Module 2

2.1. Refrigeration

Refrigeration is the process of maintaining a system at a temperature below the temperature of its surroundings. It can be accomplished by removing heat from the system. For example the household refrigerator absorbs heat from the food products and release this heat into the room where it is kept and thus a constant temperature is maintained inside the refrigerator cabinet. The equipments employed to maintain the system at a lower temperature is termed as refrigerating system and the system which is kept at lower temperature is called refrigerated system. The working fluid used in a refrigerating system is known as refrigerant.

Refrigeration may be obtained by adopting either natural methods or artificial methods. Natural methods include melting of ice. When ice melts, the heat from its surroundings flows into the ice and the surrounding space gets cooled. The natural methods of refrigeration were used in early days. Now, with the development of artificial means of refrigeration (mechanical refrigeration) the application of natural methods becomes insignificant. Hence the term refrigeration is actually used in these days for cooling by mechanical means.

The applications of refrigeration can be broadly classified into three groups as:

(i) Industrial processes which includes processing of food stuffs, farm crops, photographic materials, petroleum and other chemical products, treatment of concrete for dams, processing in textile mills, printing works etc.

(ii) Preservation of perishable goods which includes storage and transportation of food stuffs (eg. Fish, fruits, vegetables, meats, dairy products, poultry products etc).

(iii) Providing comfortable environment which includes comfort air conditioning of residences, hospitals, theatres, offices etc.

2.2. Unit of refrigeration

The rate of heat absorbed from a body or space to be cooled is termed as refrigerating effect. The standard unit of refrigeration is ton refrigeration or simply ton.

The rate of heat absorbed by the system from the body to be cooled, equivalent to the latent heat of fusion of one ton of ice from and at 0°C in 24 hours is called one ton refrigeration. The term ton refrigeration is a carry over from the time ice was used for cooling. This unit of refrigerating capacity is currently used in USA, UK and India. In many countries the standard MKS unit of kcal per hr. is in use. In general, one ton refrigeration always means 3.5167 kJ of heat removal per second.

2.3. Reversed Carnot cycle

A Carnot cycle consists of four reversible processes: two isothermal processes and two adiabatic processes [Refer section 1.4]. Here heat is absorbed from a hot reservoir at constant temperature T_1 and rejected to a cold reservoir at constant temperature T_3. The efficiency of Carnot cycle

$$= \frac{\text{Work done}}{\text{Heat absorbed}} = \frac{\text{Heat absorbed - heat rejected}}{\text{Heat absorbed}}$$

$$= 1 - \frac{\text{Heat rejected}}{\text{Heat absorbed}}$$

$$= 1 - \frac{T_3}{T_1}$$

Since all the four processes in the Carnot cycle are reversible processes, it is possible to have a cycle with all the four processes reversed. This cycle is called reversed Carnot cycle. In this cycle, heat is absorbed from a cold reservoir and is rejected to a hot reservoir with the expenditure of external work. The effectiveness of this cycle is the ratio of heat absorbed to the work required for this heat absorption from the cold reservoir. This effectiveness is expressed by a term known as coefficient of performance, COP.

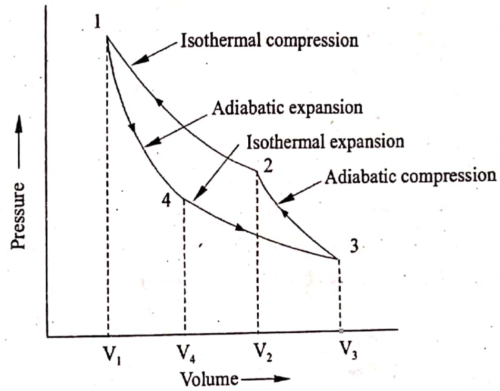


Fig. 2.1. Reversed Carnot cycle

$$\text{COP} = \frac{\text{Heat absorbed}}{\text{Work done}}$$

$$= \frac{\text{Heat absorbed}}{\text{Heat rejected - Heat absorbed}}$$

$$= \frac{1}{\frac{\text{Heat rejected}}{\text{Heat absorbed}} - 1}$$

$$=\frac{1}{\frac{T_1}{T_3}-1}$$

Example 2.1.

A Carnot cycle operates between temperatures 400K and 300K. Calculate the efficiency of Carnot cycle and COP of reversed Carnot cycle.

Solution

Given

Temperature of hot reservoir, $T_1 = 400K$

Temperature of cold reservoir, $T_3 = 300K$

$$\eta_{Carnot} = 1-\frac{T_3}{T_1}$$

$$= 1-\frac{300}{400} = 0.25$$

$$= 25\%$$

$$COP = \frac{1}{\frac{T_1}{T_3}-1} = \frac{T_3}{T_1 - T_3}$$

$$= \frac{300}{400-300}$$

$$= 3$$

2.4. Coefficient Of Performance (COP)

The effectiveness of a refrigerator is expressed by a term known as coefficient of performance. It is the ratio of desired refrigerating effect to the work spent to produce the refrigerating effect

$$COP = \frac{\text{Desired refrigerating effect}}{\text{Work spent in producing the refrigerating effect}}$$

COP of a refrigerator will be greater than unity.

2.5. Vapour compression system

In a vapour compression refrigerator the working fluid is a vapour which readily evaporates and condenses. During the evaporation process it absorbs heat and gets converted from liquid to vapour. During the condensing process it rejects heat and gets converted from vapour to liquid.

A simple vapour compression system of refrigeration consists of the following basic components:

i) Compressor

ii) Condenser

iii) Expansion valve

iv) Evaporator

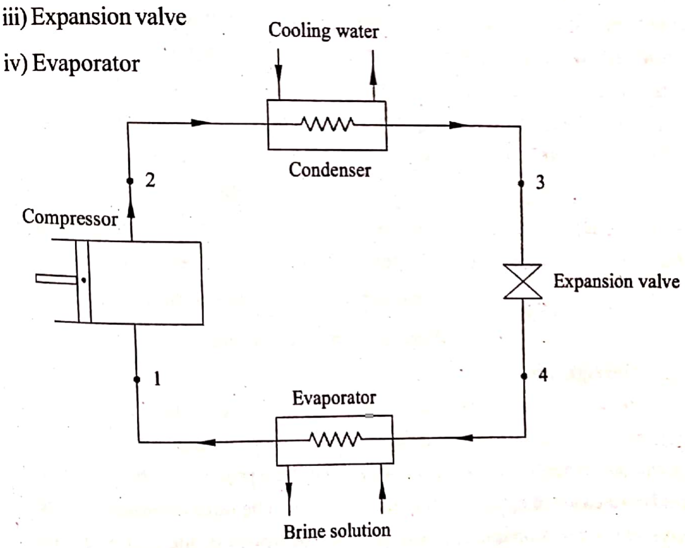


Fig. 2.2. Vapour compression cycle

The line diagram of the arrangement is shown in Fig. 2.2. Let the vapour leaving the evaporator be dry saturated. This dry saturated vapour at pressure p_1 and temperature T_1 is drawn into the compressor cylinder during its suction stroke and during the compression stroke the vapour is compressed isentropically to pressure p_2 and temperature T_2. At the end of compression the vapour is in a superheated state. The vapour at this condition passes to the condenser in which cooling water is circulated to remove heat from the vapour. The vapour is first cooled to the saturation temperature and further removal of latent heat of condensation it condenses to liquid till point 3 is reached. The high pressure liquid is expanded in an expansion valve (throttle valve). The pressure of liquid is lowered to p_1 and the condition obtained after the expansion process is shown by point 4. During throttling the liquid partly evaporates and after throttling we get wet vapour at the low temperature T_1 and low pressure p_1. This wet vapour passes through the evaporator coils immersed in the brine solution. The wet refrigerant vapour absorbs latent heat of vaporisation from the brine solution and evaporates. After evaporation the vapour reaches the condition given by point 1 ie., dry saturated at pressure p_1. This completes one cycle of operation. The cold brine solution is circulated in coils around the space to be refrigerated.

The net refrigerating effect of this system is the heat absorbed by the refrigerant from the brine solution. The work done by the compressor is the work spent to produce this refrigerating effect. Therefore,

$$COP = \frac{\text{Heat extracted in the brine solution}}{\text{Work done by the compressor}}$$

2.6. Refrigerants

The working substance used in a refrigerating system is known as refrigerant. It is actually a carrier of heat from a cold place to a hot place. It changes from liquid to vapour state during the process of absorbing heat and condenses to liquid while liberating heat. The most common refrigerants in use are ammonia, fluorinated hydrocarbons (trade name - Freon), carbon dioxide, sulphur dioxide, air, water etc.

Desirable properties of refrigerants

The important properties to be possessed by an ideal refrigerant are :

1. Condensing and evaporating pressure: Both condensing and evaporating pressure of the refrigerant should be above atmospheric pressure to avoid leakage of air into the system. But the pressure should not be very high as it requires heavy compressor, condenser etc. which increases the cost of the system.
2. Critical temperature : The critical temperature of the refrigerant should be high enough as compared to the condensing temperature, to reduce the power requirements.
3. Freezing temperature : The freezing temperature of the refrigerant should be much below the operating temperature of the plant to prevent the solidification and choking of the flow.
4. Specific heat : The specific heat of the refrigerant liquid should be low to minimise the amount of vapour formed during the throttling process.
5. Latent heat of vapourization: The latent heat of vapourisation of the refrigerant should be high to reduce the quantity of refrigerant to be circulated.
6. Specific volume: The specific volume of the refrigerant vapour should be low to reduce the size of the compressor.
7. Viscosity : Viscosity of the refrigerant should be low to reduce pressure drops, size of pipes, valves etc.
8. Thermal conductivity : The thermal conductivity of the refrigerant should be high to increase the efficiency of the condenser and evaporator..
9. Stability: The refrigerant should be chemically stable throughout the required range of operation.
10. Inflammability : The refrigerant should be non-inflammable (ie, it must not easily catch fire) to avoid fire during overheated conditions.

11. Corrosiveness: The refrigerant should be non-corrosive when comes in contact with metals.

12. Toxicity: The refrigerant should be non-toxic so that it is non-injurious to food stuff and other materials preserved.

13. Leakage detection: The refrigerant should be such that its leakage detection is simple.

14. Oil solubility: The refrigerant must not react with oil, but it must be mixable with the oil for better lubrication of the compressor.

15. Electrical resistance: The refrigerant should have high electrical resistance.

16. Availability: The refrigerant should be cheap and easily available.

2.7. Air conditioning

The science of air conditioning deals with supplying and maintaining a desired internal atmospheric condition irrespective of external conditions. This involves the simultaneous control of air purity, air motion, temperature and humidity of the air inside an enclosed space. The condition to be maintained is dictated by the need for which the conditioned space is intended.

Psychrometric properties

The properties of moist air are called psychrometric properties and the subject which deals with the behaviour of moist air is known as psychrometry. It is the foundation on which most of the air conditioning calculations are based. Several special terms used in the study of psychrometry are defined below:

1. Dry air: Dry air is a mixture of oxygen, nitrogen, carbon - dioxide, hydrogen, argon, neon, helium etc with oxygen and nitrogen as its major constituents. The volumetric composition of air is 79 % nitrogen and 21 % oxygen.

2. Moist air: It is ordinary atmospheric air which is a mixture of dry air and water vapour.

3. Saturated air: It is the air which contains maximum amount of water vapour which the air can hold at a given temperature and pressure. The maximum quantity of water vapour that can be present in the air depends up on the temperature and pressure of air.

4. Specific or absolute humidity or humidity ratio: It is defined as the ratio of the mass of water vapour to the mass of dry air in a given volume of moist air..

5. Relative humidity: It is the ratio of mass of water vapour in a given volume of moist air at a given temperature to the mass of water vapour contained in the same volume of moist air at the same temperature when the air is saturated.

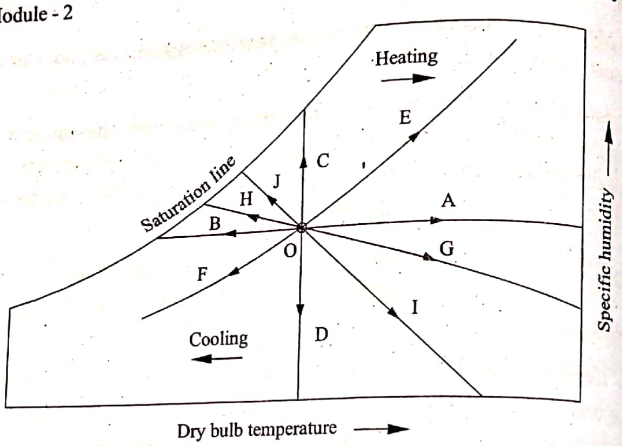
6. Dry bulb temperature: It is the temperature of air measured by an ordinary thermometer.

7. Wet bulb temperature: It is the temperature recorded by a thermometer, when its bulb is covered by a wet cloth and is exposed to a current of moving air. The difference between the dry bulb temperature and wet bulb temperature is known as wet bulb depression and it depends on the relative humidity of air. If relative humidity is high, the rate of evaporation from the wet cloth is low and hence wet bulb depression will be low. When air is dry saturated the DBT and WBT are the same.

8. Dew point temperature: It is the temperature at which the condensation of moisture begins when the air is cooled at constant pressure . The difference between dry bulb temperature and dew point temperature is known as dew point depression.

Psychrometric chart

A psychrometric chart is the graphical representation of the various thermodynamic properties of moist air. The chart enables the properties of moist air to be read off directly.



AOB - Constant dew point temperature line. COD - Constant dry bulb temperature line,

EOF - Constant relative humidity line, GOH - Constant wet bulb temperature line, IOJ - Constant specific volume line.

Fig. 2.3. Psychrometric chart

Fig. 2.3 shows a typical psychrometric chart constructed for a particular value of barometric pressure. The vertical scale of the chart is the specific humidity and the horizontal scale is the dry bulb temperature. In addition, it contains the following lines.

i) Dry bulb temperature lines: These are vertical lines drawn parallel to the ordinate.

ii) Specific humidity lines: These are horizontal lines drawn parallel to the abscissa.

iii) Wet bulb temperature lines: These are straight lines which extend diagonally.

iv) Relative humidity lines: These are curved lines parallel to the saturated line. The saturation line represents 100 % relative humidity

v) Specific volume lines: These are straight inclined lines and uniformly spaced. These lines gives the volume of dry air in m^3/kg

vi) Dew points temperature lines: These are horizontal lines, non uniformly spaced and drawn upto saturation curves.

The various basic process involved in air conditioning are :

i) Sensible heating - Process OA

(ii) Sensible cooling - Process OB

(iii) Humidifying - Process OC

(iv) Dehumidifying - Process OD

(v) Heating and humidifying - Process OE

(vi) Cooling and dehumidifying - Process OF

(vii) Cooling and humidifying - Process OH and OJ

(viii) Heating and dehumidifying - Process OG and OI.

Sensible heating and sensible cooling involve a change in dry bulb temperature. The process of humidifying and dehumidifying involve a change in the specific humidity. When the state of air moves from O to A or to B, there is no change in the moisture content of the air. Similarly when the state of air changes from O to C or to D, the DBT remains constant. The last four processes listed above involved both changes in temperature as well as humidity.

2.8. Cooling and dehumidification

Temperature control is a major process in air conditioning system. It is intended to regulate the dry bulb temperature by various psychrometric processes. This is attained by simple heating or cooling, which may be associated with humidification process.

Cooling of air means lowering its dry bulb temperature. It can be attained by passing the air over evaporator coils of a refrigerating system. In a small room air conditioner the intake air is forced to flow over the evaporator coil directly. In such a case the relative humidity aspect is neglected or is of such order that it gets adjusted by itself. In most cases, an indirect evaporator system is used for cooling the air. In such cases chilled water (or chilled brine solution) is used to cool the air. The chilled water after absorbing heat from the air rejects heat to the refrigerant in the evaporator.

Humidity control

Another important process in air conditioning is the control of humidity. This is achieved by the process of humidification (increasing humidity) or dehumidification (decreasing humidity).

Dehumidification

Dehumidification is the process of reducing water vapour content of air. It can be accomplished by the use of an air washer or by the use of absorbents. In the absorption method, air is passed through a chemical (known as drying agent). The moisture in the air enters into chemical combination with the drying agent. The chemicals like H_2SO_4 and NH_3 are normally used as drying agents. Dehumidification can also be achieved by using absorbents. These are materials having capacity to absorb moisture. Common absorbents in use are: activated alumina, calcium chloride and silica gel. Normally, this method of dehumidification is used in small air conditioners.

2.9. Summer Air Conditioning

In summer air conditioning air is cooled and generally dehumidified. The schematic arrangement of a typical summer air conditioning system is shown in Fig. 2.4. The atmospheric air flows through a damper to the air filter where dirt, dust and other impurities are removed. Air now passes through a cooling coil whose temperature is much below the required dry bulb temperature. Water is sprayed to the air. The temperature of water is below the dew point temperature of air. Due to the vapourisation of water the temperature of air further decreases. An eliminator is placed in the

path to remove water droplet carried with air. Finally this conditioned air is supplied to the required space using a blower.

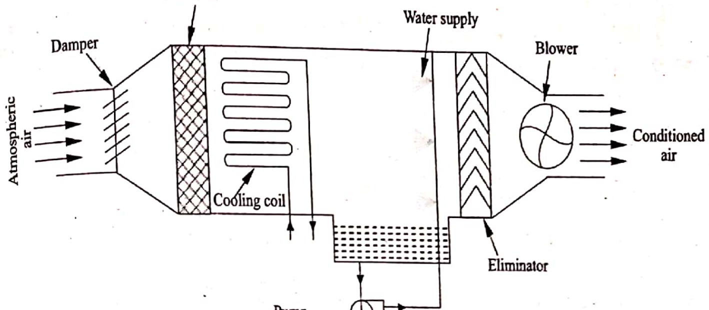
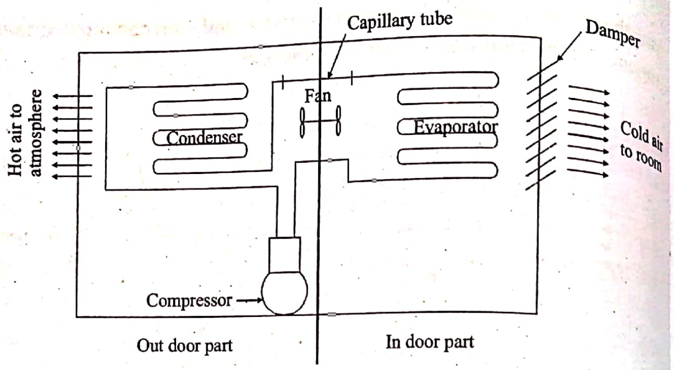


Fig. 2.4. Summer air conditioning

2.10. Unit air conditioner

A window air conditioner which is a unit air conditioner consists of a case divided into two parts, outdoor and indoor parts, by a partition. The outdoor part consists of compressor, condenser and a fan. The indoor part consists of evaporator and a fan. Capillary tube is provided in between the condenser and evaporator. The outdoor portion ramains outside the window. Dampers are provided at the front of indoor portion for changing the direction of airflow.

Low pressure vapour drawn from the evaporator is compressed to a high pressure and is delivered to the condenser. In the condenser the refrigerant vapour is condensed by releasing latent heat oil condensation to the surrounding air. This hot air is driven out using a fan. The high pressure liquid refrigerant enters the capillary tube where the pressure is reduced. This low pressure liquid vapour enters the evaporator.



Unit air conditioner

This liquid re-frigerant evaporates by absorbing latent heat of vaporization from the surrounding air. This cold air is delivered to the room using a fan. The direction of air flow can be changed using a damper. The low pressure refrigerant vapour leaving the evaporator is sucked into the compressor and is compressed to very high pressure. This high pressure vapour is condensed in the condenser. Thus one cycle of operation is completed.

2.11. Central air conditioner

This is the most important type of air conditioner. It is adopted,

(i) When the cooling capacity required is 25tons or more.

(ii) When the air flow is more than 5m^3/hr.

(iii) When different zones in a building are to be air conditioned.

In this system all the components of the system are installed in a seperate central room. The conditioned air is distributed through ducts from this central room to various rooms to be air conditioned.

2.12. Reciprocating pump

Pump is a mechanical device used to increase the pressure energy of a liquid. In most of the applications, pump is used for lifting liquids from a

lower to higher level. This is achieved by creating a low pressure at the inlet and a high pressure at the outlet of the pump. Due to the low pressure at the inlet of the pump, liquid is lifted from the sump to the pump. Due to high pressure at the outlet of the pump the liquid is lifted from the pump to the required height. Based on the working principle, pumps are classified as positive displacement and rotodynamic pumps. Reciprocating pump, gear pump, screw pump, vane pump etc., are examples of positive displacement pumps. Centrifugal pump, propeller pump etc, are examples of rotodynamic pumps. Based on a number of stages in which the pressure of the liquid is increased, rotodynamic pumps are classified as single stage and multistage pumps.

Reciprocating pump is a positive displacement pump in which the required low pressure at the inlet and the required high pressure at the outlet of the pump is obtained by the reciprocating motion of a piston or plunger inside a close fitting cylinder. The following are the main components of a reciprocating pump. 1. Cylinder, 2. Piston, 3. Piston rod, 4. Connecting rod, 5. Crank, 6. Strainer, 7. Suction pipe, 8. Suction valve, 9. Delivery valve, 10. Delivery pipe.

Working principle

Refer Fig. 2.5. Movement of piston towards right creates a vacuum inside the cylinder and atmospheric pressure forces the liquid up through the suction pipe into the cylinder. During the movement of piston towards left liquid is pushed into the delivery pipe. The suction and delivery pipes are provided with non-return valves. These non- return valves or one way valves ensure unidirectional flow of liquid. Thus the suction valve allows the liquid only to enter the cylinder and prevents the flow of liquid from the cylinder to the suction pipe. Similarly the delivery valve allows the liquids only to discharge from the cylinder and prevents the flow of liquid from the delivery pipe to the cylinder. The movement of piston inside the cylinder is obtained by connecting the piston rod to a crank by means of a connecting rod. The crank is rotated using an electric motor. Thus when the crank rotates, the piston reciprocates inside the cylinder, alternately filling and emptying the cylinder. The volume of liquid delivered is constant

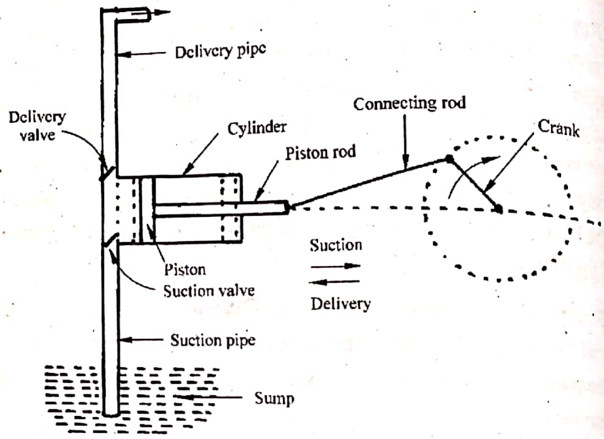


Fig. 2.5. Reciprocating pump.

regardless of pressure and is varied only due to the change of speed of rotation of the crank. A strainer is provided at the end of suction pipe in order to keep leaves, wooden pieces and other rubbish away from the pump.

2.13. Centrifugal pump

It is a rotodynamic pump in which the required low pressure at the inlet of pump and the high pressure at the outlet of the pump is obtained mainly due to centrifugal action. When a certain mass of liquid is made to rotate by an external force, it is thrown away from the axis of rotation and a centrifugal head is impressed which enables the liquid to rise to a higher level. In centrifugal pumps, in addition to the centrifugal action, as the liquid passes through the revolving wheel or impeller, the angular momentum of the liquid changes which also results in increasing the pressure of the liquid.

Impeller , casing , delivery pipe, suction pipe, foot valve and strainer are the main components of a centrifugal pump.

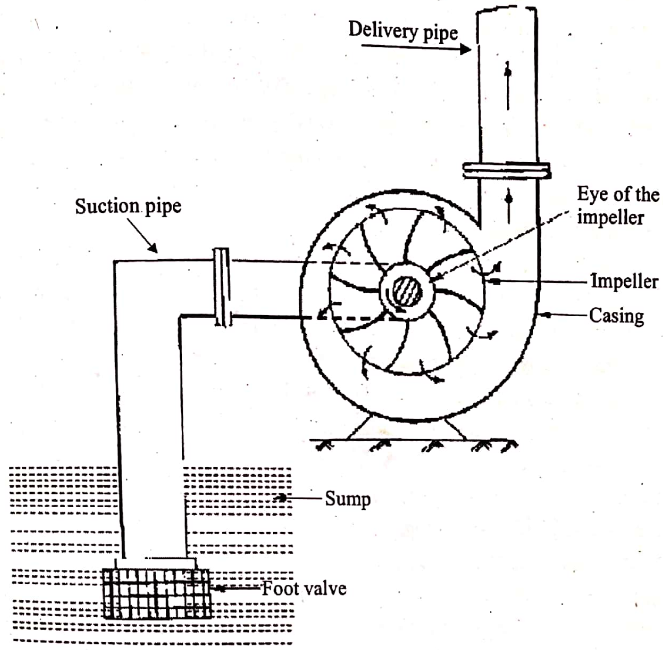


Fig. 2.6. Centrifugal pump

Refer Fig. 2.6. The impeller is a wheel or rotor which is provided with a number of curved blades or vanes. It is mounted on a shaft which is coupled to an electric motor. Casing is an air tight chamber which surrounds the impeller. The shape of the casing is such that the sectional area of flow around the periphery of the impeller gradually increases towards the delivery pipe. This gradual increase in area gradually reduces the velocity of the liquid leaving the impeller to that in the delivery pipe. This reduction in the kinetic energy of the liquid while passing through the casing is converted into useful pressure energy. Suction pipe connects the centre of the impeller to the sump from which liquid is to be pumped. The lower part of the suction pipe is fitted with a foot valve and a strainer. The liquid after filtering by the strainer passes through the foot valve. The foot valve is a non-return valve which opens only in the upward direction. Through the foot valve liquid enters the suction pipe. Delivery pipe connects the outlet of the pump to the delivery point. A valve is provided on the delivery pipe , closed to the outlet of the pump, to control the flow of liquid through the delivery pipe.

Working principle

After priming, the impeller is rotated by means of an electric motor. Filling the suction pipe and casing with the liquid to be pumped is known as priming. Priming is required to remove air and vapour from the suction pipe and casing. The removal of air from the casing is required because the vaccum crated in the eye of the impeller is proportional to the density of the liquid that is in contact with the impeller. If the impeller is made to rotate in the presence of air, the vacuum created may not be sufficient to lift the water from the sump to the eye of the impeller. Therefore it is essential to prime a centrifugal pump before it can be started. The rotation of the impeller in the casing full of liquid produces a forced vortex which imparts a centrifugal head to the liquid. This results in an increase of pressure of liquid. If the speed of the impeller of the pump is sufficiently high, the pressure of liquid in the impeller will be increased. When the delivery valve is opened the liquid within the impeller flows in an outward direction therby leaving the vanes of the impeller at the outer circumference with high velocity and pressure. The vacuum created at the eye of the impeller causes the liquid from the sump to rush through the suction pipe, replacing the liquid which is being discharged from the impeller. While the liquid flows through the rotating impeller it receives energy from the vanes which results in an increase of both pressure and velocity. The kinetic energy thus increased is converted into pressure energy while flowing through the volute casing. Thus the liquid is discharged from the pump to the delivery pipe with very high pressure.

2.14. Comparison of centrifugal and reciprocating pumps

1. The flow of liquid from a centrifugal pump is smooth and even whereas that from a reciprocating pump is pulsating.

2. Centrifugal pumps are suitable for large discahrge and low heads. Reciprocating pumps are suitable for high heads and low discharge.

3. Initial cost of centrifugal pump is less compared to the initial cost of reciprocating pumps.

4. Centrifugal pump is compact and occupies less floor space. The floor space required for a reciprocating pump is about 6 to 8 times that for a centrifugal pump.

5. Efficiency of a low head centrifugal pump is more than that of a low head reciprocating pump.

6. For small discharge and high head, the efficiency of a reciprocating pump is more than that of a centrifugal pump.

7. A centrifugal pump needs priming wheras no priming is required in a reciprocating pump.

8. Highly viscous liquid such as oils, muddy and sewage water , paper pulp etc. can be easily handled by centrifugal pumps. Valves and glands in reciprocating pumps cause trouble when it is used to pump the above said liquids.

9. Compared to reciprocating pump, the installation of centrifugal pump is easy.

10. Construction of centrifugal pump is simple. More number of parts in the reciprocating pump make the construction complicated.

11. Maintenance cost of centrifugal pump is low.

12. Due to the high speed of centrifugal pump, impeller can be directly coupled to an electric motor. In the case of reciprocating pump, some speed reduction device is required.

13. Centrifugal pump has no reciprocating parts and hence the wear and tare is less.

14. For a given discharge, the weight of centrifugal pump is less than the weight of a reciprocating pump.

2.15. Hydraulic turbine

Hydraulic turbine is a device which converts the energy of water into mechanical energy. The turbine drives the generator which converts the mechanical energy into electrical energy. Hydraulic turbine consists of a wheel called runner provided with a number of curved or straight vanes (blades) on its periphery.

Hydraulic machines are classified on the basis of the action of water on these moving blades. According to the action of water, turbines are classified as impulse turbine and reaction turbine.

2.16 Impulse turbine

In an impulse turbine, the potential energy of water is converted into kinetic energy by a set of nozzles. This produces powerful jets impinging on the vanes, buckets provided on the periphery of a wheel. The wheel is fixed to a shaft, which is coupled with a generator.

2.17. Pelton turbine

Fig. 2.7. shows a Pelton wheel hydraulic turbine, which is the most commonly used impulse turbine. The nozzle producing the jets is shown in the Fig. 2.7. There is a spear head provision in the nozzle to control the opening, which controls the velocity of the issuing jet. The buckets provided on the wheel are in the form of double hemispherical cups. The water after imparting its energy to the turbine, is discharged into the tailrace.

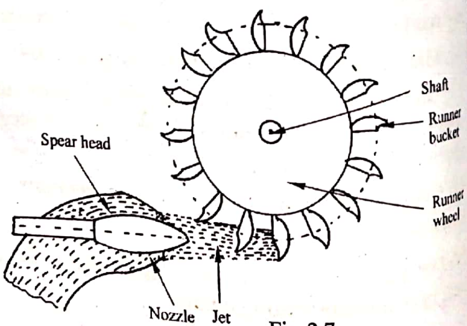


Fig. 2.7

This type of turbine is used where high head of water is

available. Other examples of impulse turbine include Turgo wheel, Jonval turbine and Girard turbine.

2.18. Francis turbine

It is a reaction turbine. In reaction turbines the water entering the runner possess pressure energy and this water in turn does work on the vanes by the principle of reaction.

Fig. 2.8. shows a simple diagramatic representation of a Francis turbine, which is the mostly used reaction turbine. It consists of an inner of rotating vanes forming the runner, surrounded by an outer ring of stationary guiding mechanism. Water from the penstock which is the pipe connecting the reservoir and the turbine flows into a scroll casing surrounding the turbine runner. From the scroll casing water flows through the guiding mechanism and enters the runner.

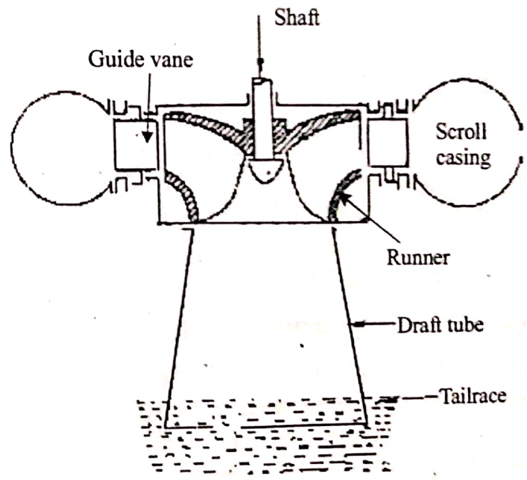


Fig. 2.8. Francis turbine

After imparting energy to the runner, the water discharges through draft tube. Draft tube is a metallic pipe or concrete tunnel having gradually increasing cross-sectional area. It connects the runner exit of the reaction turbine and the tailrace. Draft tube provides a negative suction head at the runner outlet which increases the net working head on turbine and thus the output.

2.19. Kaplan turbine

It is an axial flow reaction turbine where water enters and leaves the runner vanes parallel to the axis of shaft. It is particularly suited for low head (upto 30m) and high discharge of water. The main components of Kaplan turbine are:

1. Scroll casing
2. Guide vane mechanism
3. Boss with adjustable vanes
4. Draft tube

Since Kaplan and Francis turbines are reaction turbines, the working principle of Kaplan turbine is same as that of Francis turbine. Water from the penstock flows into the scroll casing sorrounding the turbine runner. From the scroll casing water flows through the guide mechanism and enters the runner vanes. The force exerted by water on the vanes causes the runner shaft to rotate. After imparting energy to the runner, the water is discharged through the draft tube.

2.20. Overall efficiency of centrifugal pump

Pump is a hydraulic device which convert mechanical energy of rotating shaft into kinetic and pressure energy of water. It is generally used to lift water from a low to a high level. Static head is the total vertical lift through which water is lifted by the pump. It is denoted by H. When Q m^3/s water is lifted through a height, H, the workdone/s is $\rho \times g \times QH$.

ρ is the mass density of water, $1000 kg/m^3$.

g is the acceleration due to gravity, $9.81 m/s^2$.

Q is the discharge of water in m^3/s.

H is the total head in m.

P is the power supplied from the electric motor to the pump in kW (Input power).

$$\text{Output power of pump} = \frac{\rho g\, QH}{1000}\ \text{kW}$$

$$\text{Overall efficiency } \eta_0 = \frac{\text{Output power}}{\text{Input power}}$$

$$= \frac{\rho g\, QH}{1000\, P}$$

Example 2.1

A centrifugal pump discharges water at a rate of 2000 litres/s against a head of 16m when running at 300 rpm. Calculate the power required to run the pump if the overall efficiency of pump is 50%.

Solution

Given

$$Q = 2000 lit/s = 2\ m^3/s$$

$$H = 16m$$

$$\eta_0 = 0.5$$

To calculate, P

$$\text{Overall efficiency, } \eta_0 = \frac{\rho g\, QH}{P \times 1000}$$

$$\text{Power required, } P = \frac{\rho g\, QH}{\eta_0 \times 1000}$$

$$= \frac{1000 \times 9.81 \times 2 \times 16}{0.5 \times 1000}$$

$= 627.84$ kW.

Example 2.2

A centrifugal pump discharges water at 120 litres/s against a head of 25m. If power required is 40kW, calculate the overall efficiency of the pump.

Solution

Given

$Q = 120$ lit/s $= 0.12$ m³/s

$H = 25$m

$P = 40$kW

To calculate, η_0

$$\eta_0 = \frac{\rho g QH}{P \times 1000}$$

$$= \frac{1000 \times 9.81 \times 0.12 \times 25}{40 \times 1000} \text{ kW}$$

$= 73.58\%$

2.21. Overall efficiency of turbines

A hydraulic turbine converts hydraulic energy of water into mechanical energy of a rotating shaft. Mechanical energy is the output and hydraulic energy, kinetic and potential energy of water is the input to the turbine. The overall efficiency is the ratio of output power to input power.

$$\eta_0 = \frac{\text{Output power}}{\text{Input power}}$$

Input power to Pelton wheel is the kinetic energy of jet striking the bucket

$$KE = \frac{1}{2}mv^2 = \frac{1}{2}\rho QV^2$$

Potential energy of water of head H is

$$mgH = \rho QgH$$

Equating KE and PE of water,

$$\frac{1}{2}\rho QV^2 = \rho QgH$$

$$V = \sqrt{2gH}$$

When a is the area of cross section of jet striking the bucket, then discharge from the nozzle, $Q = aV$.

a is the area of jet im m² and V is the velocity of jet in m/s.

$Q = aV$ m³/s

Output power being the power of shaft it can be measured directly.

$$\text{Overall efficiency, } \eta_0 = \frac{P \times 1000}{\rho g Q H}$$

P = output power in kW

ρ = mass density of water in kg/m³

g = acceleration due to gravity in m²/s

Q = discharge in m³/s

H = head in m.

Example 2.3

A Pelton wheel working under a head of 500m produces 15 MW at 500rpm. If the overall efficiency of the turbine is 85%, calculate the discharge of turbine.

Solution

Given

$H = 500m,\ P = 15MW = 15\times10^6 W = 15\times10^3 kW$

$$\eta_0 = 85\% = 0.85$$

To calculate, Discharge Q

$$\eta_0 = \frac{P\times1000}{\rho gQH}$$

$$Q = \frac{P\times1000}{\eta_0\rho gH}$$

$$= \frac{15\times10^3\times1000}{0.85\times1000\times9.81\times500}$$

$$= 3.6\ m^3/s$$

Example 2.4

Two jets strike the buckets of Pelton wheel which develops 15MW. The diameter of each jet is 15cm and the net head is 500m. Calculate the overall efficiency of the turbine.

Solution

Given

No. of jets = 2

Power $P = 15MW = 15\times10^3 kW$

diameter of jet = 15cm = 0.15m

H = 500m

To calculate, η_0

Discharge from one nozzle $= a\times V$

Discharge from two nozzles $= 2\times a\times V$

Velocity of jet, $V = \sqrt{2gH}$

$$= \sqrt{2\times9.81\times500}$$

$$= 99.05\ m/s$$

$$Q = 2\times a\times V$$

$$= 2\times\frac{\pi d^2}{4}\times99.05$$

$$= 3.5\ m^3/s$$

$$\eta_0 = \frac{P\times1000}{\rho gQH}$$

$$= \frac{15\times10^3\times1000}{1000\times9.81\times3.5\times500}$$

$$= 0.8737 = 87.37\%$$

Example 2.5

Calculate the discharge from a Francis turbine with overall efficiency 75%, working under a head of 7.5m and producing a power of 150kW.

Solution

Given

$$\eta_0 = 75\% = 0.75$$

$$P = 150kW$$

$H = 7.5m$

To calculate, Q

$$\eta_0 = \frac{P \times 1000}{\rho g Q H}$$

$$Q = \frac{P \times 1000}{\eta_0 \times \rho g H}$$

$$= \frac{150 \times 1000}{0.75 \times 1000 \times 9.81 \times 7.5}$$

$$= 2.72 \ m^3/s$$

Example 2.6

A Kaplan turbine working under a head of 20m develops 12000kW power. Calculate the overall efficiency of the turbine when the discharge from the turbine is $70m^3/s$.

Solution

Given

$H = 20m$

$P = 12000kW$

$Q = 70m^3/s$

To calculate, η_0

$$\eta_0 = \frac{P \times 1000}{\rho g Q H}$$

$$= \frac{12000 \times 1000}{1000 \times 9.81 \times 70 \times 20}$$

$$= 0.8737$$

$$= 87.37\%$$

2.22. Belt drive

Whenever power is to be transmitted from one shaft to another which are at a considerable distance apart, a belt drive is generally used. Pulleys are mounted on the driver and driven shafts and an endless belt is fitted tightly over these pulleys. The factor responsible for power transmission, or in other words making the belt and pulleys run together, is the frictional resistance between the belt and the pulley. The amount of power transmitted depends upon the velocity of belt, the tension under which the belt is placed on the pulleys and the arc of contact of the belt and smaller pulley.

Types of belts

Though there are many types of belts for transmission of power, flat belts and V-belts are widely used. Flat belts are used to transmit moderate amount of power. These are used upto 10m distance between driving and driven shafts. V-belts are more suitable for transmission of large amount of power between two shafts having a short center to center distance. The ideal distance is 1.25 to 1.5 times the diameter of the larger pulley.

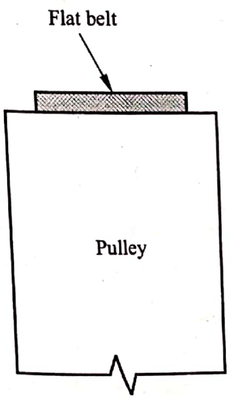


Fig. 2.9. Flat belt

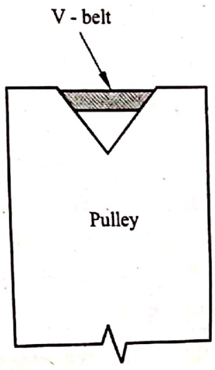


Fig. 2.10. V - belt

The belts used for transmission of power must have larger strength, flexibility and life and must have a high coefficient of friction. In addition to leather belts, belts made of rubber, balata and cotton or fabric are also widely used. Rubber belts, consisting of layers of fabric impregnated with a rubber composition and having a thin layer of rubber on the faces, are very flexible but are quickly destroyed if allowed to come in contact with oil or grease. Balata belts are similar to rubber belts except that balata gum is used in place of rubber. It is about 25 % stronger than rubber belt. Cotton or fabric belts are made from canvas or cotton duck in which a number of layers, depending upon the thickness desired are put and stitched together. These are treated with linsoil to make it water proof. The cotton belts are cheaper and suitable for rough service where little attention is needed.

Types of belt drives

(i) Open belt drive

It is used with shafts arranged in parallel and to be rotated in the same direction. The driver pulley pulls the belt from one side and delivers the

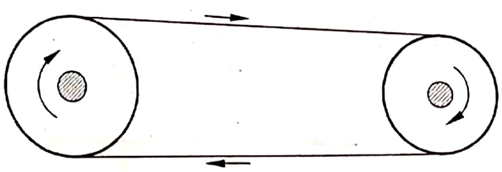


Fig. 2.11. Open belt drive.

same to the other side. Hence the tension on the former side will be greater than the later side. The side where tension is more, is called tight side and the other side is called slack side.

(ii) Cross belt drive

It is used with shafts arranged in parallel and to be rotated in opposite directions. At the point where the belt crosses, it rubs against itself and wears.

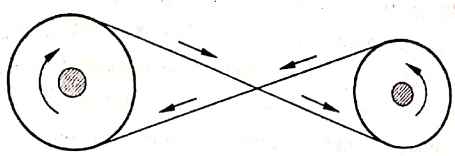


Fig. 2.12. Cross belt drive

In order to minimize wear, the shafts should be placed at a minimum distance of 20 b, where b is the width of belt. Also the speed of the belt should be less than 15 m/sec.

2.23. Chain drive

Chain drive consists of an endless chain running over special profile toothed wheels called sprockets. One of the sprockets will be the driver and the other driven. The smaller sprocket is called pinion and the bigger one is called wheel. The chain is made up of plates, pins and bushing. These parts are usually made of high grade steel.

From the application point of view chain drives are classified as power transmission chains, hoisting chains and pulling chains. Power transmission chains are used when power is to be transmitted from one shaft to another. Hoisting chains are used for lifting loads. Pulling chains are used in elevators, conveyors etc.

Main types of chains used to transmit power are:

i) Roller Chain: Refer Fig. 2.13. It consists of rollers, bushes, pins inner plates and outer plates. The pin passes centrally through the bush and the roller surrounds the bush. The roller turns freely on the bush and the bush turns freely on the

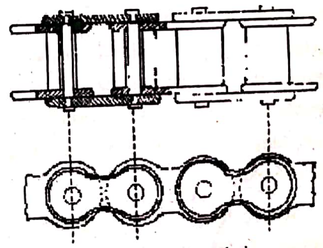


Fig. 2.13. Roller chain

pin. Two adjacent rollers are held by two inner plate (roller link plates). These inner plates connect the two bushes as shown in the figure. The bushes turn freely on the inner plates. Two adjacent bushes are held by two outer plates called pin link plates. These outer plates connect the two central pins and keep them in position. To prevent the sliding of outer plates laterally outwards, the pin ends are hammered to the shape of rivet head. In order to reduce friction all the contact surfaces are lubricated.

ii) Silent or inverted tooth chain: Refer Fig. 2.14. It consists of special profile plates corresponding to the profile of the sprocket teeth.

Fig. 2.14. Silent chain

These types of chains are more complex in design and require careful maintenance. It is employed when heavier loads are to be transmitted and maximum quietness is desired.

2.24. Gear Drive

The term gear is generally used to denote toothed wheel. For transmission of power one gear is mounted on the driving shaft and another one of the driven shaft, their teeth meshing with each other. The distance between the two shafts should be just sufficient to enable meshing of the gear teeth. If the driving and driven shafts are at a long distance so that a direct meshing of two gears is not possible, then required number of gears may have to be incorporated in between the two gears so as to make the drive possible.

Gear teeth are formed either by casting or by machine cutting. The cutting of gear teeth is done by milling, shaping or hobbing. A variety of

materials are used for the manufacture of gears depending on requirement. The cheapest material used is ordinary grey iron. For heavy duty gears cast steel and alloy steel are preferred. Non-ferrous metals like phosphor bronze, nickel, manganese etc. are used under corrosive environments.

There are many types of gears and the following are the important ones:

(i) Spur gears: Spur gears are those which have teeth cut parallel to the axis of the shaft. Spur gears are used to transmit power between parallel shafts. Fig. 2.15 (a)

(ii) Helical gears: Helical gears are used in the same way as spur gears, but the teeth cut on the periphery are of helical screw form. A helical tooth is thus inclined at an angle to the axis of the shaft. Fig. 2.15 (b)

(iii) Bevel gears : Bevel gears are used to connect two non parallel shafts with intersecting axes. Even though bevel gears are meant for shafts at right angle to each other, it can also be used for any angle. Fig. 2.15 (c)

(iv) Worm gears: Worm gears are used for power transmission between non-intersecting shafts that are generally

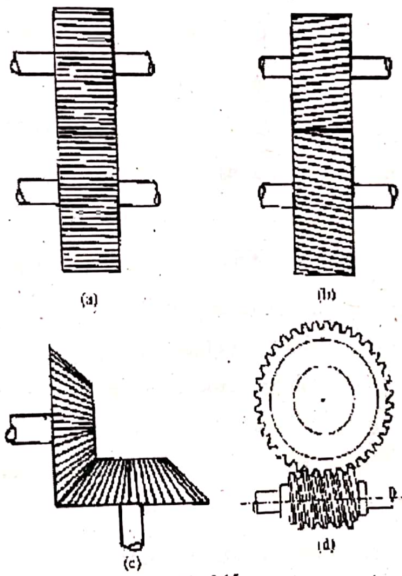


Fig. 2.15.

at right angles to each other. The worm gearing consists of worm and worm wheel. A worm is a threaded screw and is used as the driver. The worm wheel is a toothed wheel. The teeth of the worm wheel remain engaged with the threads of the worm. Fig. 2.15 (d).

Fields of Application

Belt drive is commonly used for transmission of power when exact velocity ratio is not required. Flat belts are used when the distance between the shafts is more and only moderate amount of power is to be transmitted . When the distance between the shafts is less and a large amount of power is to be transmitted, the V - belts are used. Belt drive is comparatively cheaper than other drives.

Some of the advantages of flat belts are:

(i) Can be used with high speed drives.

(ii) Can be used in industrial and abbrassive environment.

(iii) Absorbs shock and vibrations.

(iv) Offers longer life when properly maintained.

Some of advantages of V- belts are:

(i) Can be used for high speed ratios as high as 10:1.

(ii) No possibility of belt coming out of grooves.

(iii) Low percentage of slip.

(iv) A number of drives can be taken from a single pulley by providing a number of grooves on the same pulley.

Chain drives are used in bicycles, motorcycles, agriculture machinery, rolling mills, conveyors , transport mechanisms etc.

Advantages of chain drives are:

(i) Can provide non-slip drive

(ii) Very high efficiency

(iii) Less load on shafts

(iv) Occupies less space

(v) Can be operated at adverse temperatures.

(vi) Can transmit motion to several shafts by a single chain.

Disadvantages of chain drives are:

(i) High cost

(ii) More weight

(iii) Velocity fluctuations due to stretching during use.

(iv) Needs accurate mounting and careful maintenance

Gear drives are used when positive drives are necessary and when the centre to centre distance between the shafts is relatively short. Also gears are used whenever motion is to be transmitted between non parallel and non-intersecting shafts. Gears are of great practical utility in almost all kinds of precission engineering works. Hardened gear find application in aircraft, automobile and other industries.

Advantages of gear drives are:

(i) High efficiency

(ii) Less maintenance cost

(iii) Can be used for non intersecting and non parallel shafts.

(iv) Very high accuracy.

2.25. Gear

Various terms used in the study of gears have been explained below:

1. Pitch cylinders: Pitch cylinders of a pair of gears in mesh are the imaginary cylinders which by rolling together transmit the same motion as the pair of gears.

2. Pitch circle: It is the circle with radius equal to the radius of the pitch cylinder.
3. Pitch circle diameter: It is the diameter of pitch circle.
4. Pitch point: It is the point of contact of two pitch circles.
5. Circular pitch: It is the distance measured along the circumference of pitch circle from a point from one tooth to the corresponding point on the adjacent tooth. It is denoted by P_C.

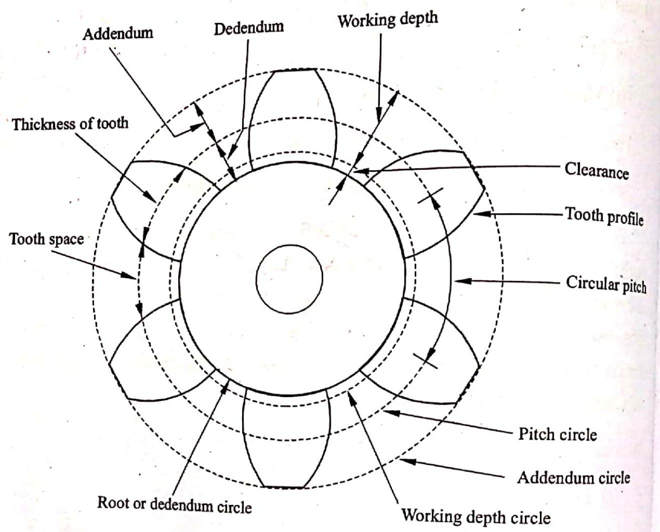


Fig. 2.16

$P_C = \frac{\pi d}{T}$, where d is the pitch circle diameter and T is the number of teeth.

6. Pitch angle: It is the angle substended by the circular pitch at the centre of the pitch circle.
7. Diametral pitch: It is the number of teeth per unit length of the pitch circle diameter. It is denoted by P.

$$P = \frac{T}{d}$$

8. Module: It is the ratio of pitch circle diameter in millimeter to the number of teeth. It is denoted by m.

$$m = \frac{d}{T}$$

9. Addendum circle: It is the circle passing through the tips of teeth.
10. Addendum: It is the radial distance between pitch circle and addendum circle.
11. Dedendum or root circle: It is the circle passing through the roots of the teeth.

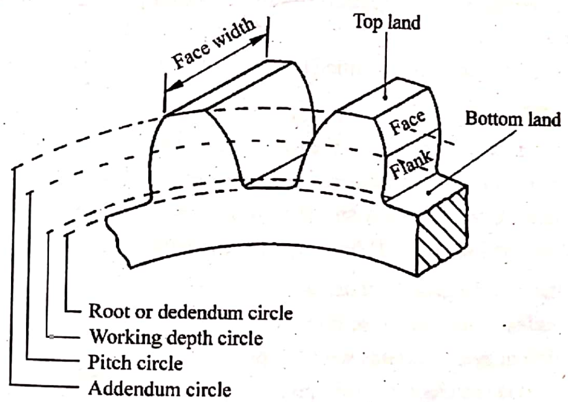


Fig. 2.17.

12. Dedendum: It is the radial distance between pitch circle and dedendum circle.
13. Full depth of teeth: It is the radial distance between dedendum circle and addendum circle

Full depth = Addendum + Dedendum

14. Clearance: It is the radial difference between the addendum and the dedendum of a tooth.

15. Top land: It is the surface at the top of tooth.
16. Bottom land: It is the surface at the root of tooth, in between two adjacent teeth.
17. Tooth thickness: It is the width of the tooth measured along the pitch circle
18. Tooth space: It is the width of space between the two adjacent teeth measured along the pitch circle.
19. Backlash: It is the difference between the tooth space and the tooth thickness, measured along the pitch circle.
20. Face: It is the tooth surface between the pitch circle and the top land.
21. Flank: It is the tooth surface between the pitch circle and the bottom land.
22. Face width: It is the length of tooth measured parallel to the axis of gear.
23. Profile: It is the curve formed by the face and flank of the tooth.

Velocity ratio of gear drive

The gear ratio is defined as the ratio of the speed of driven gear to the speed of driving gear. It is denoted by the letter 'G'. A schematic diagram of two mating spur gears A and B is shown in Fig. 2.18. Let the pitch circle diameters of A and B be d_1 and d_2 respectively.

In case the driving gear A rotates with N_1 rpm (ω_1 rad/sec) in clockwise direction, then the driven gear B rotates with N_2 rpm (ω_2 rad/sec) in anticlockwise direction.

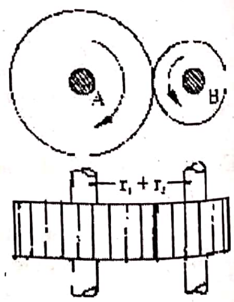


Fig. 2.18

The peripheral velocity of driving gear A is equal to $\frac{\omega_1 d_1}{2}$

The peripheral velocity of driven gear B is equal to $\frac{\omega_2 d_2}{2}$. Since the gear drive is positive, the peripheral velocity of driven gear will be equal to the peripheral velocity of the driver gear.

Hence,
$$\omega_2 \frac{d_2}{2} = \omega_1 \frac{d_1}{2}$$
$$\frac{\omega_2}{\omega_1} = \frac{d_1}{d_2}$$
$$\text{or } \frac{N_2}{N_1} = \frac{d_1}{d_2} \quad \text{.................... ..(i)}$$

Circular pitch of gear A, $p_{C1} = \pi \frac{d_1}{T_1}$ where T_1 is the number of teeth on driving gear A.

Circular pitch of gear B, $p_{C2} = \pi \frac{d_2}{T_2}$ where T_2 is the number of teeth on driven gear B.

Two gears will mesh together correctly, only if the gears have the same circular pitch.

$$\therefore p_{C1} = p_{C2}$$
$$\pi \frac{d_1}{T_1} = \pi \frac{d_2}{T_2}$$
$$\text{or } \frac{d_1}{d_2} = \frac{T_1}{T_2} \quad \text{....................(ii)}$$

From (i) and (ii)
$$\frac{N_2}{N_1} = \frac{T_1}{T_2}.$$

i.e., Velocity ratio or gear ratio, 'G', $\frac{N_2}{N_1} = \frac{T_1}{T_2} = \frac{d_1}{d_2}$

Example 2.7.

Two spur wheels, A and B, on parallel shafts, are in mesh. A has 40 teeth and rotates at 250 r.p.m. B is to rotate at 100 r.p.m. Find the number of teeth on B.

Solution:

Given: $T_A = 40$ $N_B = 100$ rpm $N_A = 250$ rpm

To find: T_B

We have, $\frac{N_B}{N_A} = \frac{T_A}{T_B}$

$$T_B = T_A \times \frac{N_A}{N_B}$$

$$= 40 \times \frac{250}{100} = 100$$

$$T_B = 100$$

Example 2.8.

Two mating spur gears have 60 and 40 teeth. Their common module is 5 mm. Determine the centre to centre distance between the gears axis.

Solution:

Given: $T_1 = 60, \ m = 5$ mm, $T_2 = 40$

To find : L

$$\text{Module, } m = \frac{d}{T}$$

$$d_1 = mT_1 = 5 \times 60 = 300 \text{ mm.}$$

$$d_2 = mT_2 = 5 \times 40 = 200 \text{ mm}$$

We have,

$$L = r_1 + r_2 = \frac{d_1}{2} + \frac{d_1}{2} = \frac{300}{2} + \frac{200}{2}$$

$$= 150 + 100 = 250$$

$$L = 250 \text{ mm.}$$

2.26. Gear trains

Any combination of gear wheels by means of which motion is transmitted from one shaft to another shaft is called gear train.

Simple gear train

A simple gear train is one in which each shaft carries one gear only. Each of the intermdiate gear acts both as a driven and as a driver. These intermediate gear have no effect on the velocity ratio and hence these gears are known an idlers. Fig. 2.19 (a) shows a simple gear train with one idler and Fig. 2.19(b) shows a simple gear train with two idlers.

Referring Fig. 2.19 (a),

$$\frac{N_2}{N_1} = \frac{d_1}{d_2}; \ \frac{N_3}{N_2} = \frac{d_2}{d_3}$$

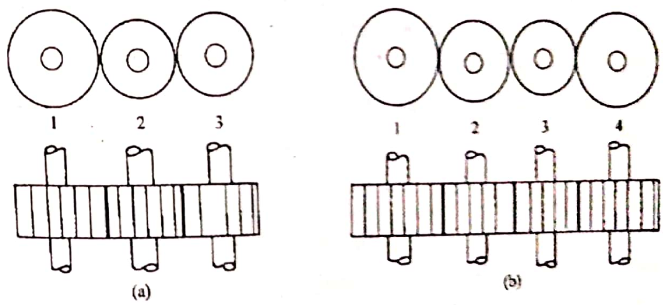


Fig. 2.19. Simple gear train

$$\frac{N_2}{N_1} \times \frac{N_3}{N_2} = \frac{d_1}{d_2} \times \frac{d_2}{d_3}$$

$$\frac{N_3}{N_1} = \frac{d_1}{d_3} \quad \text{.........................(i)}$$

Referring Fig. 2.19 (b),

$$\frac{N_2}{N_1} = \frac{d_1}{d_2}; \frac{N_3}{N_2} = \frac{d_2}{d_3}; \frac{N_4}{N_3} = \frac{d_3}{d_4}$$

$$\frac{N_2}{N_1} \times \frac{N_3}{N_2} \times \frac{N_4}{N_3} = \frac{d_1}{d_2} \times \frac{d_2}{d_3} \times \frac{d_3}{d_4}$$

$$\frac{N_4}{N_1} = \frac{d_1}{d_4} \quad \text{.....................(ii)}$$

From equations (i) and (ii), it can be seen that the speed ratio is independent of the number and diameter of intermediate gears. It can also be seen that when the number of idlers is odd, the driver and driven gears rotates in the same direction and when the number of idlers is even, the driver and driven gears rotate in opposite directions. In simple gear train the function of idlers is to fill the gap between the of rotation of the driven gear as required.

Compound gear train

When a series of gears are connected in such a way that two or more gears rotates about same axis, it is called a compound gear train. The intermediate shafts carryy more than one gear. The speed ratio depends on the diameter of driver, the driven and the intermediate gears. Refer Fig. 2.20. Gears 1 and 3 are driver gears 2 and 4 are the driven gears.

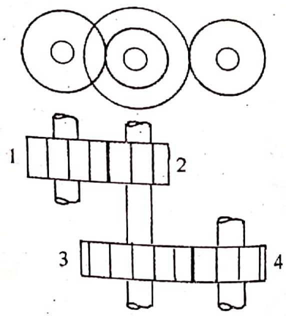


Fig. 2.20. Compound gear train

Referring Fig. 2.20.

Reverted gear train

A reverted gear train is one in which the axes of the first and last gears coincide. Such an arrangement is shown in Fig. 2.21, which has its application as a speed reducer.

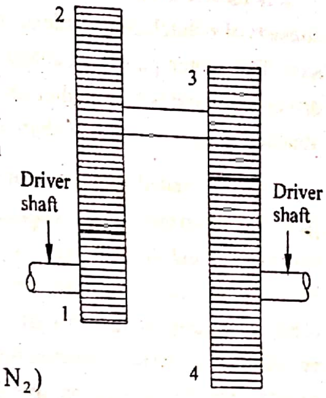


Fig. 2.21. Reverted gear train

Referring Fig. 2.21

$$\frac{N_2}{N_1} = \frac{d_1}{d_2}; \frac{N_4}{N_3} = \frac{d_3}{d_4}$$

$$\frac{N_2}{N_1} \times \frac{N_4}{N_3} = \frac{d_1}{d_2} \times \frac{d_3}{d_4} \quad (N_3 = N_2)$$

2.27. Single plate clutch

A clutch is a device used to connect a driving shaft to a driven shaft so that the driven shaft may be started or stopped at will, without stopping the driving shaft. Single plate clutch is a friction clutch, which transmits power by friction.

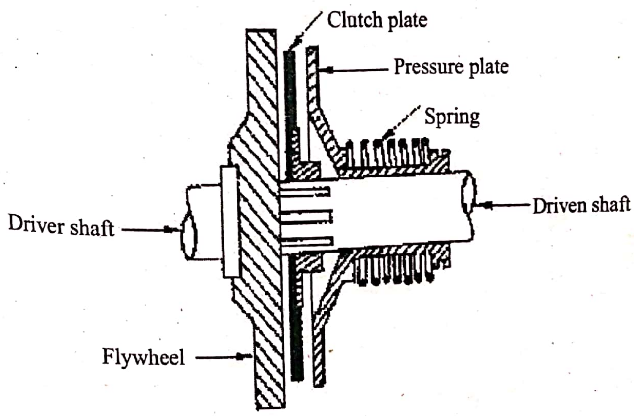


Fig. 2.22. Single plate clutch

It is mostly used in automobiles to connect the engine to the shaft. It consists of a clutch plate made of steel and having frictional lining on each side. This clutch plate is attached to a hub, which rotates along with the driven shaft and is free to slide axially on the driven shaft. A flywheel is attached to the end of crankshaft as shown in Fig. 2.22.

A spring loaded pressure plate presses the clutch plate against the flywheel, when the clutch is engaged. A friction between the lining on the clutch plate and the flywheel on one side and the friction between the lining on the clutch plate and pressure plate on the other side cause the clutch plate and the driven shaft to rotate. When the pressure plate is pulled back by further compression of the spring, contact between the flywheel and clutch plate breakes and then the flywheel rotates without driving the clutch plate and the driven shaft. Thus the rotation of driven shaft can be stopped without stopping the engine.