`UNIT-III

Syllabus:
Fluids: Fluid properties pressure, density and viscosity etc. Types of fluids, Newton's law of viscosity, Pascal's law, Bernoulli's equation for incompressible fluids, only working principle of Hydraulic machines, pumps, turbines, Reciprocating pumps.

Fluid: A fluid is a substance that continuously flows or deforms continuously under the influence of a shear stress. A substance in the liquid or gas phase is referred to as a fluid.

Fluid Mechanics: Fluid mechanics is defined as that branch of science that deals with the behavior of fluids at rest (fluid statics) or in motion (fluid dynamics).

Fluid Static (Hydrostatic): The study of fluid at rest.

Fluid Kinematics: The study of fluid in motion, without considering the pressure forces and energy causing motion is called fluid kinematics.

Fluid Dynamics: The study of fluid in motion, with considering the pressure forces and energy causing motion is called dynamics.

Properties of fluid:

1.Density or mass density: Density is defined as mass per unit volume. S.I unit of density or mass density is kg/m^3. The density of water at 4°C is 1000 kg/m^3.

$$\rho \text{ (rho)} = \frac{mass}{Volume} = \frac{m}{V}$$

The density of mercury is 13600 kg/m^3.

2. Specific gravity or relative density: Specific gravity or relative density is defined as the ratio of the density of a substance to the density of some standard substance at a specified temperature (usually water at 4°C, for which ρ_{H2O} = 1000 kg/m^3).

$$\text{Specific gravity: SG} = \frac{\rho}{\rho H2O} = \frac{Density\ of\ a\ substance}{Density\ of\ some\ standard\ substance}$$

3. Weight density or specific weight: It is defined as a ratio of weight of a fluid to its volume. The weight of a unit volume of a substance is called specific weight or weight density. S.I unit of specific weight or weight density is N/m^3.

$$w = \frac{weight\ of\ fluid}{volume\ of\ fluid} = \frac{mass\ of\ fluid\ X\ acceleration\ due\ to\ gravity}{volume\ of\ fluid}$$

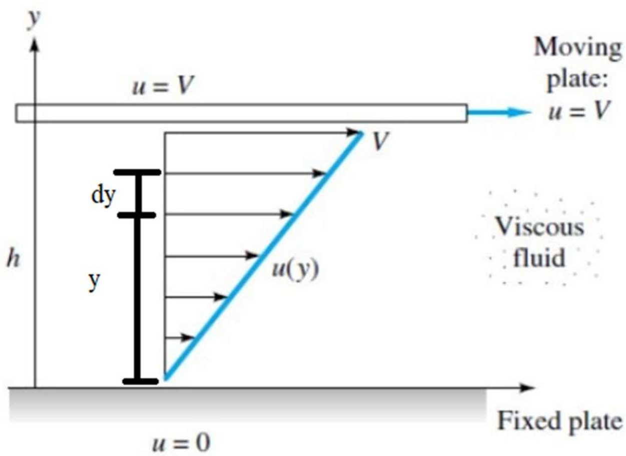
$$w = \frac{mass\ of\ fluid\ X\ g}{volume\ of\ fluid} = \rho\ X\ g$$

4.Specific volume: The reciprocal of density is the specific volume v, which is defined as volume per unit mass. S.I unit of specific volume is m^3/kg.

$$, v = \frac{V}{m} = \frac{1}{m}$$

5. **Viscosity:** Viscosity is a property that represents the internal resistance of a fluid to motion or the "fluidity". It is a property of a fluid which offers resistance to movement of one layer of fluid over another adjacent layer of fluid.

Considered the two adjacent layers of the fluid flowing at the velocity u and u +du respectively, moving one over the other steadily over a horizontal surface separated by a small distance dy. The upper layer of fluid moving with the velocity u + du tries to drag the lower layer along with it with a force F, while the lower layer moving with the velocity u tries to retard the motion of the upper layer by exerting force equal and opposite to F. Thus, these equal and opposite forces cause shear stress τ. This shear stress is directly proportional to the rate of change of velocity with respect to y in the normal direction or velocity gradient.



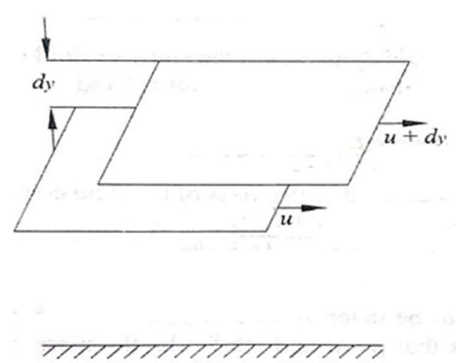


Fig. 3.1

$$\tau = \mu \frac{du}{dy}$$

The above relation is called Newton's law of viscosity where, μ (mu) is the constant of proportionality and is known as the coefficient of dynamic viscosity or dynamic viscosity or absolute viscosity whose unit S.I unit is $\frac{N.s}{m^2}$ (or $Pa.s$) where Pa is the pressure unit pascal).

Significance of Newton's law of viscosity:

1. Useful in classifying the fluids
2. Determining response of a fluid to a shearing stress.
3. Understanding various fluid phenomenon.

A common viscosity unit is poise, which is equivalent to 0.1 Pa-s (or centipoise, which is one-hundredth of a poise).

$$1 \text{ poise} = 0.1\ Pa.s = 0.1\ \frac{N.s}{m^2} = 0.1\ \frac{Kg}{m.s}$$

$$1 \text{ centipoise} = 0.01 \text{ poise}$$

The shear force acting on a fluid is given by:

$$\text{Shear Force } = F = \tau A = \mu A \frac{du}{dy}$$

Kinematic Viscosity: Kinematic Viscosity is the ratio of dynamic viscosity to density.

$$v = \frac{Dynamic\ Viscosity}{Density} \text{ (S.I Unit } = \frac{m^2}{s}\text{)}$$

Two common units of kinematic viscosity are $\frac{m^2}{s}$ and stoke.

$$1 \text{ stoke} = 1\ \frac{cm^2}{s} = 0.0001\ \frac{m^2}{s}$$

$$1 \text{ centistoke} = 0.01 \text{ stoke}$$

Variation of viscosity with temperature:
Viscosity is caused by the cohesive forces between the molecules in liquids and by the molecular collisions in gases, and it varies greatly with temperature. The viscosity of liquids decreases with temperature, whereas the viscosity of gases increases with temperature (Fig. 2–28). This is because in a liquid the molecules possess more energy at higher temperatures, and they can oppose the large cohesive intermolecular forces more strongly. As a result, the energized liquid molecules can move more freely. In a gas, on the other hand, the intermolecular forces are negligible, and the gas molecules at high temperatures move randomly at higher velocities. This results in more molecular collisions per unit volume per unit time and therefore in greater resistance to flow.

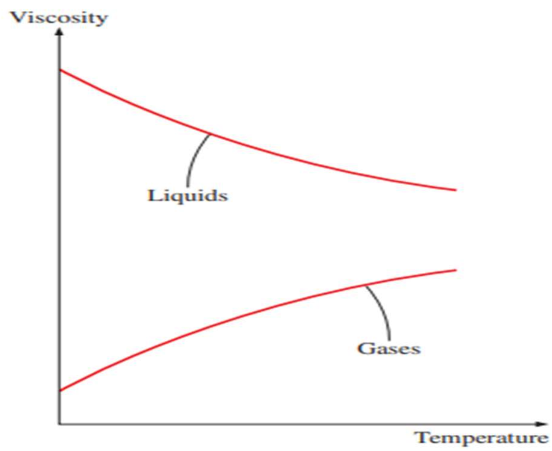


Fig. 3.2

Pressure at a point: Consider a small area dA in large mass of fluids. If the fluid is stationary, then the force exerted by the surrounding fluid on area dA will always be perpendicular to the surface dA. Let dF is the force acting on the area dA in the normal direction. Pressure or intensity if pressure (P) is defined as a normal force (dF) exerted by a fluid per unit area (dA) .

$$\mathrm{P} = \frac{dF}{dA}$$

If the force (F) is uniformly distributed over the area (A), then pressure at any point is given by

$$\mathrm{P} = \frac{F}{A} = \frac{Force}{Area}$$

Therefore, Force or Pressure Force = F = P X A

$$SI\ unit\ of\ pressure = \frac{N\ (Newton)}{m^2\ (meter^2)} = Pascal\ (Pa)$$

$$Other\ units\ of\ pressure = bar, mm\ of\ mercury, atm\ (atmospheric\ pressure)\ etc$$

1 bar = 10^5 Pa (Pascal)= 100 KPa (Kilo-pascal)
1 atm = 1.013 bar = 1.013 x 10 ^{5} Pa (Pascal) =1.013 x 100 KPa (Kilo-pascal) = 760 mm of mercury (Hg) = 1013 mbar(milli-bar)
$1\,\frac{kgf\ (kilogram-force)}{cm^2} = 9.807\,\frac{N\ (Newton)}{cm^2} = 9.807 \times 10^4 \frac{N\ (Newton)}{c^2} = 9.807 \times 10^4$ Pa = 0.9807 bar = 0.9679 atm

Atmospheric pressure(P_{atm})**:** The atmospheric air exerts a normal pressure upon all the surfaces with which it is in contact, and is known as atmospheric pressure.

Absolute Pressure (P_{abs}) **:** The actual pressure at a given position is called the absolute pressure, and it is measured relative to absolute vacuum (i.e., absolute zero pressure). Any pressure measured above the absolute zero pressure (considering absolute zero as a datum or reference) is termed as absolute pressure. An absolute zero pressure can exist only in complete vacuum.

Gauge Pressure: Any pressure measured above the atmospheric pressure (considering atmospheric pressure as a datum or reference) is termed as absolute pressure. The difference between the absolute pressure and the local atmospheric pressure is called the gauge pressure (P_{gauge})can be positive or negative.

Vacuum Pressure (P_{vac})**:** Pressures below atmospheric pressure are sometimes called vacuum pressures and are measured by vacuum gages that indicate the difference between the atmospheric pressure and the absolute pressure.
Absolute, gauge, and vacuum pressures are related to each other by following relations:

$$Pgauge = Pabs - Patm$$
$$Pvac = Patm - Pabs$$

Types of Fluids:

1. Ideal fluid: It is a fluid that does not have viscosity and cannot be compressed. This type of fluid cannot exist practically.
2. Real fluid: All types of fluids that possess viscosity are classified as real fluids. Examples: Kerosene and castor oil.
3. Newtonian fluid: A real fluid that abides by Newton’s law of viscosity is known as a Newtonian fluid. Example: Hydrogen and water
4. Non-Newtonian fluid: Fluids that do not abide by Newton’s law of viscosity are known as non-Newtonian fluid. E.g., corn flour and water
5. Ideal plastic fluid: If the shear stress is directly proportional to the velocity gradient, and if the value of shear stress is greater than the resultant, it is referred to as ideal plastic fluid. E.g., Water suspension of clay and fly ash
6. Incompressible fluid: If a fluid’s density does not vary with the application of force, it is known as an incompressible fluid. Example: The stream of water flowing at high speed from a garden hose pipe.
7. Compressible fluid: If a fluid’s density varies with the application of force, it is called a compressible fluid. Example: gas and steam.

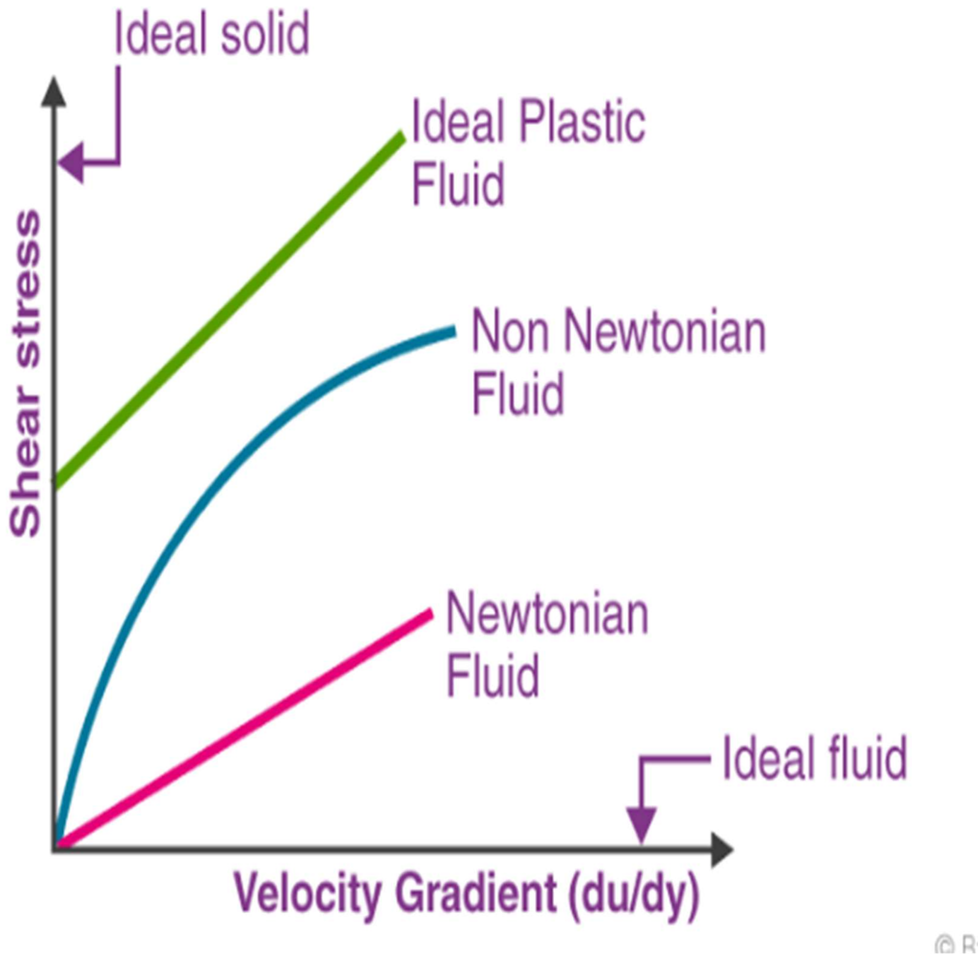


Fig. 3.3

Pascals Law:

It states that the pressure or intensity of pressure at a point in a static fluid is equal in all directions. This is proved as :

The fluid element is of very small dimensions *i.e.*, dx, dy and ds.

Consider an arbitrary fluid element of wedge shape in a fluid mass at rest as shown in Fig. 2.1. Let the width of the element perpendicular to the plane of paper is unity and p_x,

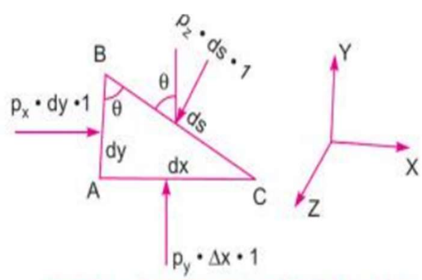


Fig. 2.1 *Forces on a fluid element.*

p_y and p_z are the pressures or intensity of pressure acting on the face AB, AC and BC respectively. Let $\angle ABC = \theta$. Then the forces acting on the element are :

1. Pressure forces normal to the surfaces, and
2. Weight of element in the vertical direction.

The forces on the faces are :

Force on the face AB $= p_x \times$ Area of face AB

$= p_x \times dy \times 1$

Similarly force on the face $AC = p_y \times dx \times 1$

Force on the face BC $= p_z \times ds \times 1$

Weight of element $=$ (Mass of element) $\times g$

$$= (\text{Volume} \times \rho) \times g = \left(\frac{AB \times AC}{2} \times 1\right) \times \rho \times g,$$

where ρ = density of fluid.

Resolving the forces in x-direction, we have

$$p_x \times dy \times 1 - p\,(ds \times 1)\sin(90° - \theta) = 0$$

or $$p_x \times dy \times 1 - p_z\, ds \times 1 \cos\theta = 0.$$

But from Fig. 2.1, $ds \cos\theta = AB = dy$

$$\therefore \quad p_x \times dy \times 1 - p_z \times dy \times 1 = 0$$

or $$p_x = p_z \qquad \text{...(2.1)}$$

Similarly, resolving the forces in y-direction, we get

$$p_y \times dx \times 1 - p_z \times ds \times 1 \cos(90° - \theta) - \frac{dx \times dy}{2} \times 1 \times \rho \times g = 0$$

or $$p_y \times dx - p_z\, ds \sin\theta - \frac{dxdy}{2} \times \rho \times g = 0.$$

But $ds \sin\theta = dx$ and also the element is very small and hence weight is negligible.

$$\therefore \quad p_y dx - p_z \times dx = 0$$

or $$p_y = p_z \qquad \text{...(2.2)}$$

From equations (2.1) and (2.2), we have

$$p_x = p_y = p_z \qquad \text{...(2.3)}$$

The above equation shows that the pressure at any point in x, y and z directions is equal.

Since the choice of fluid element was completely arbitrary, which means the pressure at any point is the same in all directions.

Pressure variation in a fluid at rest:

The pressure at any point in a fluid at rest is obtained by the Hydrostatic Law which states that the rate of increase of pressure in a vertically downward direction must be equal to the specific weight of the fluid at that point. This is proved as :

Consider a small fluid element as shown in Fig. 2.2

Let ΔA= Cross-sectional area of element

ΔZ = Height of fluid element

p = Pressure on face AB

Z = Distance of fluid element from free surface.

The forces acting on the fluid element are :

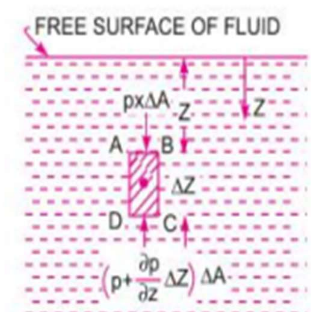


Fig. 2.2 *Forces on a fluid element.*

1. Pressure force on $AB = p \times \Delta A$ and acting perpendicular to face AB in the downward direction.

2. Pressure force on $CD = \left(p + \frac{\partial p}{\partial Z}\Delta Z\right) \times \Delta A$, acting perpendicular to face CD, vertically upward direction.

3. Weight of fluid element = Density $\times g \times$ Volume $= \rho \times g \times (\Delta A \times \Delta Z)$.

4. Pressure forces on surfaces BC and AD are equal and opposite. For equilibrium of fluid element, we have

$$p\Delta A - \left(p + \frac{\partial p}{\partial Z}\Delta Z\right)\Delta A + \rho \times g \times (\Delta A \times \Delta Z) = 0$$

or
$$p\Delta A - p\Delta A - \frac{\partial p}{\partial Z}\Delta Z\Delta A + \rho \times g \times \Delta A \times Z = 0$$

or
$$-\frac{\partial p}{\partial Z}\Delta Z\Delta A + \rho \times g \times \Delta A\Delta Z = 0$$

or
$$\frac{\partial p}{\partial Z}\Delta Z\Delta A = \rho \times g \times \Delta A\Delta Z \quad \text{or} \quad \frac{\partial p}{\partial Z} = \rho \times g \ \text{[cancelling } \Delta A\Delta Z \text{ on both sides]}$$

$$\therefore \quad \frac{\partial p}{\partial Z} = \rho \times g = w \qquad (\because \ \rho \times g = w) \qquad \text{...(2.4)}$$

where w = Weight density of fluid.

Equation (2.4) states that rate of increase of pressure in a vertical direction is equal to weight density of the fluid at that point. This is **Hydrostatic Law.**

By integrating the above equation (2.4) for liquids, we get

$$\int dp = \int \rho g dZ$$

or
$$p = \rho g Z \qquad \text{...(2.5)}$$

where p is the pressure above atmospheric pressure and Z is the height of the point from free surfaces.

From equation (2.5), we have $Z = \frac{p}{\rho \times g}$ ...(2.6)

Here Z is called **pressure head.**

Energy possessed by the fluid:

1.Pressure Energy: It is the energy required to move the liquid mass across the control surface at the entry and exist cross section without imparting velocity to it.

Consider, one dimensional, incompressible fluid flow system in a control volume. At the entry assume the pressure intensity P, velocity V and density of the fluid ρ to be uniform at the cross-section area A. During small time dt this section move by a small distance ds and covers a volume dV. Work done during the displacement of this fluid, i.e.,

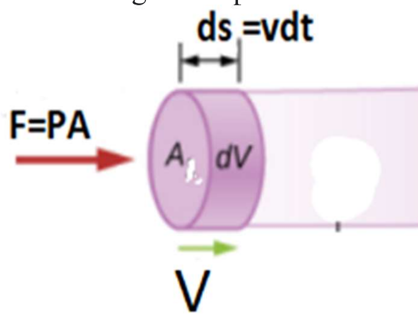


Fig. 3.4

$$Work\ done = Pressure\ Energy = Pressure\ force\ X\ Displacement = PAds = PAVdt$$
(N-m S.I unit)

Pressure head: The pressure energy of liquid per unit weight of liquid is called pressure head.

$$Pressure\ Head = \frac{Pressure\ Energy}{Weight} = \frac{PAds}{mg} = \frac{PAds}{\rho Adsg} = \frac{P}{\rho g}\ (m\ S.I\ unit)$$

2.Potential Energy or Datum Energy: Potential energy is the energy possessed by the fluid by virtue of its position with reference to arbitrary datum or reference line. It represents the work required to move fluid against gravitational force from the reference line. S.I unit of potential energy is Joule (N-m). Let mass of fluid be m, g is acceleration due to gravity and h is the height up to which fluid is taken then,

$$Potential\ energy\ = mgh$$

Potential head: The potential energy of liquid per unit weight of liquid is called potential head.

$$Potential\ Head = \frac{Potential\ Energy}{Weight} = \frac{mgZ}{mg} = Z\ (in\ m)$$

3.Kinetic Energy: The kinetic energy of an object is the energy that it possesses due to its motion. It is the work require to accelerate the fluid of mass m from rest to velocity V. S.I unit of kinetic energy is Joule (N-m).

Consider a fluid of mass m having acceleration $\frac{dV}{dt}$ and moved to a distance ds.

$$dW = F.ds$$

$$dW = ma.ds$$

$$dW = m\frac{dV}{dt}.ds$$

$$dW = mdv.\frac{ds}{dt}$$
$$dW = mdv.v$$

Integrating above equation we get,

$$\int_0^W dW = \int_0^v mv.dv$$

Kinetic Energy = $W = \frac{1}{2}mv^2$

Kinetic head or velocity head: The kinetic energy of liquid per unit weight of liquid is called kinetic head.

$$Kinetic\ Head = \frac{Kinetic\ Energy}{Weight} = \frac{mv^2}{2mg} = \frac{v^2}{2g}\ (in\ m)$$

Bernoulli's Theorem:

Bernoulli's Theorem: In an ideal incompressible fluid when the flow is steady and continuous, the total mechanical energy of the moving fluid comprising the potential energy, pressure energy and the kinetic energy remains constant.

Bernoulli's Principle Formula

Bernoulli's equation formula is a relation between pressure head, kinetic head and gravitational head of a fluid in a container.

The formula for Bernoulli's principle is given as follows:

$$\frac{P}{\rho g} + Z + \frac{V^2}{2g} = \text{Constant}$$

Where P is the pressure exerted by the fluid, V is the velocity of the fluid, ρ is the density of the fluid and Z is the height of the container.

The following are the assumptions made in the derivation of Bernoulli's equation:

1. The fluid is ideal or perfect, that is viscosity is zero.
2. The flow is steady (The velocity of every liquid particle is uniform).
3. There is no energy loss while flowing.
4. The flow is incompressible.
5. The flow is Irrotational.
6. There is no external force, except the gravity force, is acting on the liquid.

Proof:

Consider a pipe with varying diameter and height through which an incompressible fluid is flowing.

Considered and ideal incompressible liquid through a non-uniform pipe as shown in figure. Let us consider two section L-L and M-M and assume that the pipe is running full and there is continuity of flow between the two sections.

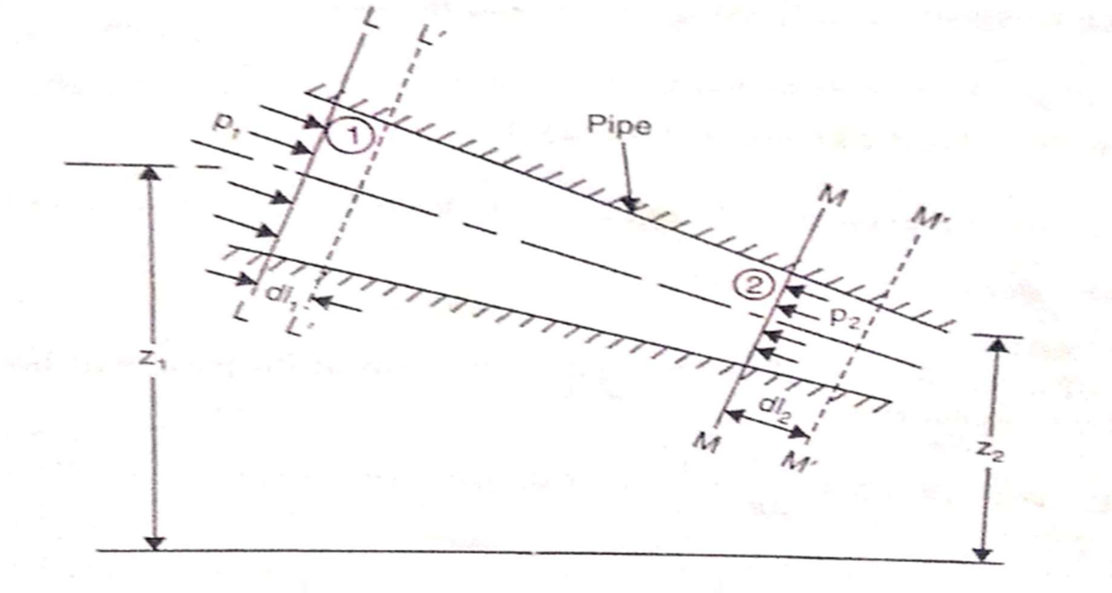


Fig. 3.5

Let,
Z_1 = Height of section L-L above datum.
P_1 = Pressure of liquid at section L-L.
V_1 = Velocity of liquid at section L-L.
A_1 = Area of the pipe at section L-L.

Z_2 = Height of section M-M above datum.
P_2 = Pressure of liquid at section M-M.
V_2 = Velocity of liquid at section M-M.
A_2 = Area of the pipe at section M-M.
ρ = Density of fluid.
w = weight density of fluid.

Let the liquid between the section L-L and M-M move to L'-L' and M'-M' through a small length dl_1 and dl_2 as shown in figure.

Let,

As the flow is continuous,

Weight of liquid between section L-L and section L'-L'= Weight of liquid between section M-M and section M'-M' = W = $wA_1.dl_1 = wA_2.dl_2$

$$\frac{W}{w} = \text{wA1. dl1} = \text{wA2. dl2}$$

Work done by pressure at L-L in moving liquid to L'-L' = Force X Distance = $P_1.A_1.dl_1$
Work done by pressure at M-M in moving liquid to M'-M' = Force X Distance = $-P_2.A_2.dl_2$
Total work done by the pressure = $P_1.A_1.dl_1-P_2.A_2.dl_2$

$$= P_1\frac{W}{w} - P_1\frac{W}{w}$$

$$= (P_1-P_2)\frac{W}{w}$$

Change of potential energy = $mgZ_2-mgZ_1 = W(Z_1 - Z_2)$

Change in kinetic energy = $\frac{1}{2}mv_2^2 - \frac{1}{2}mv_1^2 = \frac{1}{2}m(v_2^2-v_1^2)\frac{g}{g} = \frac{1}{2}\frac{W}{g}(v_2^2-v_1^2)$

We know that,
Total work done by the pressure + Change in potential energy = Change in kinetic energy

$$(P_1-P_2)\frac{W}{w} + W(Z_1 - Z_2) = \frac{1}{2}\frac{W}{g}(v_2^2-v_1^2)$$

Rearranging the above equation we get,

$$\frac{P_1}{w} + Z_1 + \frac{v_1^2}{2g} = \frac{P_2}{w} + Z_2 + \frac{v_2^2}{2g}$$

This is Bernoulli's equation

BERNOULLI'S EQUATION FROM EULER'S EQUATION

Bernoulli's equation is obtained by integrating the Euler's equation of motion (6.3) as

$$\int\frac{dp}{\rho} + \int gdz + \int vdv = \text{constant}$$

If flow is incompressible, ρ is constant and

$$\therefore \quad \frac{p}{\rho} + gz + \frac{v^2}{2} = \text{constant}$$

or

$$\frac{p}{\rho g} + z + \frac{v^2}{2g} = \text{constant}$$

or

$$\frac{p}{\rho g} + \frac{v^2}{2g} + z = \text{constant} \qquad \text{...(6.4)}$$

Equation (6.4) is a Bernoulli's equation in which

$\frac{p}{\rho g}$ = pressure energy per unit weight of fluid or pressure head.
$v^2/2g$ = kinetic energy per unit weight or kinetic head.
z = potential energy per unit weight or potential head.

PRACTICAL APPLICATIONS OF BERNOULLI'S EQUATION

Bernoulli's equation is applied in all problems of incompressible fluid flow where energy considerations are involved. But we shall consider its application to the following measuring devices :

1. Venturimeter.
2. Orifice meter.
3. Pitot-tube.

Limitation of Bernoulli's theorem:

Limitations of Bernoulli's principle

Limitations of Bernoulli's equation are as follows:
1. The Bernoulli equation has been derived by assuming that the velocity of every practical of the liquid across any cross-section of the pipe is uniform. Practically, it is not true
2. While deriving Bernoulli's equation, the viscous drag of the liquid has not been taken into consideration. The viscous drag comes into play, when a liquid is in motion.
3. Bernoulli's equation has been derived on the assumption that there is no loss of energy, when a liquid is in motion. In fact, some kinetic energy is converted into heat energy and a part of it is lost due to shear force.
4. If the liquid is flowing along a curved path, the energy due to centrifugal force should also be taken into consideration

Laminar flow: It is the movement of fluid particles along well-defined paths or streamlines, where all the streamlines are straight and parallel. Hence, the particles move in laminar or layers gliding smoothly over the adjacent layer. Laminar flow occurs in small diameter pipes in which fluid flows at lower velocities and high viscosity. This type of flow is also called streamline flow or viscous Flow.

LAMINAR FLOW

Fig. 3.6

Turbulent flow: It is defined as the flow in which the fluid particles move in a zigzag way. Due to the movement of fluid particles in a zigzag way, the formation of eddies takes place, which is responsible for high energy loss. In turbulent flow, the speed of the fluid at a point continuously changes in both magnitude and direction. Turbulent flow tends to occur in large diameter pipes in which fluid flows with high velocity.

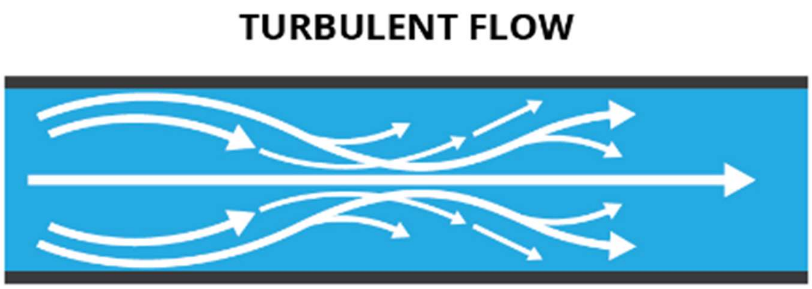


Fig. 3.7

COMPRESSIBILITY AND BULK MODULUS

Compressibility is the reciprocal of the bulk modulus of elasticity, K which is defined as the ratio of compressive stress to volumetric strain.

Consider a cylinder fitted with a piston as shown in Fig. 1.9.

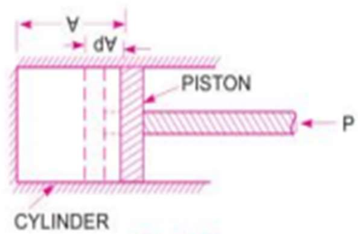


Fig. 1.9

Let $\forall$ = Volume of a gas enclosed in the cylinder

p = Pressure of gas when volume is $\forall$

Let the pressure is increased to $p + dp$, the volume of gas decreases from $\forall$ to $\forall - d\forall$.

Then increase in pressure $= dp$ kgf/m^2

Decrease in volume $= d\forall$

$\therefore$ Volumetric strain $= -\dfrac{d\forall}{\forall}$

– ve sign means the volume decreases with increase of pressure.

$$\therefore \text{ Bulk modulus } K = \frac{\text{Increase of pressure}}{\text{Volumetric strain}}$$

$$= \frac{dp}{\frac{-d\forall}{\forall}} = \frac{-dp}{d\forall}\forall \quad \text{...(1.10)}$$

$$\text{Compressibility} = \frac{1}{K} \quad \text{...(1.11)}$$

Fluid Coupling: Fluid coupling or hydraulic coupling is a hydrodynamic device used for power transmission from one shaft to another through a liquid medium. In fluid coupling, there is no mechanical contact between driving shaft and driven shaft.

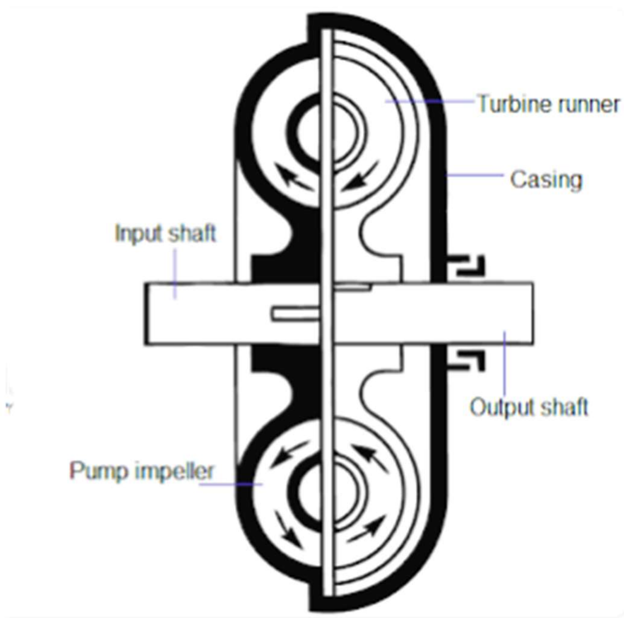


Fig. 3.8

Construction: Hydraulic coupling consists of a pump impeller and turbine runner, which are identical in shape, completely housed in an oil filled casing. Typically, mineral oil is used as working fluid. This oil serves to transmit torque from the pump impeller to the turbine runner. The pump impeller (primary wheel) is connected to the drive shaft (input shaft), and the turbine runner (secondary wheel) is connected to the driven shaft (output shaft). Both shafts are in coaxial. Both pump impeller and turbine runner have vanes to guide fluid flow direction.

Working: As soon as the prime mover (engine or motor) starts rotating, the pump impeller also starts rotating and throws the oil outward by centrifugal action. The oil then enters the turbine runner and exerts a force on the runner blade. The magnitude of the torque increases with an increase in the speed of the driving shaft and eventually when this torque overcome the inertia effects of turbine runner, then the turbine runner and the driven shaft begin to rotate. The oil from the runner then flows back into the pump impeller, thus complete (oil) circuit is established.

Application of Fluid coupling: They are used in mining, textile industries, oil and gas industries and other material handling industries.

Efficiency of fluid coupling = $\frac{\textit{Power at output}}{\textit{power at input}}$

$$\eta = \frac{\text{Power transmitted to driven shaft}}{\text{Power available to the driving shaft}}$$

Power at any shaft = 2 πNT/60

Substituting this value in efficiency equation, here “A” stands for diving shaft, “B” stands for driven shaft

$$\eta = \frac{N_B \, T_B}{N_A \, T_A}$$

But the torque transmitted is same $T_A = T_B$
Then

$$\text{Efficiency}, \eta = \frac{N_B}{N_A}$$

N_A = Speed of driving shaft.
N_B = Speed of driven shaft.
T_A = Torque at driving shaft.
T_B = Torque at driven shaft.

Slip of fluid coupling S

Slip of fluid coupling defined as the ratio of the difference of speed of driving shaft and driven shaft to the speed of the driving shaft.

$$Slip, S = \frac{N_A - N_B}{N_A}$$

Hydraulic Machines: Devices used for the conversion of hydraulic energy into mechanical energy or mechanical energy to hydraulic energy are known as Hydraulic Machines.

Hydraulic Turbine: The hydraulic machines which are used for the conversion of hydraulic energy (energy of flowing water) into mechanical energy (in the form of rotation of runner) are known as Hydraulic Turbines. Hydraulic turbines are energy producing devices—they extract energy from the fluid (water) and transfer most of that energy to some form of mechanical energy output, typically in the form of a rotating shaft.

Classification of hydraulic turbines:

1. According to the type of energy at inlet:

a. Impulse turbine: If at the inlet of turbine, the energy available is only kinetic energy, the turbine is known as Impulse turbine. As the water flows over the vanes, the pressure is atmospheric from inlet to outlet of the turbine
b. Reaction turbine: If at the inlet of the turbine, the water possesses kinetic energy as well as pressure energy, the turbine is known as Reaction turbine. As the water flows through runner, the water is under pressure and the pressure energy goes on changing in to kinetic energy.

2. According to the direction of flow through runner:

a. Tangential flow turbine: If the water flows along the tangent of runner, the turbine is known as tangential flow turbine. Example: Pelton wheel turbine.
b. Radial flow turbine: If the water flows in the radial direction through the runner, the turbine is called radial flow turbine. Example: Francis turbine accordingly,
Radial turbine is further classified as,

i. Inward flow turbine: If water flows through the runner from outwards to inwards, turbines will be termed as inward radial flow turbine.
ii. Outward flow turbine: If water flows through the runner from inwards to outwards, turbines will be termed as outward radial flow turbine.

c. Axial flow turbine: If the water flows through the runner along the direction parallel to the axis of rotation of the runner, the turbine is called axial flow turbine. Example: Kaplan turbine and propeller turbine.
d. Mixed flow turbine: If the water flows through the runner in the radial direction but leaves in the direction parallel to the axis of rotation of the runner, the turbine is called mixed flow turbine. Example: Modern Francis turbine.

3. According to the head at inlet of the turbine:

a. Low head turbine: The net head is less than 30 m and also these turbines require large quantity of water. Example: Kaplan turbine.
b. Medium head turbine: The net head varies from 30 m to 100 m, and also these turbines require moderate quantity of water. Example: Francis turbine.
c. High head turbine: The net head is greater than 100 m and these turbines require a small quantity of water. Example: Pelton wheel turbine.

4. Based on the name of the originator:
a. Impulse turbine – Pelton wheel

b. Reaction turbine – Francis turbine, Kaplan turbine

Difference between Reaction turbine and Impulse turbine:

Basis of Difference	**Impulse Turbine**	**Reaction Turbine**
Definition	The type of turbine in which only kinetic energy of water (impulse force) is used to rotate the turbine is known as impulse turbine	The type of water turbine in which both kinetic energy as well as pressure energy of water is used turn the turbine is called the reaction turbine.
Water flow	In an impulse turbine, the water flows through a nozzle and strikes to the blades of the turbine.	In reaction turbine, the water is guided by the guide blades (fixed blades) to flow over the turbine.
Force on blades	In impulse turbine, an impulsive force rotates the turbine.	In reaction turbine, a reaction force on the blades is rotation the turbine.
Change in pressure of water	In impulse turbine, all the pressure of water is converted into kinetic energy before striking the turbine blades.	In reaction turbine, there is no change in the pressure of water before striking the turbine blades.
Water head	The impulse turbines are most suitable for large water heads.	The reaction turbines are suitable for relatively low water heads
Water flow rate	The impulse turbines are suitable for comparatively low water flow rates.	Reaction turbines are suitable in cases where water flow rates are higher.
Examples	Popular examples of impulse turbine are: Pelton wheel turbine.	Popular examples of reaction turbines are: Francis turbine and Kaplan turbine.

Table 3.1

Difference between Inward Flow Reaction turbine and Outward Flow Reaction Impulse turbine:

S. No	Inward flow reaction turbine	Outward flow reaction turbine
1	Water enters at outer periphery of runner and flows radially inward toward the centre thus flow is radially inwards toward the centre.	Here the flow is radially outwards and the fluid get discharged at the outer periphery of the runner.
2	Easy and effective speed control.	Difficult to control the speed.
3	Discharge is constant.	Discharge increases.
4	Used in medium and high head conditions.	Used in small head and practically very low in use.
5	Commonly used in power projects.	Not much in use.

Table 3.2

Impulse Turbine: In an impulse turbine the available potential energy of water is first converted into kinetic energy by means of nozzle. The high velocity of jet coming out of the nozzle strike series of blades (bucket shaped) fixed around the periphery of the rim of a circular disc. The resulting change in the momentum of water forces the blade to move, which in turn, rotates the disc.

a. **Pelton Turbine:** Pelton Wheel or Pelton turbine is a tangential flow impulse turbine. This turbine is used for high heads. The water strikes the bucket along the tangent of the tangent of the runner. The energy available at the inlet of the turbine is only kinetic energy. The pressure at the inlet and outlet is atmospheric pressure. The nozzle increases the kinetic energy of the water flowing through the penstock. At the outlet of the nozzle, the water comes out in the form of a jet and strikes the buckets (vanes) of the runner.

The main parts of Pelton turbine are:

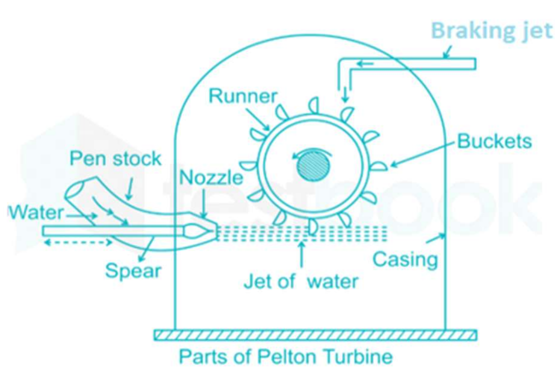


Fig. 3.9

1. Penstock: It is a large sized conduit which conveys water from high level reservoir to the turbine. For the regulation of water flow from the reservoir to the turbine, the penstock is provided with control valves.
2. Nozzle and flow regulating arrangement(spear): The amount of water striking the buckets is controlled by providing a spear in the nozzle. The spear is a conical needle operated in the axial direction depending up on the size of the unit. When the spear is pushed forward, the amount of water striking the runner is reduced and when the spear is pushed back, the amount of water striking the runner increases.
3. Runner with Buckets: Runner consists of a circular disc on the periphery of which a number of buckets evenly spaced are fixed.
4. Casing: It is made of cast iron or fabricated steel plates. Its function is to prevent the splashing of water and to discharge water to tail race. It also acts as safeguard against accidents.
5. Breaking Jet: When the nozzle is completely closed by moving the spear in the forward direction, the amount of water striking the runner reduces to zero. But the runner due to inertia goes on revolving for a long time. To stop the runner in a short time, a small nozzle is provided which directs the jet of water on the back of vanes. This jet of water is called Breaking Jet.

Working of Pelton: The water is transferred from the source having water of high head to turbine inlet through a long conduit called Penstock. Nozzle arrangement at the end of penstock helps the water to increase the velocity of water and water flows out as a high-speed jet with high velocity and discharge at atmospheric pressure from the nozzle. When a high-speed water jet injected through a nozzle hits buckets of Pelton wheel. It induces an impulsive force. This force makes the turbine rotate. The rotating shaft runs a generator and produces electricity. The kinetic energy of the jet is reduced when it hits the bucket and also due to spherical shape of buckets the directed jet will change its direction and takes U-turn and falls into tail race.

Reaction Turbine: When water slides over the runner blade the part of the pressure energy changes into kinetic energy causing a reaction force on the blade, causing the turbine to rotate. In reaction turbines the water entering the runner exerts an impulsive force and at the discharge it exerts a reaction force opposite to the direction of the flow. The reactive force is more than the impulsive force in the reaction turbine.

a. **Francis turbine**: Francis Turbine is a combination of both impulse and reaction turbine, where the blades rotate using both reaction and impulse force of water flowing through them producing electricity more efficiently. The modern Francis turbine is an inward mixed Flow reaction turbine (in the earlier stages of development, Francis turbine had a purely radial flow runner) i.e. the water under pressure will enter the runner from guide vanes towards the centre in the radial direction and discharge out of the runner axially. The Francis turbine operates under medium head and also requires medium quantity of water.

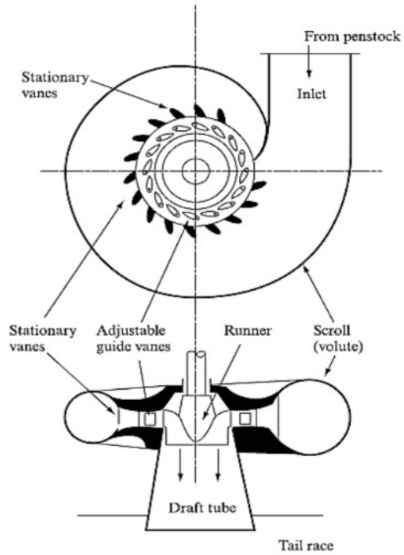


Fig. 3.10

The following main parts or Construction of Francis turbine are:

1.Penstock: The penstock is also known as the Input pipe. The penstock is a large size conduit that conveys water from the upstream of the dam or reservoir to the turbine runner.

2. Scroll casing: The casing has a passage that is the closed type and has a cross-sectional area gradually decreasing along the direction of the flow, so that water enters the runner at constant velocity throughout the circumference of the runner and area becomes maximum at the inlet and zeroes at the exit.

3.Stay vanes and guide vanes: Stay vanes and guide vanes guides the water to the runner blades. Stay vanes remain stationary at their position, stay vanes removes the swirls from the water, which are generated due to flow through spiral casing and guide vanes are not stationary, they change their angle as per the requirement to control the angle of striking of water to turbine blades to increase the efficiency.

4. Runner and Runner blades: The driving force on the runner is both due to impulsive and reaction effects. In a Francis turbine, runner blades are divided into 2 parts. The lower half is made in the shape of small bucket so that it uses the impulse action of water to rotate the turbine. The upper part of the blades uses the reaction force of water flowing through it. These two forces together make the runner to rotate.

5. Draft Tube: It is an expanding tube used to discharge water through the runner and to the tail race. The main function of the tube is to reduce the velocity of (water flowing) at the time of discharge.

Working of Francis: The water from the penstock enters to spiral casing and then it passes through the stay vanes and guide vanes. After passing through guide vanes part of pressure energy changes to kinetic energy. The water is admitted to the runner through guide vanes and strikes the runner blade. Francis turbine, runner blades are divided into 2 parts. The lower half is made in the shape of small bucket so that it uses the impulse action of water to rotate the turbine. The upper part of the blades uses the reaction force (due to pressure difference on two sides of blade) of water flowing through it. Thus, runner blades make use of both pressure energy and kinetic energy of water and rotates the runner in most efficient way. After doing the work the water having decreased kinetic energy and pressure energy, is discharged to the tailrace through a tube known as the draft tube. The water coming out of runner blades would lack both the kinetic energy and pressure energy, so we use the draft tube convert the kinetic energy of water to pressure energy to recover the pressure as water advances towards tail race.

Hydraulic Pump: Hydraulic pump is a hydraulic machine which converts mechanical energy into hydraulic energy or energy of fluid (water). Hydraulic pumps are energy absorbing devices since energy is supplied to them, and they transfer most of that energy to the fluid (water), usually via a rotating shaft thereby increase in pressure head or kinetic energy or both.

Classification of pump:

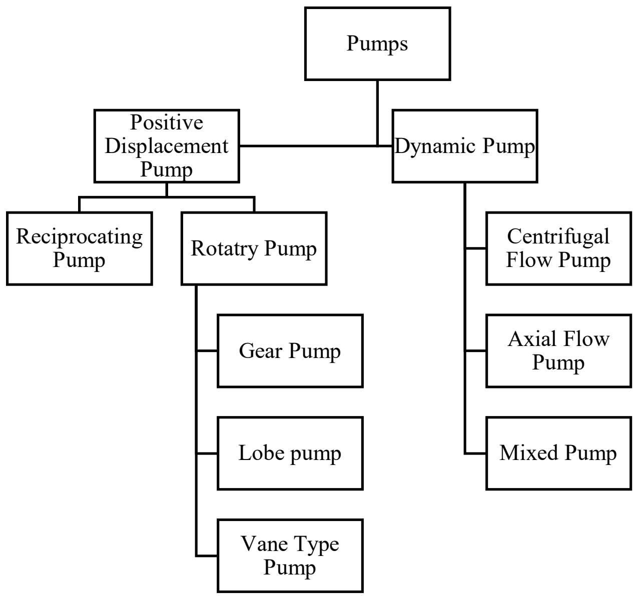


Fig. 3.11

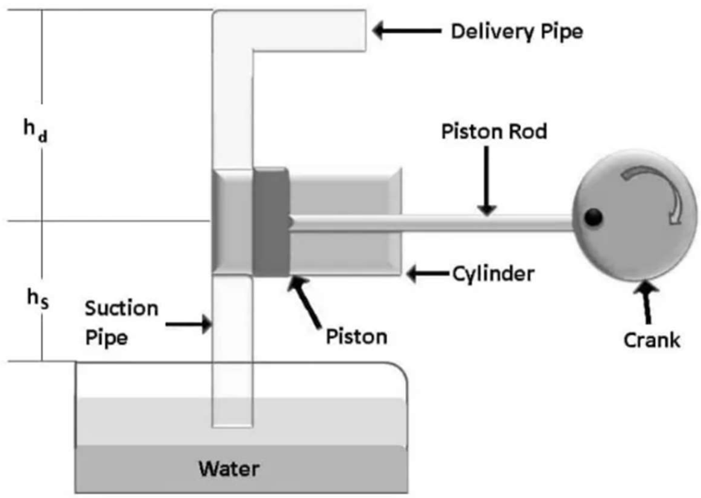
There are two basic types of pumps:

1.Positive displacement pumps: In positive-displacement pump, fluid is directed into a closed volume. Energy transfer to the fluid is accomplished by movement of the boundary of the closed volume, causing the volume of cylinder to expand or contract, thereby sucking fluid in or squeezing (compressing) fluid out, respectively. Your heart is a good example of a positive-displacement pump.
Positive displacement pumps are further classified into two categories:
a. Reciprocating Pump
b. Rotary Pump
   i. Gear Pump
   ii. Lobe pump
   iii. Vane Type Pump

2. Dynamic pumps: In dynamic pump, there is no closed volume; instead, rotating blades supply energy or impart momentum to the fluid. For pumps, these rotating blades are called impeller blades. For this reason, they are sometimes called rotodynamic pumps or simply rotary pumps (not to be confused with rotary positive-displacement pumps, which use the same name)
Dynamic pumps are further classified into three categories:

a. Centrifugal-flow pump: In a centrifugal-flow pump, fluid enters axially (in the same direction as the axis of the rotating shaft) in the center of the pump, but is discharged radially (or tangentially) along the outer radius of the pump casing. For this reason, centrifugal pumps are also called radial-flow pumps.
b. Axial-flow pump: In an axial-flow pump, fluid enters and leaves axially, typically along the outer portion of the pump because of blockage by the shaft, motor, hub, etc.
c. Mixed flow pump: A mixed-flow pump is intermediate between centrifugal and axial, with the flow entering axially, not necessarily in the center, but leaving at some angle between radially and axially.

Reciprocating Pump: A reciprocating pump is a type of positive displacement pump that uses a reciprocating component (i.e., plunger or piston) to converts the mechanical energy of the fluid into hydraulic energy (energy of liquid) to pump the fluid from one area to another. It does this work by sucking liquid into cylinder containing a reciprocating piston which exerts a thrust force on the liquid and increases its hydraulic energy (energy of liquid). Reciprocating pump for transfer water or other fluids by the reciprocating action of piston.



Reciprocating Pump

Fig. 3.12

The following are the main parts of the reciprocating pump:
1. Cylinder: In the cylinder, the piston is moving to and fro. The moment of the piston obtains by a connecting rod which connects the piston and crank.
2. Suction Pipe: It is a pipe that connects the cylinder and sump. The suction pipe allows the water to flow in the cylinder from sump.
3. Delivery Pipe: It is a pipe that delivers the water to a required height. The delivery pipe joins the pump cylinder to the discharge outlet.
4. Suction Valve: In this valve, the flow of water enters from the suction pipe into the cylinder. It allows only one-directional flow. Hence it is also known as a non-return valve. This valve is found on the suction pipe inlet.
5. Delivery Valve: With this valve, the flow of water is discharged from the cylinder into the delivery pipe. It is also a non-return valve located between the delivery pipe outlets. The valve is in the closed position during suction.

6. Piston and Piston Rod: It is a solid part that moves forward and backward inside the cylinder for the suction and delivery of the liquid. Whereas the piston rod helps the piston to move in a linear direction.
7. Crank and Connecting Rod: A crank is a circular disc that is connected to a motor. While the connecting rod connects the crank to the piston. As a result, the rotational motion of the crank is converted into linear movement of the piston.
8. Strainer: A strainer is an essential part of the pump that is located at the end of the suction pipe. This helps in preventing the entry of solids from the water source into the cylinders

Working Principle of Reciprocating Pump:

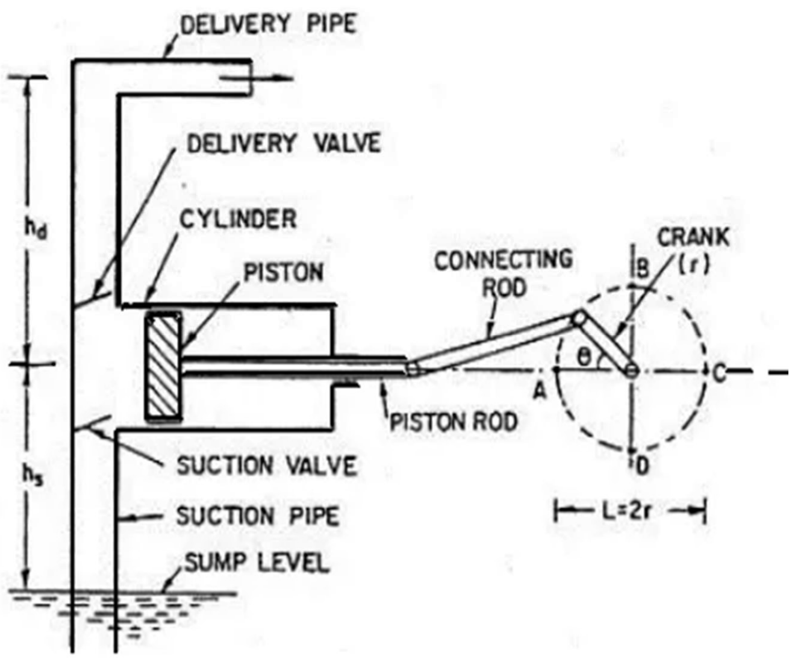


Fig. 3.13

The rotary motion given to the crankshaft by a prime mover is converted into reciprocating motion of the piston by the connecting rod.

In a **first stroke of the piston** (called suction stroke), the crank is rotating from A to C (from 0° to 180°) the piston is moving towards the right side of the cylinder. Due to this, the vacuum creates in the cylinder. This vacuum causes the suction valve to open and the water enters the cylinder.

In the next stroke called delivery stroke, the water leaves the cylinder. In the delivery stroke, the crank is rotating from C to A (from 180° to 360°) the piston is moving to the left side of the cylinder. Due to this, the pressure of the liquid increases inside the cylinder. This pressure causes the suction valve to close and delivery valve to open. Then the water is forced into the delivery pipe and raised to a required height.

Rotary Pump:

A rotary pump is a type of positive displacement pump that uses the rotating action of its component parts, as the meshing of vanes or screws to transfer fluid from one area to other. Rotary pumps are a type of positive displacement pump where for each revolution, a fixed volume of fluid is moved.

a. Gear Pump: Gear pump consist of identical intermeshing spur gear. Both the gears are mounted on two different shaft and are placed in a stationary housing. One gear keyed to the driving shaft while the other revolves ideally. The fluid entering the inlet port fill the space between the teeth. The fluid trap between the teeth is carried forward by the revolving gear and finally pushed out of the discharge port. These are used in automobiles.

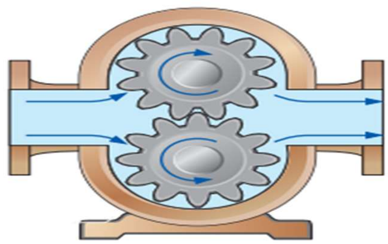


Fig. 3.14

b. Lobe Pump: It consist of two identical lobes. Both the lopes are amounted on the different shaft and our place in housing. One lobe is keyed to the driving shaft while the other revolves freely on the shaft The fluid entering the inlet port fills the space between the two lobes. The fluid trapped between the lopes carried forward by the rotating lobe and finally pushed out of the outlet port.

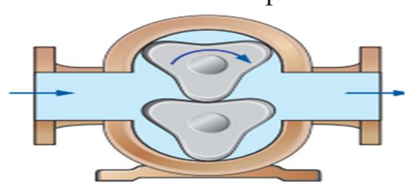


Fig. 3.15

c. Vane Type Pump: It consist of a rotor which has slot cut radially in which the vanes slide. The vanes are spring loaded i.e., the vanes are tightly held against the cylinder housing (casing) by means of spring it provides the leakproof joint between the suction and discharge connection. When the rotor rotates the vanes moves to and fro inside the slot of rotor. During the suction, the space between the vanes increases. During the further movement of the rotor the space between the vanes decreases and the fluid is discharge.

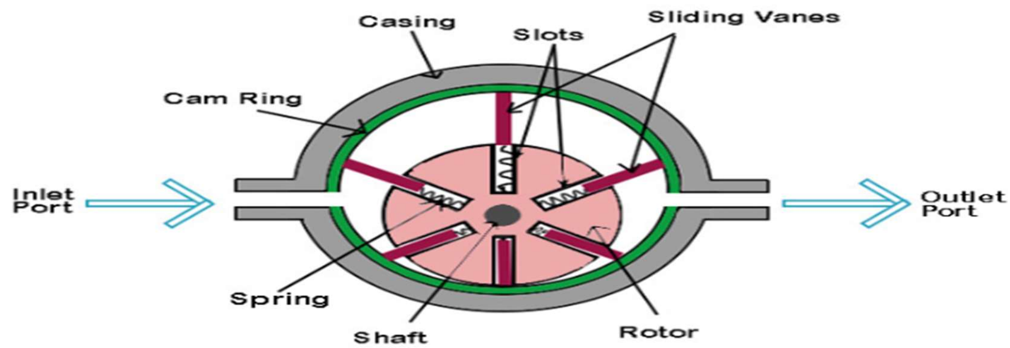


Fig. 3.15

Centrifugal pump: **Centrifugal pumps** are used to transport fluids by the conversion of rotational kinetic energy to the hydrodynamic energy of the fluid flow. The rotational energy typically comes from an engine or electric motor. The working principle of a centrifugal pump is when a certain mass of fluid rotates by an external force (leading to an external torque), fluid is thrown away from the centrifugal axis of rotation by centrifugal force then there is an increase in the pressure head of the liquid. This increase in the pressure head causes the water to be transferred from one point to another. It is a centrifugal force applying to the fluid that makes it flow inside the casing.

Main parts of centrifugal pump

1. Impeller: The rotating part of the pump, consisting of a series of backward curved vanes & is mounted on a shaft which is connected to the shaft of an electric motor.

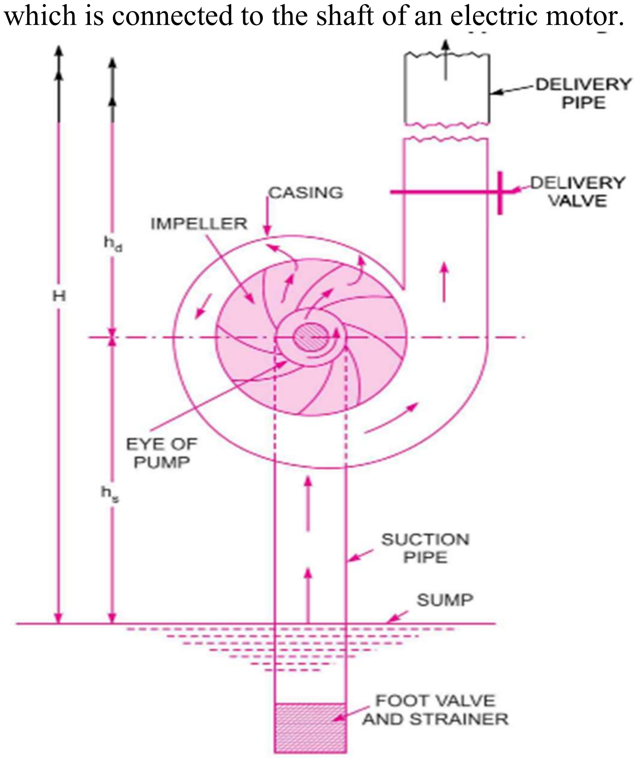


Fig. 3.16

2. Casing: Similar to the casing of reaction turbine, it is an airtight passage surrounding the impeller & is designed in such a way that the kinetic energy of the water discharged at the outlet of the impeller is converted into pressure energy before the water leaves the spiral casing of gradually increasing cross-section area & enters the delivery pipe.
3. Suction pipe, foot valve & strainer: Suction pipe connects the centre of the impeller to the sump from which liquid is to be lifted. It is airtight & provided with a strainer at its lower end so as to prevent the entry of solid particles & other foreign materials etc. into the pump. The foot valve is a one-way valve located above the strainer into the suction pipe. It serves to fill the pump with liquid before it is started & prevents back flow when the pump is stopped.

4. Delivery pipe A pipe whose one end is connected to the outlet of the pump & other end delivers the water at a required height is known as delivery pipe.

Working of a centrifugal pump: The pump is initially primed where in the suction pipe, casing & portion of the delivery pipe upto the delivery valve is completely filled with the liquid to be pumped. Rapid motion imparted to the impeller then builds up centrifugal force which throws the liquid towards the impeller periphery. This causes pressure gradient in the suction pipe i.e.; a partial vacuum exists at the impeller eye (centre of the impeller) while the liquid in the sump is at atmospheric pressure. Consequently, liquid from the sump is sucked in the impeller eye. When the liquid passes through the impeller, it receives energy & that results in the growth of both pressure & velocity. The casing collects the liquid from the impeller & guides it to the delivery pipe. Since the casing increases in cross sectional area towards the delivery, kinetic head represented by the high discharge velocity is partially transferred into pressure head before the liquid leaves the pump. The process is continuous as long as motion is given to the impeller & there is supply of liquid to draw upon.
Difference between hydraulic turbine and pump:

S.No.	Hydraulic Turbines	Hydraulic Pumps
1	Change hydraulic energy into mechanical energy.	Convert mechanical energy into hydraulic energy.
2	Produce electrical energy.	May utilize electrical energy to produce pressure energy
3	Very costly and complex design.	Less costly and have easy design.
4	Maintenance cost is high as it has many components	Less maintenance cost as it has very less components.
5	Examples: Pelton turbine, Francis turbine etc.	Example: Centrifugal pump, reciprocating pump etc.,

Table 3.3

Difference between hydraulic turbine and compressor:

S.No.	Hydraulic Turbines	Compressor
1	Change hydraulic energy into mechanical energy.	Convert mechanical energy into hydraulic energy.
2	Power generating device.	Power consuming device.
3	A turbine is a prime mover.	A compressor has to be driven by a prime mover.

Table 3.4

Positive-displacement machines: In positive-displacement machines, fluid is directed into a closed volume. Energy transfer to the fluid is accomplished by movement of the boundary of the closed volume, causing the volume to expand or contract, thereby sucking fluid in or squeezing fluid out, respectively. Your heart is a good example of a positive-displacement machine.

Dynamic machines: In dynamic machines, there is no closed volume; instead, rotating blades supply or extract energy to or from the fluid

Pneumatic machines: Machines which are operated by the compressed air called pneumatic machine. These machines convert compressive energy of air into mechanical work and power. Some commonly used pneumatic machines include pneumatic drill, pneumatic press etc.

Compressors: A compressor is a mechanical device that increases the pressure of a gas by reducing its volume. An air compressor is a specific type of gas compressor. Compressors are similar to pumps: both increase the pressure on a fluid and both can transport the fluid through a pipe. The main distinction is that the focus of a compressor is to change the density or volume of the fluid, which is mostly only achievable on gases. Gases are compressible, while liquids are relatively incompressible, so compressors are rarely used for liquids. The main action of a pump is to pressurize and transport liquids.

Difference between hydraulic turbine and compressor:

S.No.	Hydraulic Turbines	Compressor
1	Change hydraulic energy into mechanical energy.	Convert mechanical energy into hydraulic energy.
2	Power generating device.	Power consuming device.
3	A turbine is a prime mover.	A compressor has to be driven by a prime mover.