate two chillers at part-load.
- The distribution system should be designed such that individual chillers can feed all branch lines. Isolation valves must be provided to ensure that chilled water (or other coolant) does not flow through chillers not in operation.
- Valves should also be provided on branch lines to isolate sections where cooling is not required. This reduces pressure drops in the system and reduces power consumption in the pumping system.
- Individual compressors should be loaded to their full capacity before operating the second compressor. In some cases it is economical to provide a separate smaller capacity chiller, which can be operated on an on-off control to meet peak demands, with larger chillers meeting the base load.
- Flow control is also commonly used to meet varying demands. In such cases the savings in pumping at reduced flow should be weighed against the reduced heat transfer in coils due to reduced velocity.
- In some cases, operation at normal flow rates, with subsequent longer periods of no-load (or shut-off) operation of the compressor, may result in larger savings.

4.7.7 Chilled Water Storage

- Depending on the nature of the load, it is economical to provide a chilled water storage facility with very good cold insulation. Also, the storage facility can be fully filled to meet the process requirements so that chillers need not be operated continuously.
- This system is usually economical if small variations in temperature are acceptable. It has the added advantage of allowing the chillers to be operated at periods of low electricity demand to reduce peak demand charges.
- Low tariffs offered by some electric utilities for operation at night time can also be taken advantage of by using a storage facility. An added benefit is that lower ambient temperature at night lowers condenser temperature and thereby increases the COP.
- If temperature variations cannot be tolerated, it may not be economical to provide a storage facility since the secondary coolant would have to be stored at a temperature much lower than required to provide for heat gain.
- The additional cost of cooling to a lower temperature may offset benefits. The solutions are case specific. For example, in some cases it may be possible to employ large heat exchangers, at a lower cost burden than low temperature chiller operation, to take advantage of the storage facility even when temperature variations are not acceptable. The Ice bank systems which store ice rather than water are often economical.

4.7.8 System Design Features

- In overall plant design, adoption of good practices improves the energy efficiency significantly. Some areas for consideration are:
  - Design of cooling towers with FRP impellers and film fills, PVC drift eliminators, etc.
  - Use of softened water for condensers in place of raw water.
  - Use of economic insulation thickness on cold lines, heat exchangers, considering cost of heat gains and adopting practices like infrared thermography for monitoring -applicable especially in large chemical / fertiliser / process industry.
  - Adoption of roof coatings / cooling systems, false ceilings / as applicable, to minimise refrigeration load.
  - Adoption of energy efficient heat recovery devices like air to air heat exchangers to pre-cool the fresh air by indirect heat exchange; control of relative humidity through indirect heat exchange rather than use of duct heaters after chilling.

- Adopting of variable air volume systems; adopting of sun film application for heat reflection; optimising lighting loads in the air conditioned areas; optimising a number of air changes in the air conditioned areas are a few other examples.

4.8 Energy Saving Opportunities

- Cold Insulation
- Insulate all cold lines / vessels using economic insulation thickness to minimise heat gains; and to choose appropriate (correct) insulation.
- Building Envelope
- Optimise air conditioning volumes by measures such as use of false ceiling and segregation of critical areas for air conditioning by air curtains.
- Building Heat Loads Minimisation
- Minimise the air conditioning loads by measures such as roof cooling, roof painting, efficient lighting, pre-cooling of fresh air by air- to-air heat exchangers, variable volume air system, optimal thermo-static setting of temperature of air conditioned spaces, sun film applications, etc.
- Process heat loads minimisation

Minimise process heat loads in terms of TR capacity as well as refrigeration level;

- flow optimisation
- heat transfer area increase to accept higher temperature coolant
- avoiding wastages like heat gains, loss of chilled water, idle flows
- frequent cleaning / de-scaling of all heat exchangers

- At the Refrigeration A/C Plant Area;
    - ensure regular maintenance of all A/C plant components as per manufacturer guidelines
    - ensure an adequate quantity of chilled water and cooling water flows, avoid bypass flows by closing valves of idle equipment
    - minimise part load operations by matching loads and plant capacity on line; adopt variable speed drives for varying process load
    - make efforts to continuously optimise condenser and evaporator parameters for minimising specific energy consumption and maximising capacity
    - adopt VAR system where economics permit as a non-CFC solution

Summary

- The Heating, Ventilation, and Air Conditioning (HVAC) and refrigeration system transfers heat energy from one atmosphere to the other. HVAC includes the bi-directional flow of heat, in the sense that when earth's atmospheric temperature is too low, then the requirements of a closed atmosphere are to be maintained. Heat is injected into the closed atmosphere.
- Depending on applications, there are several options / combinations, which are available for use are Air Conditioning (for comfort / machine), split air conditioners, fan coil units in a larger system, air handling units in a larger system.
- In Vapour Compression Refrigeration (VCR) heat flows naturally from a hot to a colder body. In refrigeration system the opposite must occur i.e. heat flows from a cold to a hotter body. This is achieved by using a substance called a refrigerant, which absorbs heat and hence boils or evaporates at a low pressure to form a gas. This gas is then compressed to a higher pressure, such that it transfers the heat it has gained to ambient air or water and turns back (condenses) into a liquid. In this way heat is absorbed, or removed, from a low temperature source and transferred to a higher temperature source.
- In Vapour Absorption Refrigeration (VAR), the absorption chiller is a machine which produces chilled water by using heat such as steam, hot water, gas, oil etc. Chilled water is produced by the principle that a liquid (refrigerant), which evaporates at low temperature, absorbs heat from the surroundings when it evaporates. Pure water is used as refrigerant and lithium bromide solution is used as the absorbent.
- TR is a measure of refrigeration capacity. One TR means the heat rate that will melt one ton of ice in 24 hours. 1 TR means 3024 kCal/hr.
- The various types of refrigeration systems and refrigerants are Compression Refrigeration, Absorption Refrigeration. The energy efficiency of such systems depends a lot on the refrigerant use, leakages in the system, type and quality of insulation, etc. Each of them presents a number of ways and opportunities in energy savings.
- COP is the coefficient of Performance. It is the ratio of the cooling effect in kW to the Power Input to the Compressor.

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Self Assessment

1. Screw compressor performance can be optimised by changing the _______.
    a. volume ratio
    b. pressure ratio
    c. temperature ratio
    d. distance ratio

2. One ton of refrigeration (TR) is equal to_____.
    a. 3.62 kW
    b. 14000 BTU/h
    c. 3.75 BTU/h
    d. 3024 Kcal/h

3. HVAC includes the _____flow of heat.
    a. uni-directional
    b. bi-directional
    c. multi-directional
    d. mono-directional

4. Vapour Compression Refrigeration (VCR) and Vapour Absorption Refrigeration (VAR) are two types of _____.
    a. household AC systems
    b. industrial AC systems
    c. refrigeration plants
    d. HVAC systems

5. Which of the following statements is false?
    a. The HCFCs have a 2–10% ozone depleting potential as compared to CFCs.
    b. An atmospheric lifetime for CFCs is to 100 or more years.
    c. The use of CFCs is now beginning to be phased out due to their damaging impact on the protective ozone layer.
    d. A gain in the production of Chlorinated Fluorocarbon (CFC) refrigerants is made mandate as it protects ozone layer.

6. Centrifugal compressors have a single major moving part -_____ that compresses the refrigerant gas by the centrifugal force
    a. a compeller
    b. a mover
    c. an impeller
    d. a rotor

7. Screw compressors also called_____.
    a. helical rotary compressors
    b. vertical rotary compressors
    c. horizontal rotary compressors
    d. circular rotary compressors

8. The performance of a refrigeration system is indicated with the help of _________.
    a. Specific pressure consumption
    b. Specific power consumption
    c. Specific temperature consumption
    d. Specific volume consumption

9. The specific power consumption for certain TR output does not include which of the options given below.
    a. Compressor
    b. Condenser water pump
    c. Chilled water pump
    d. Cooling rise fan

10. Match the following:

1) Indoor air loop	A. Water absorbs heat from the chillers' condenser, and the condenser water pump sends it to the cooling tower
2) Chilled water loop	B. Driven by the supply air fan through a cooling coil, where it transfers its heat to chilled water
3) Refrigerant loop	C. Driven by the chilled water pump, water returns from the cooling coil to the chillers' evaporator to be re-cooled
4) Condenser water loop	D. The chillers' compressor pumps heat from the chilled water to the condenser water

    a. 1-A, 2-B, 3-C, 4-D
    b. 1-B, 2-C, 3-D, 4-A
    c. 1-C, 2-D, 3-A, 4-B
    d. 1-D, 2-A, 3-B, 4-C

Chapter V

Fans and Blowers

Aim

The aim of this chapter is :

- explain fans and blowers
- enlist types of fans and blowers
- explicate the performance evaluation

Objectives

The objectives of the chapter are :

- describe the important factors helping energy conservation opportunities
- explicate efficient system operation and flow control strategies
- explain energy conservation opportunities

Learning outcome

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

- define fans and blowers
- identify different types of fans and blowers
- understand the concept of efficient system operation and flow control strategies

5.1 Introduction

Fans and blowers provide air for ventilation and industrial process requirements. Fans generate a pressure to move air (or gases) against a resistance caused by ducts, dampers, or other components in a fan system. The fan rotor receives energy from a rotating shaft and transmits it to the air.

Industrial fans and blowers are machines whose primary function is to provide a large flow of air or gas to various processes of many industries. This is achieved by rotating a number of blades, connected to a hub and shaft and driven by a motor or turbine. The flow rates of these fans range from approximately 200-2,000,000 cubic feet (5.7 to 57000 cubic meters) per minute.

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. Fan systems are essential to keep manufacturing processes working, and consist of a fan, an electric motor, a drive system, ducts or piping, flow control devices, and air conditioning equipment (filters, cooling coils, heat exchangers, etc.). An example system is illustrated in Fig. 5.1.

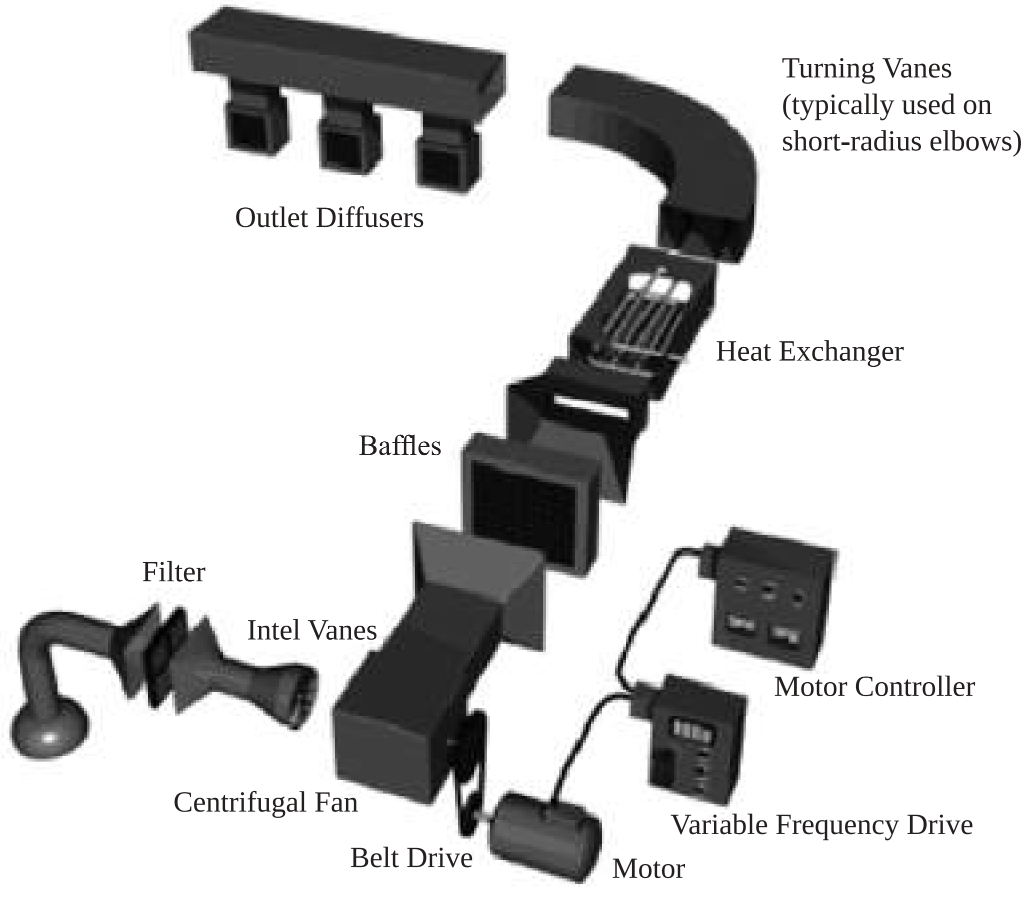


Fig. 5.1 Typical fan system components

[Source: US Department of Energy (DOE), 1989]

5.2 Difference Between Fans, Blowers and Compressors

Fans, blowers and compressors are differentiated by the methods used to move air, and by the system pressure they must operate against. As per the American Society of Mechanical Engineers (ASME) the specific ratio –the ratio of the discharge pressure over the suction pressure – is used for defining the fans, blowers and compressors (see Table 5.1).

Equipment	Specific Ratio	Pressure rise (mmWg)
Fans	Up to 1.11	1136
Blowers	1.11 to 1.20	1136-2066
Compressors	More than 1.20	-

Table 5.1 Differences between fans, blowers and compressors

5.3 Types of Fans and Blowers

Fan and blower selection depends on the volume flow rate, pressure, type of material handled, space limitations, and efficiency.

5.3.1 Types of Fan

Fan efficiencies differ from design to design and also by types. Typical ranges of fan efficiencies are given in Table 5.2.

Type of fan	**Peak Efficiency Range**
Centrifugal Fan	
Airfoil, backward curved/ inclined	79-83
Modified radial	72-79
Radial	69-75
Pressure blower	58-68
Forward curved	60-65
Axial fan	
Vanaxial	78-85
Tubeaxial	67-72
Propeller	45-50

Table 5.2 Fan efficiencies

- Fans are divided into two general categories:
    - centrifugal flow
    - axial flow
- In centrifugal flow, airflow changes direction twice – once when entering and secondly, while leaving (forward curved, backward curved or inclined, radial) (see Fig. 5.2).

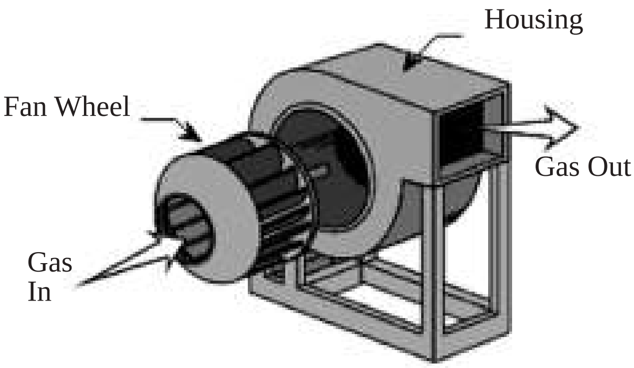


Fig. 5.2 Centrifugal flow fan

- Centrifugal fans increase the speed of an air stream with a rotating impeller. The speed increases as the air stream reaches the ends of the blades, which is then converted into pressure. These fans are able to produce high pressures, which makes them suitable for harsh operating conditions, such as systems with high temperatures, moist or dirty air streams and material handling. Centrifugal fans are categorized by their blade shapes as summarized in Table 5.3.

Type of fan and blade	Advantages	Disadvantages
Radial fans, with flat blades	• Suitable for high static pressures (up to 1400 mmWC) and high temperatures	Only suitable for low-medium airflow rates
	• Simple design allows custom build units for special applications • Can operate at low air flows without vibration problems • High durability • Efficiencies up to 75% • Have large running clearances, which is useful for airborne-solids (dust, wood chips and metal scraps) handling services	
Forward curved fans, with forward curved blades	• Can move large air volumes against relatively low pressure ▪ Relative small size ▪ Low noise level (due to low speed) and well suited for residential heating, ventilation, and air conditioning (HVAC) applications	• Only suitable for clean service applications but not for high pressure and harsh services • Fan output is difficult to adjust accurately • Driver must be selected carefully to avoid motor overload because power curve increases steadily with airflow • Relatively low energy efficiency (55-65%)

Backward inclined fan, with blades that tilt away from the direction of rotation: flat, curved, and airfoil	• Can operate with changing static pressure (as this does not overload the motor) • Suitable when system behaviour at high air flow is uncertain ▪ Suitable for forced-draft services ▪ Flat bladed fans are more robust ▪ Curved blades fans are more efficient (exceeding 85%) ▪ Thin air-foil blades fans are most efficient	• Not suitable for dirty air streams (as fan shape promotes accumulation of dust) • Airfoil blades fans are less stable because of staff as they rely on the lift created by each blade • Thin airfoil blades fans subject to erosion

Table 5.3 Types of centrifugal fans
(Source US DOE, 1989)

- In axial flow, air enters and leaves the fan with no change in direction (propeller, tube axial, vane axial) (see Fig. 5.3).

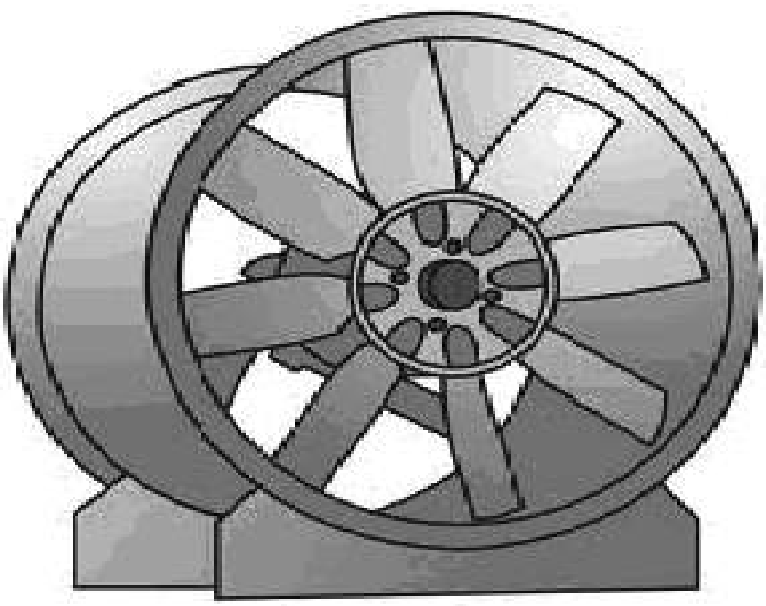


Fig. 5.3 Axial flow fan

- Axial fans move an air stream along the axis of the fan. The way these fans work can be compared to a propeller on an aeroplane; the fan blades generate an aerodynamic lift that pressurizes the air. They are popular in industry because of their cost effectiveness, compact form and lightness in weight. The main types of axial flow fans are summarised in Table 5.4.

Type of fan	Advantages	Disadvantages
Propeller fan	• generate high airflow rates at low pressures • not combined with extensive ductwork (because they generate little pressure) • inexpensive because of their simple construction • achieve maximum efficiency, near-free delivery, and are often used in rooftop ventilation applications • can generate flow in reverse direction, which is helpful in ventilation applications	• relative low Energy efficiency • comparatively noisy
Tube-axial fan, essentially a propeller fan placed inside a cylinder	• higher pressures and better operating efficiencies than propeller fans • suited for medium-pressure, high airflow rate applications, e.g. ducted HVAC installations • can quickly accelerate to rated speed (because of their low rotating mass) and generate flow in reverse direction, which is useful in many ventilation applications • create sufficient pressure to overcome duct losses and are relatively space efficient, which is useful for exhaust applications	• relatively expensive • moderate airflow noise • relatively low energy efficiency (65%)

Vane-axial fan	• suited for medium- to high pressure • applications (up to 500 mmWC), such as induced draft service for a boiler exhaust • can quickly accelerate to rated speech (because of their low rotating mass) and generate flow in reverse directions, which is useful in many ventilation applications • suited for direct connection to motor shafts • most energy efficient (up to 85% if equipped with airfoil fans and small clearances)	• relatively expensive compared to propeller fans

Table 5.4 Types of axial fans
(Source from US DOE, 1989)

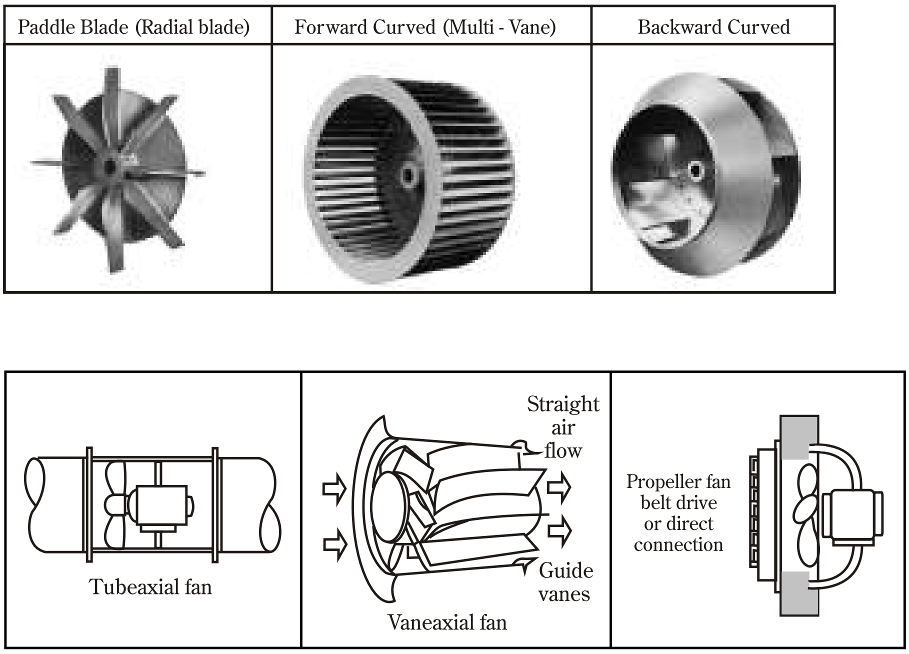


Fig. 5.4 Types of centrifugal and axial fans

5.3.2 Types of Blowers

Blowers can achieve much higher pressures than fans, as high as 1.20 kg/cm^2. They are also used to produce negative pressures for industrial vacuum systems.

Major types are:

- centrifugal blower
- positive-displacement blower

Centrifugal blowers

Centrifugal blowers look more like centrifugal pumps compared to 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. In a single-stage blower, air does not take many turns, and hence it is more efficient.

Centrifugal blowers typically operate against pressures of 0.35- 0.70 kg/cm^2, but can achieve higher pressures. One characteristic is that, air-flow tends to drop drastically as system pressure increases. This can be a disadvantage in material conveying systems that depend on a steady air volume. As a result of which, they are most often used in applications that are not prone to clogging.

Fig. 5.5 Centrifugal blowers

Positive-displacement blowers

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. They are especially suitable for applications prone to clogging, since they can produce enough pressure -typically up to 1.25 kg/cm^2 - to blow clogged materials free. They turn much slower than centrifugal blowers (e.g. 3,600 rpm), and are often belt driven to facilitate speed changes.

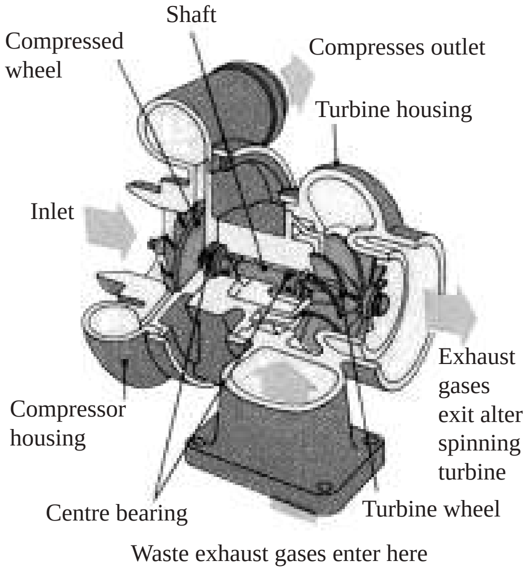


Fig. 5.6 Positive-displacement blowers

5.4 Fan Performance Evaluation and Efficient System Operation

5.4.1 System Characteristics

- The term “system resistance” is used while 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.
- The system resistance varies with the square of the volume of air flowing through the system. For a given volume of air, the fan with narrow ducts and multiple short radius elbows in a system is going to work harder to overcome a greater system resistance than it would have had in a system with larger ducts and a minimum number of long radius turns.
- Long narrow ducts with many bends and twists will require more energy to pull air through them. Consequently, for a given fan speed, the fan will be able to pull less air through this system than through a short system with no elbows. Thus, system resistance increases substantially as the volume of air flowing through the system increases; square of air flow.
- Conversely, resistance decreases as flow decreases. To determine what volume the fan will produce, it is necessary to know the system resistance characteristics.
- In existing systems, system resistance can be measured. In systems that have been designed, but not built, it must be calculated. Typically a system resistance curve (see Fig. 5.7) is generated for various flow rates on the X-axis and the associated resistance on the Y-axis.

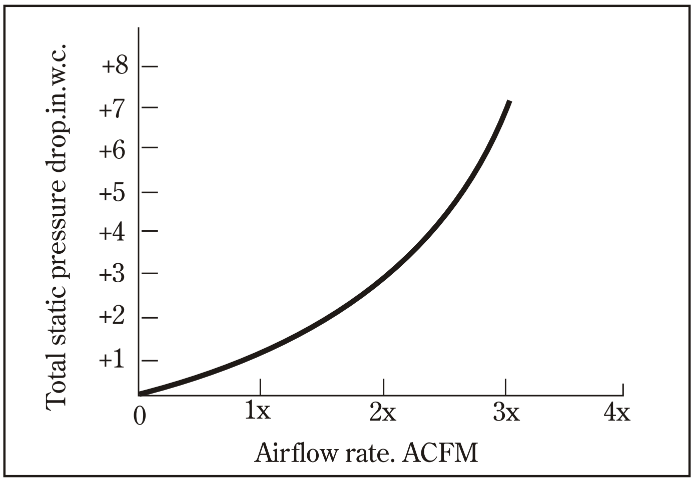


Fig. 5.7 System characteristics

5.5 Fan Characteristics

- 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.
- Typically, a curve will be developed for a given set of conditions usually including fan volume, system static pressure, fan speed and brake horsepower required to drive the fan under the stated conditions.
- Some fan curves will also include an efficiency curve so that a system designer will know where on that curve the fan will be operating under the chosen conditions (see Fig.5.8). In the many curves shown in the figure, the curve static pressure (SP) vs. flow is especially important.
- The intersection of the system curve and the static pressure curve defines the operating point. When the system resistance changes, the operating point also changes. Once the operating point is fixed, the power required could be found by following a vertical line that passes through the operating point to an intersection with the power (BHP) curve.

- A horizontal line drawn through the intersection with the power curve will lead to the required power on the right vertical axis. In the depicted curves, the fan efficiency curve is also presented.

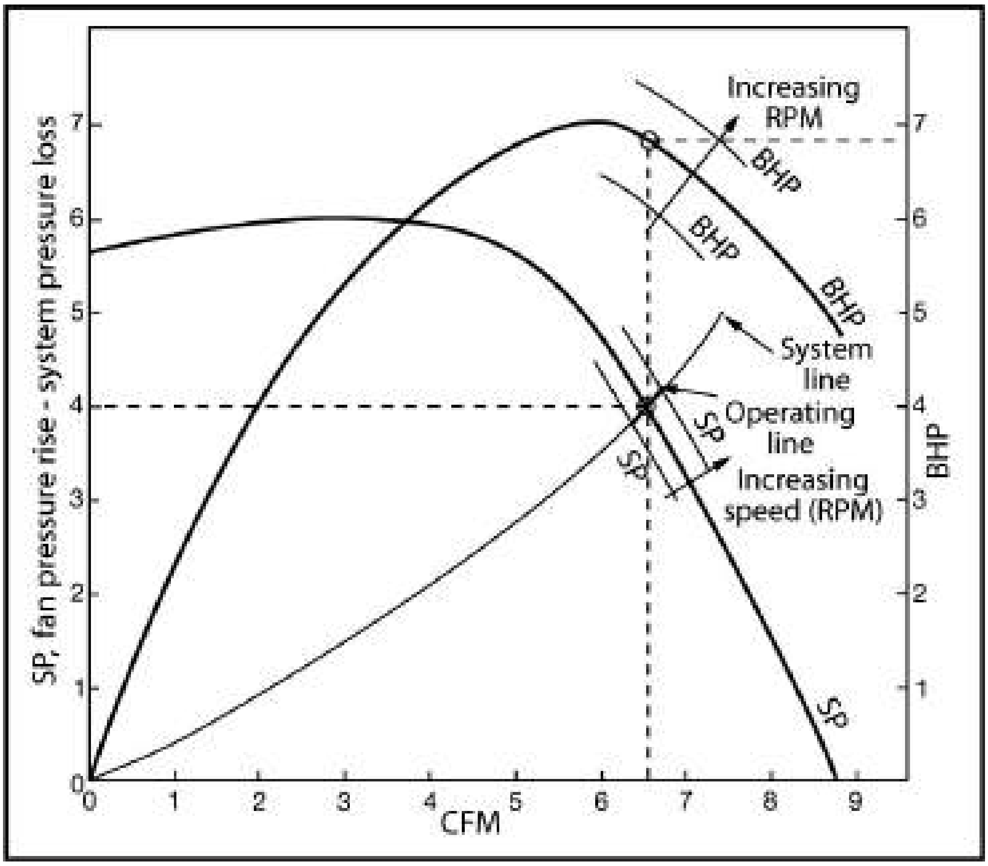


Fig. 5.8 Fan characteristics curve by manufacturer

5.6 System Characteristics and Fan Curves

In any fan system, the resistance to air flow (pressure) increases when the flow of air is increased. As mentioned before, it varies as the square of the flow. The pressure required by a system over a range of flows can be determined and a "system performance curve" can be developed (shown as SC) (see Fig. 5.9).

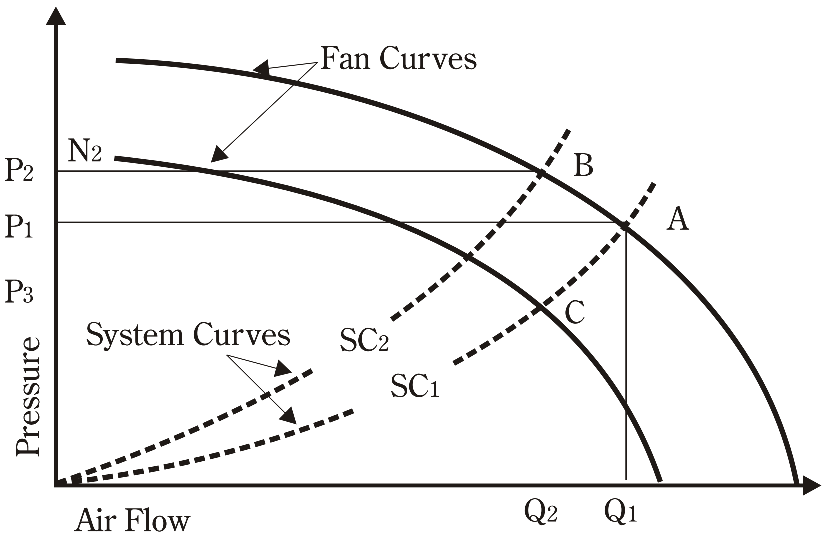
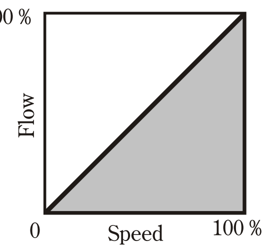
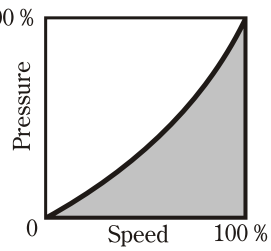
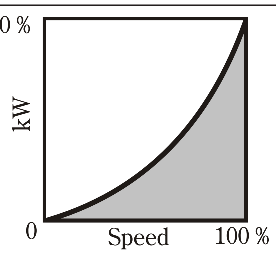


Fig. 5.9 System curve

- This system curve can then be plotted on the fan curve to show the fan's actual operating point at "A" where the two curves (N_1 and SC_1) intersect. This operating point is at air flow Q_1 delivered against pressure P_1.
- A fan operates along a performance given by the manufacturer for a particular fan speed. (The fan performance chart shows performance curves for a series of fan speeds.) At fan speed N_1, the fan will operate along the N_1 performance curve as shown in Fig. 5.9. The fan's actual operating point on this curve will depend on the system resistance; fan’s operating point at “A” is flow (Q_1) against pressure (P_1).
- Two methods can be used to reduce air flow from Q_1 to Q_1:
  - First method is to restrict the air flow by partially closing a damper in the system. This action causes a new system performance curve (SC_2) where the required pressure is greater for any given air flow. The fan will now operate at "B" to provide the reduced air flow Q_2 against higher pressure P_2.
  - Second method to reduce air flow is by reducing the speed from N_1 to N_2, keeping the damper fully open. The fan would operate at "C" to provide the same Q_2 air flow, but at a lower pressure P_3.
- Thus, reducing the fan speed is a much more efficient method to decrease airflow since less power is required and less energy is consumed.

5.7 Fan Laws

The fans operate under a predictable set of laws concerning speed, power and pressure. A change in speed (rpm) of any fan will predictably change the pressure rise and power necessary to operate it at the new RPM. This is shown in Fig. 5.10.

Flow ∞ Speed	Pressure ∞ (Speed)2	Power ∞ (Speed)3
		
$\frac{Q_1}{Q_2} = \frac{N_1}{N_2}$	$\frac{SP_1}{SP_2} = \left(\frac{N_1}{N_2}\right)^2$	$\frac{kW_1}{kW_2} = \left(\frac{N_1}{N_2}\right)^2$
Varying the RPM by 10% decreases or increases air delivery by 10%.	Reducing the RPM by 10% decreases the static pressure by 19% and an increase in RPM by 10% increases the static pressure by 21%.	Reducing the RPM by 10% decreases the power requirement by 27% and an increase in RPM by 10% increases the power requirement by 33%

Where,
Q – flow
SP – Static Pressure
kW – Power
N – speed (RPM)

Fig. 5.10 Speed, pressure and power of fans
(Source - Bureau of Energy Efficiency India, 2004)

5.8 Fan Design and Selection Criteria

- The precise determination of air-flow and required outlet pressure is the most important step in the proper selection of fan type and size. The air-flow required depends on the process requirements; normally determined from heat transfer rates or combustion air or flue gas quantity to be handled.
- The system pressure requirement is usually more difficult to compute or predict. A detailed analysis should be carried out to determine pressure drop across the length, bends, contractions and expansions in the ducting system, pressure drop across filters, drop in branch lines, etc.

- These pressure drops should be added to any fixed pressure required by the process (in the case of ventilation fans there is no fixed pressure requirement). Frequently, a very conservative approach is adopted allocating large safety margins, resulting in over-sized fans which operate at flow rates much below their design values and, consequently, at very poor efficiency.
- Once the system flow and pressure requirements are determined, the fan and impeller type are then selected. For best results, values should be obtained from the manufacturer for specific fans and impellers.
- The choice of fan type for a given application depends on the magnitudes of the required flow and static pressure. For a given fan type, the selection of the appropriate impeller depends additionally on rotational speed.
- The speed of operation varies with the application. High speed small units are generally more economical because of their higher hydraulic efficiency and relatively low cost. However, at low pressure ratios, large, low-speed units are preferable.

5.8.1 Fan Performance and Efficiency

Typical static pressures and power requirements for different types of fans are given in the Figure 5.11. Also fan performance characteristics based on the fan and impeller type (See Fig. 5.12).

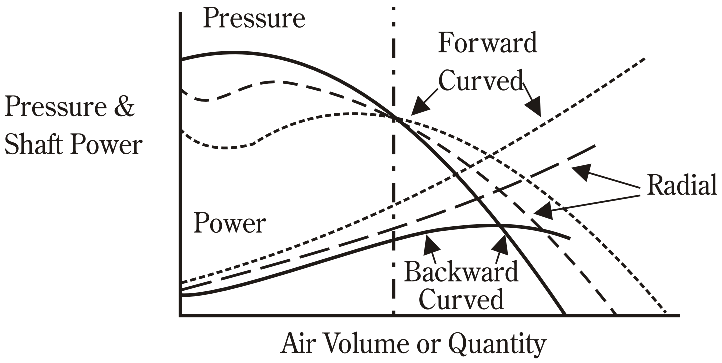


Fig. 5.11 Fan static pressure and power requirements for different fans

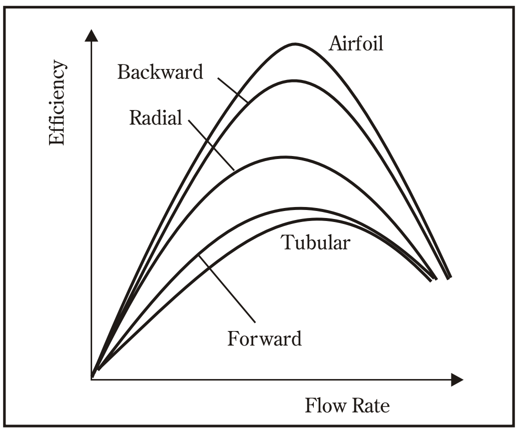


Fig .5.12 Fan performance characteristics based on fans/ impellers

- In the case of centrifugal fans, the hub-to-tip ratios (ratio of inner-to-outer impeller diameter), the tip angles (angle at which forward or backward curved blades are curved at the blade tip - at the base the blades are always oriented in the direction of flow), and the blade width determine the pressure developed by the fan.
- Forward curved fans have large hub-to-tip ratios compared to backward curved fans and produce lower pressure.
- Radial fans can be made with different heel-to-tip ratios to produce different pressures.
- At both design and off-design points, backward-curved fans provide the most stable operation. Also, the power required by most backward curved fans will decrease at a flow higher than the design values.

- A similar effect can be obtained by using inlet guide vanes instead of replacing the impeller with different tip angles. Radial fans are simple in construction and are preferable for high-pressure applications.
- Forward curved fans however, are less efficient than backward curved fans and power rises continuously with flow. Thus, they are generally more expensive to operate despite their lower first cost.
- Among centrifugal fan designs, aerofoil designs provide the highest efficiency (upto 10% higher than backward curved blades), but their use is limited to clean, dust-free air.
- Axial-flow fans produce lower pressure than centrifugal fans, and exhibit a dip in pressure before reaching the peak pressure point. Axial-flow fans equipped with adjustable / variable pitch blades are also available to meet varying flow requirements.
- Propeller-type fans are capable of high-flow rates at low pressures. Tube-axial fans have medium pressure, high flow capability and are not equipped with guide vanes.
- Vane-axial fans are equipped with inlet or outlet guide vanes, and are characterised by high pressure, medium flow-rate capabilities.
- Performance is also dependent on the fan enclosure and duct design. Spiral housing designs with inducers, diffusers are more efficient as compared to square housings. The density of inlet air is another important consideration, since it affects both volume flow-rate and capacity of the fan to develop pressure.
- Inlet and outlet conditions (whirl and turbulence created by grills, dampers, etc.) can significantly alter fan performance curves from that provided by the manufacturer (which are developed under controlled conditions).
- Bends and elbows in the inlet or outlet ducting can change the velocity of air, thereby changing fan characteristics (the pressure drop in these elements is attributed to system resistance). All these factors, termed the System Effect Factors, should, therefore, be carefully evaluated during fan selection since they would modify the fan performance curve.
- Centrifugal fans are suitable for low to moderate flow at high pressures, while axial-flow fans are suitable for low to high flows at low pressures. Centrifugal fans are generally more expensive than axial fans. Fan prices vary widely based on the impeller type and the mounting (direct-or-belt-coupled, wall-or-ductmounted).
- Among centrifugal fans, aerofoil and backward-curved blade designs tend to be somewhat more expensive than forward-curved blade designs and will typically provide more favourable economics on a life-cycle basis.
- Reliable cost comparisons are difficult since costs vary with a number of application-specific factors. A careful technical and economic evaluation of the available options is important in identifying the fan that will minimise life-cycle costs in any specific application.

5.8.2 Safety Margin

The choice of the safety margin also affects the efficient operation of the fan. In all cases where fan requirement is linked to the process/other equipment, the safety margin is to be decided, based on the discussions with the process equipment supplier. In general, the safety margin can be 5% over the maximum requirement on flow rate.
In the case of boilers, the induced draft (ID) fan can be designed with a safety margin of 20% on the volume and 30% on the head. The forced draft (FD) fans and primary air (PA) fans do not require any safety margins. However, safety margins of 10% on volume and 20% on pressure are maintained for FD and PA fans.

- Some Pointers on Fan Specifications

The right specifications of the parameters of the fan at the initial stage are a prerequisite for choosing the appropriate and energy efficient fan.

The user should specify the following information to the fan manufacturer to enable the right selection:

- design operating point of the fan- volume and pressure
- normal operating point volume and pressure
- maximum continuous rating

Low load operation: This is particularly essential for units, which in the initial few years may operate at lower capacities, with plans for up-gradation at a later stage. The initial low load and the later higher load operational requirements need to be specified clearly, so that, the manufacturer can supplies a fan which can meet both the requirements, with different sizes of the impeller.

The maximum temperature of the gas at the fan during upset conditions should be specified to the supplier. This will enable the choice of the right material of the required creep strength. In addition, the following data should be furnished to the supplying the fan for proper design.

- The density of the gas at different temperatures at the fan outlet.
- Composition of the gas -- This is very important for choosing the material of construction of the fan.
- Dust concentration and nature of dust. Dust concentration and the nature of dust (e.g. bagasse- soft dust, coal-hard dust) should be clearly specified.
    - The proposed control mechanisms that are going to be used to control the fan.
    - Operating frequency varies from plant-to-plant, depending on the source of the power supply. Since this has a direct effect on the speed of the fan, the frequency prevailing or being maintained in the plant also needs to be specified to the supplier.
    - Altitude of the plant.
    - The choice of speed of the fan can be best left to the fan manufacturer. This will enable him to design the fan of the highest possible efficiency. However, if the plant has some preferred speeds on account of any operational need, the same can be communicated to the fan supplier.

5.8.3 Installation of the Fan

- The installation and mechanical maintenance of the fan play a critical role with efficiency. The following clearances (typical values) should be maintained for the efficient operation of the impeller.
- Impeller Inlet Seal Clearances
    - Axial overlap 5 to 10 mm for 1 metre plus dia impeller
    - Radial clearance 1 to 2 mm for 1 metre plus dia impeller
    - Back plate clearance 20 to 30 mm for 1 metre plus dia impeller
    - Labyrinth seal clearance 0.5 to 1.5 mm
- The inlet damper positioning is also to be checked regularly so that the "full open" and "full close" conditions are satisfied. The fan user should get all details of the mechanical clearances from the supplier at the time of installation. These should be strictly adhered to, for the efficient operation of the fan.
- A checklist on these clearances should be prepared and checked after every maintenance activity so that the efficient operation of the fan is ensured on a continuous basis.

5.8.4 System Resistance Change

- System resistance has a major role in determining the performance and efficiency of a fan. System resistance also changes depending on the process. Example, the formation of the coatings / erosion of the lining in the ducts, changes system resistance marginally.
- In some cases, the change of equipment (e.g. Replacement of Multi-cyclones with ESP / Installation of low pressure drop cyclones in the cement industry), duct modifications, drastically shift the operating point, resulting in lower efficiency. In such cases, to maintain efficiency as before, the fan has to be changed.
- Hence, system resistance has to be periodically checked, more so when modifications are introduced and actions taken accordingly, for the efficient operation of the fan.

5.9 Flow Control Strategies

Typically, once a fan system is designed and installed, the fan operates at a constant speed. There may be occasions when a speed change is desirable, i.e., when adding a new run of duct that requires an increase in air flow (volume) through the fan. There are also instances when the fan is oversized and flow reductions are required.

Various ways to achieve a change in flow are: pulley change, damper control, inlet guide vane control, variable speed drive and the series and parallel operation of fans.

5.9.1 Pulley Change

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.

For this, the fan must be driven by a motor through a v-belt system. The fan speed can be increased or decreased with a change in the drive pulley or the driven pulley or in some cases, both pulleys.
As shown in Figure 5.13, a higher sized fan operating with damper control was downsized by reducing the motor (drive) pulley size from 8” to 6”. The power reduction was 12 kW.

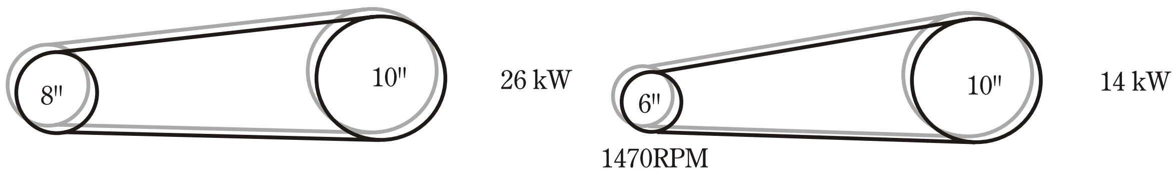


Fig.5.13 Pulley change

5.9.2 Damper Controls

Some fans are designed with damper controls (see Figure 5.14). 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. However, dampers provide a limited amount of adjustment, and they are not particularly energy efficient.

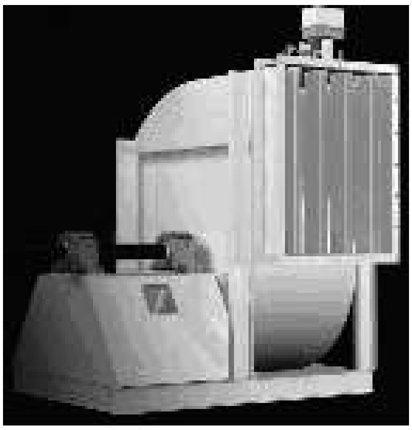


Fig. 5.14 Damper control

Inlet guide vanes are another mechanism that can be used to meet the variable air demand (see Fig. 5.15).

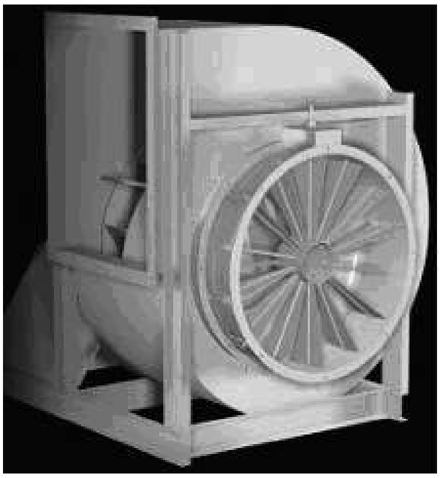


Fig. 5.15 Inlet guide vanes

Guide vanes are curved sections that lay against the inlet of the fan when they are open. But when closed, the vanes extend out into the air stream. As they are closed, guide vanes pre-swirl the air entering the fan housing. This changes the angle at which air is presented to the fan blades, which, in turn, changes the characteristics of the fan curve. Guide vanes are energy efficient for modest flow reductions from 100 percent flow to about 80 percent. Below 80 % flow, energy efficiency drops sharply.

Axial-flow fans can be equipped with variable pitch blades, which can be hydraulically or pneumatically controlled to change blade pitch, while the fan is stationary. Variable-pitch blades modify fan characteristics substantially and thereby provide dramatically higher energy efficiency than the other options discussed thus far.

5.9.3 Variable Speed Drives

- Although variable speed drives are expensive, they provide almost infinite variability in speed control. Variable speed operation involves reducing the speed of the fan to meet reduced flow requirements.
- Fan performance can be predicted at different levels of speed using the fan laws. Since the power input to the fan changes as the cube of the flow, this will usually be the most efficient form of capacity control. However, variable speed control may not be economical for systems which have infrequent flow variations.
- When considering variable speed drive, the efficiency of the control system (fluid coupling, eddy-current, VFD, etc.) should be accounted for in the analysis of power consumption.

5.9.4 Series and Parallel Operation

- Parallel operation of fans is another useful form of capacity control. Fans in parallel can be additionally equipped with dampers, variable inlet vanes, variable-pitch blades, or speed controls to provide a high degree of flexibility and reliability.
- Combining fans in series or parallel can achieve the desired air flow without greatly increasing the system package size or fan diameter. Parallel operation is defined as having two or more fans blowing together side by side.
- The performance of two fans in parallel will result in doubling the volume flow, but only at free delivery.

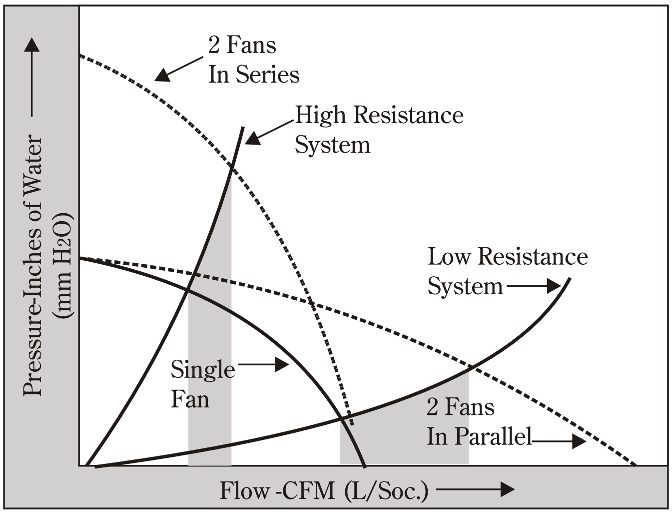


Fig.5.16 Series and parallel operation

- As Figure 5.16 shows, when a system curve is overlaid on the parallel performance curves, the higher the system resistance, the less increase in flow results with parallel fan operation. Thus, this type of application should only be used when the fans can operate at a low resistance almost in a free delivery condition.
- Series operation can be defined as using multiple fans in a push-pull arrangement. By staging two fans in series, the static pressure capability at a given airflow can be increased, but again, not to double at every flow point, as the above figure displays.
- In series operation, the best results are achieved in systems with high resistance. In both series and parallel operation, particularly with multiple fans, certain areas of the combined performance curve will be unstable and should be avoided. This instability is unpredictable and is a function of the fan and motor construction and the operating point.
- Factors to be considered in the selection of flow control methods are a comparison of various volume control methods with respect to power consumption (%) required power are shown in Fig. 5.17.

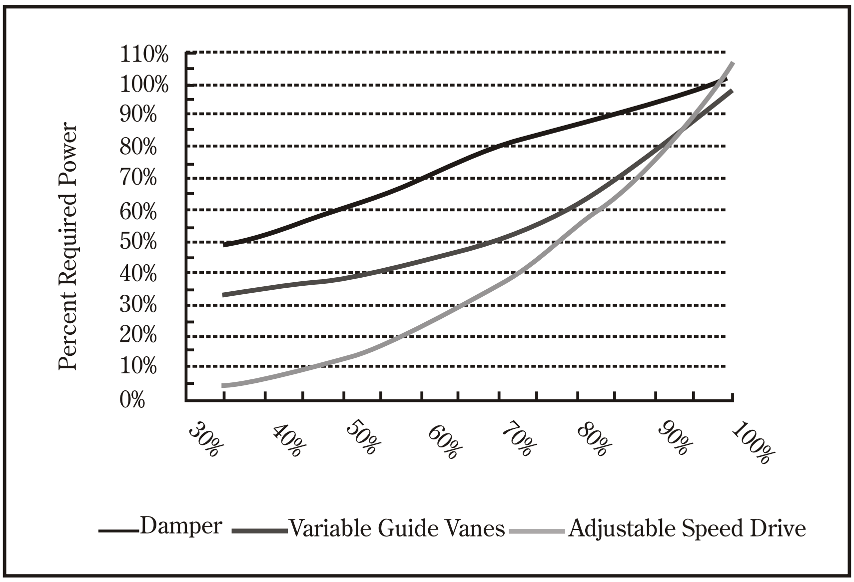


Fig.5.17 Comparison of various volume control methods

- All methods of capacity control mentioned above have turn-down ratios (ratio of maximum to minimum flow rate) determined by the amount of leakage (slip) through the control elements.