LECTURE NOTES

ON

MECHANICS OF FLUIDS AND HYDRAULIC MACHINES

B. Tech IV Semester (IARE-R16)

Dr. CH.V.K.N.S.N Moorthy, Professor
Department of Mechanical Engineering

Mr. A. Somaiah
Assistant Professor

DEPARTMENT OF MECHANICAL ENGINEERING

MECHANICAL ENGINEERING
INSTITUTE OF AERONAUTICAL ENGINEERING
(AUTONOMOUS)
DUNDIGAL, HYDERABAD - 500 04

UNIT - I

Fluid Mechanics

Mechanics : Deals with action of forces on bodies at rest or in motion.

State of rest and Motion: They are relative and depend on the frame of reference. If the position with reference to frame of reference is fixed with time, then the body is said to be in a state of rest. Otherwise, it is said to be in a state of motion.

Scalar and heater quantities: Quantities which require only magnitude to represent them are called scalar quantities. Quantities which acquire magnitudes and direction to represent them are called vector quantities.

Eg: Mass, time internal, Distance traveled _ Scalars Weight, Displacement, Velocity _ Vectors

Velocity and Speed: Rate of displacement is called velocity and Rate and distance travelled is called Speed.

Unit: m/s

Acceleration: Rate of change of velocity is called acceleration. Negative acceleration is called retardation.

Momentum: The capacity of a body to impart motion to other bodies is called momentum.

The momentum of a moving body is measured by the product of mass and velocity the moving body

Momentum = Mass x Velocity Unit: Kgm/s

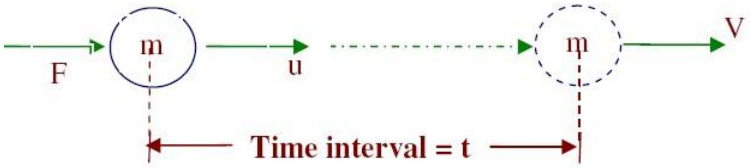
Newton's first law of motion: Every body continues to be in its state of rest or uniform motion unless compelled by an external agency.

Inertia: It is the inherent property the body to retain its state of rest or uniform motion.

Force: It is an external agency which overcomes or tends to overcome the inertia of a body.

Newton's second law of motion: The rate of change of momentum of a body is directly proportional to the magnitudes of the applied force and takes place in the direction of the applied force.

Measurement of force:



Change in momentum in time 't' = mv – mu

$$\text{Rate of change of momentum} = \frac{mv - mu}{t}$$

$$F \,\alpha\, \frac{mv - mu}{t}$$

$$F \,\alpha\, m\left(\frac{v - u}{t}\right)$$

$$F \,\alpha\, ma$$

$$F = K\, ma$$

If F = 1 When m = 1 and u = 1 Then K = 1

F = ma.

Unit: Newton (N)

Mass: Measure of amount of matter contained by the body it is a scalar quantity. Unit: Kg.

Weight: Gravitational force on the body. It is a vector quantity. F = ma

W = mg

Unit: Newton (N) $g = 9.81\ m/s^2$

Volume: Measure of space occupied by the body.

Unit: m^3

m^3 = 1000 liters

Work: Work done = Force x Displacement _ Linear motion. Work done = Torque x Angular displacement _ Rotatory motion.

Unit: Nm or J

Energy: Capacity of doing work is called energy. Unit: Nm or J

Potential energy = mgh Kinetic energy = ½ mv^2

Power: Rate of doing work is called Power.

$$\text{Power:} = \frac{\text{Force x displacement}}{\text{time}}$$

$$= \text{Force x Velocity} \rightarrow \text{Linear Motion.}$$

$$P = \frac{2\Pi N T}{60} \rightarrow \text{Rotatory Motion.}$$

Matter: Anything which possesses mass and requires space to occupy is called matter.

States of matter:

Matter can exist in the following states Solid state.

Solid state: In case of solids intermolecular force is very large and hence molecules

are not free to move. Solids exhibit definite shape and volume. Solids undergo certain amount of deformation and then attain state of equilibrium when subjected to tensile, compressive and shear

Fluid State: Liquids and gases together are called fluids. Incase of liquids

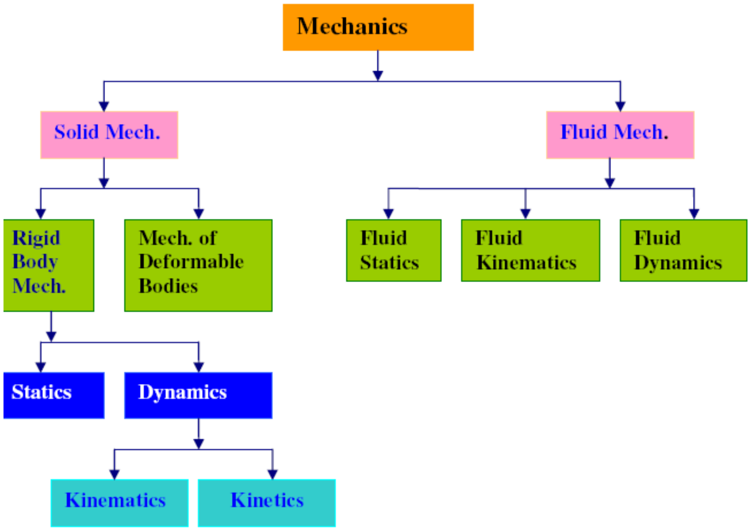
Intermolecular force is comparatively small. Therefore liquids exhibit definite volume. But they assume the shape of the container

Liquids offer very little resistance against tensile force. Liquids offer maximum resistance against compressive forces. Therefore, liquids are also called incompressible fluids. Liquids undergo continuous or prolonged angular deformation or shear strain when subjected to tangential force or shear force. This property of the liquid is called flow of liquid. Any substance which exhibits the property of flow is called fluid. Therefore liquids are considered as fluids.

In case of gases intermolecular force is very small. Therefore the molecules are free to move along any direction. Therefore gases will occupy or assume the shape as well as the volume of the container.

Gases offer little resistance against compressive forces. Therefore gases are called compressible fluids. When subjected to shear force gases undergo continuous or prolonged angular deformation or shear strain. This property of gas is called flow of gases. Any substance which exhibits the property of flow is called fluid. Therefore gases are also considered as fluids.

Branches of Mechanics:



I. Fluid Statics deals with action of forces on fluids at rest or in equilibrium.

II. Fluid Kinematics deals with geometry of motion of fluids without considering the cause of motion

Properties of fluids:

1. Mass density or Specific mass (ρ):

Mass density or specific mass is the mass per unit volume of the fluid.

$$\rho = \frac{Mass}{Volume}$$

$$\rho = \frac{\mathrm{M}}{\mathrm{V}} \text{ or } \frac{\mathrm{dM}}{\mathrm{dV}}$$

2. Weight density or Specific weight (ϒ):

Weight density or Specific weight of a fluid is the weight per unit volume. Unit: kg/m3 or kgm3

With the increase in temperature volume of fluid increases and hence mass density decreases. In case of fluids as the pressure increases volume decreases and hence mass density increase

3. Specific gravity or Relative density (S):

It is the ratio of specific weight of the fluid to the specific weight of a standard fluid.

$$S = \frac{\gamma \text{ of fluid}}{\gamma \text{ of standard fluid}}$$

Unit: It is a dimensionless quantity and has no unit.

In case of liquids water at 4^0C is considered as standard liquid.

$\underline{\gamma \text{ (specific weight)}}$ of water at 4°C (standard liquid) is $9.81 \frac{kN}{m^3}$ or $9.81 \times 10^3 \frac{kN}{m^3}$

Note: We have

1. $S = \frac{\gamma}{\gamma_{\text{standard}}}$

   $\therefore \quad \gamma = S \times \gamma_{standard}$

2. $S = \frac{\gamma}{\gamma_{\text{standard}}}$

   $S = \frac{\rho \times g}{\rho_{\text{standard}} \times g}$

   $S = \frac{\rho}{\rho_{\text{standard}}}$

Specific gravity or relative density of a fluid can also be defined as the ratio of mass density of the fluid to mass density of the standard fluid. Mass density of standard water is 1000 kg/m3.

4. Specific volume (∀): It is the volume per unit mass of the fluid.

$$\therefore \quad \forall = \frac{Volume}{mass}$$

$$\forall = \frac{V}{M} \text{ or } \frac{dV}{dM}$$

Unit: m3/kg

As the temperature increases volume increases and hence specific volume increases. As the pressure increases volume decreases and hence specific volume decreases.

Effect of temperature on surface tension of liquids:

In case of liquids, surface tension decreases with increase in temperature. Pressure has no or very little effect on surface tension of liquids.

Problems:

1. What is the pressure inside the droplet of water 0.05 mm in diameter at 20^0C if the pressure
outside the droplet is 103 kPa Take $\sigma = 0.0736$ N/m at 20^0C.

$$p = \frac{4\sigma}{D}$$

$$= \frac{4x0.0736}{0.05x10^{-3}}$$

$$p = 5.888x10^{+3}\,N/m^2$$

$$p = p_{inside} - p_{outside}$$

$$p_{inside} = (5.888 + 103)10^3$$

$$p_{inside} = 108.88x10^3\,Pa$$

$$p_{inside} = ?$$

$$D = 0.05x10^{-3}\,m$$

$$p_{outside} = 103kPa$$

$$= 103x10^3\,N/m^2$$

$$\sigma = 0.0736N/m$$

2. liquid bubble 2cm in radius has an internal pressure of 13Pa. Calculate the surface tension of liquid film.

$$p = \frac{8\sigma}{D}$$

$$\sigma = \frac{13x4x10^{-2}}{8}$$

$$\sigma = 0.065\mathrm{N/m}$$

$$R = 2\mathrm{cm}$$

$$D = 4\mathrm{cm}$$

$$= 4x10^{-2}\mathrm{m}$$

$$p = 13\mathrm{Pa}(\mathrm{N/m}^2)$$

Compressibility:

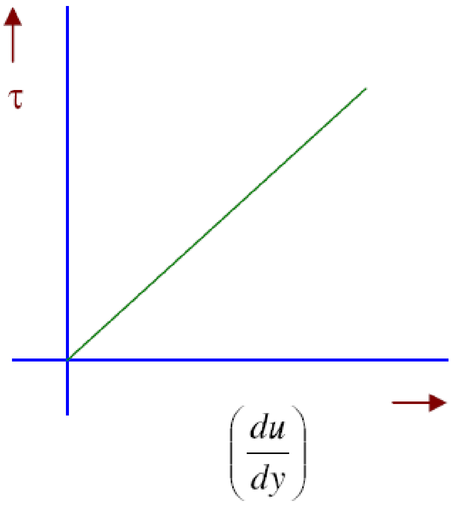
It is the property by virtue of which there will be change in volume of fluid due to change in pressure.

Rheological classification of fluids: (Rheology _ Study of stress – strain behavior).

1. **Newtonian fluids:** A fluid which obeys Newton's law of viscosity i.e., t = μ. *du/dy* is called Newtonian fluid. In such fluids shear stress varies directly as shear strain.

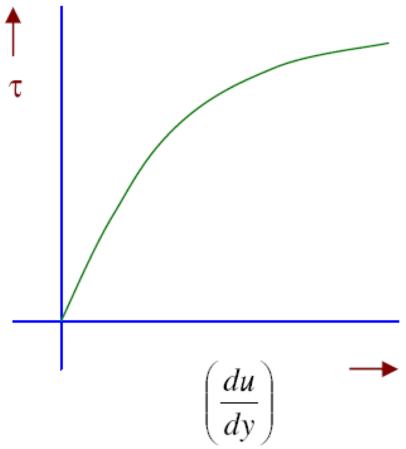
In this case the stress strain curve is a stress line passing through origin the slope of the line gives dynamic viscosity of the fluid.

Eg: Water, Kerosene.



3. **Non- Newtonian fluid:** A fluid which does not obey Newton's law of viscosity is called non-Newton fluid. For such fluids,

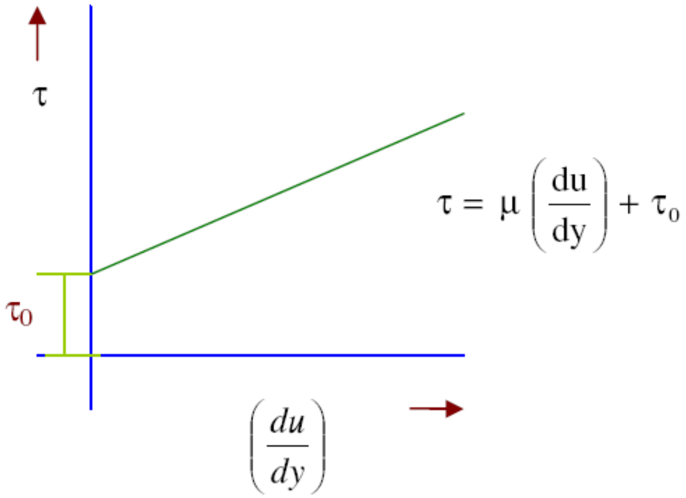
$$\tau = \mu . \left(\frac{du}{dy}\right)^n$$



3. Ideal Plastic fluids:

In this case the strain starts after certain initial stress (t0) and then the stress strain relationship will be linear. t0 is called initial yield stress. Sometimes they are also called Bingham's Plastics.

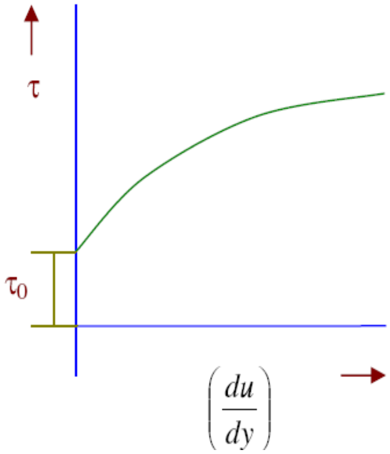
Eg: Industrial sludge.



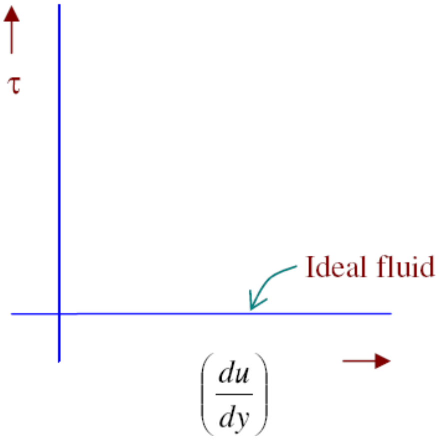
4. Thixotropic fluids:

These require certain amount of yield stress to initiate shear strain. After wards stress-strain relationship will be non – linear.

Eg; Printers ink.

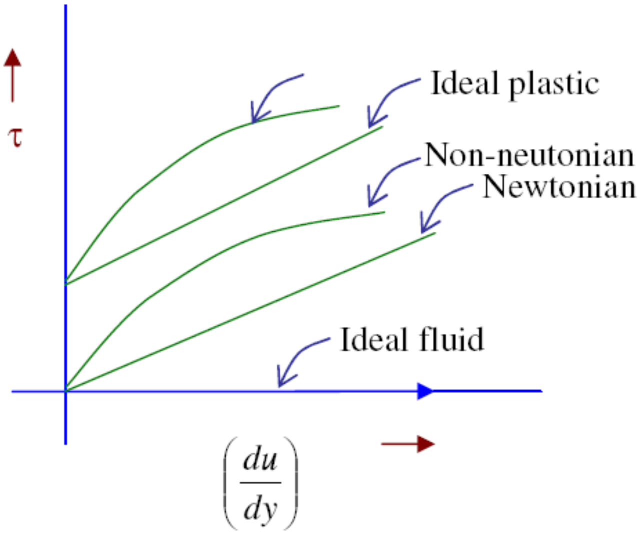


Ideal fluid: Any fluid for which viscosity is assumed to be zero is called Ideal fluid. For ideal fluid t = 0 for all values of du/dy

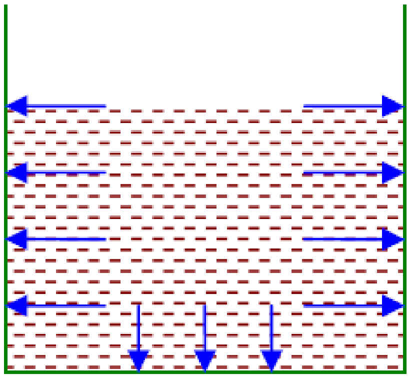


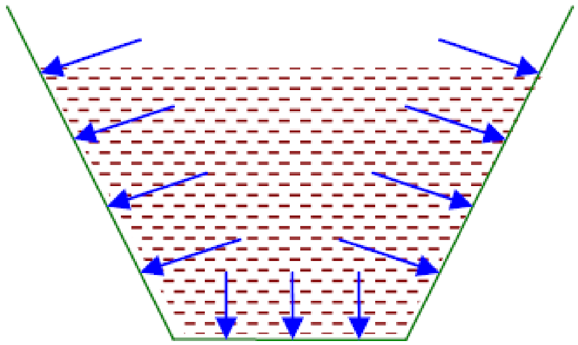
5. Real fluid :

Any fluid which posses certain viscosity is called real fluid. It can be Newtonian or non – Newtonian, thixotropic or ideal plastic.



PRESSURE AND ITS MEASUREMENTS:





Fluid is a state of matter which exhibits the property of flow. When a certain mass of fluids is held in static equilibrium by confining it within solid boundaries, it exerts force along direction perpendicular to the boundary in contact. This force is called fluid pressure.

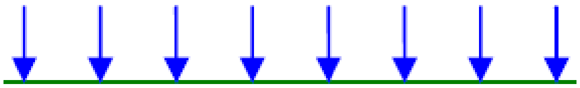
- **Pressure distribution:**

It is the variation of pressure over the boundary in contact with the fluid. There are two types of pressure distribution.

a) Uniform Pressure distribution.

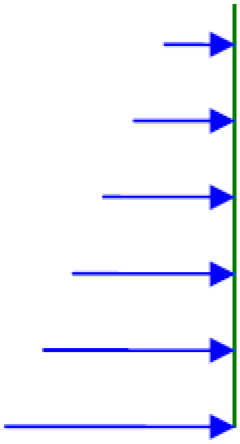
b) Non-Uniform Pressure distribution.

(a) Uniform Pressure distribution:



If the force exerted by the fluid is same at all the points of contact boundary then the pressure distribution is said to be uniform.

(b) Non –Uniform Pressure distribution:



If the force exerted by the fluid is not same at all the points then the pressure distribution is said to be non-uniform.

Intensity of pressure or unit pressure or Pressure:

Intensity of pressure at a point is defined as the force exerted over unit area considered around that point. If the pressure distribution is uniform then intensity of pressure will be same at all the points.

Calculation of Intensity of Pressure:

When the pressure distribution is uniform, intensity of pressure at any points is given by the ratio of total force to the total area of the boundary in contact.

Intensity of Pressure 'p' =F/A

When the pressure distribution is non- uniform, then intensity of pressure at a point is given by dF/dA.

Unit of Intensity of Pressure: N/m^2 or pascal (Pa).

Note: 1 MPa =1N/mm^2

- **Atmospheric pressure**

Air above the surface of liquids exerts pressure on the exposed surface of the liquid and normal to the surface.

This pressure exerted by the atmosphere is called atmospheric pressure.

Atmospheric pressure at a place depends on the elevation of the place and the temperature.

Atmospheric pressure is measured using an instrument called ‘Barometer’ and hence atmospheric pressure is also called Barometric pressure.

Unit: kPa .

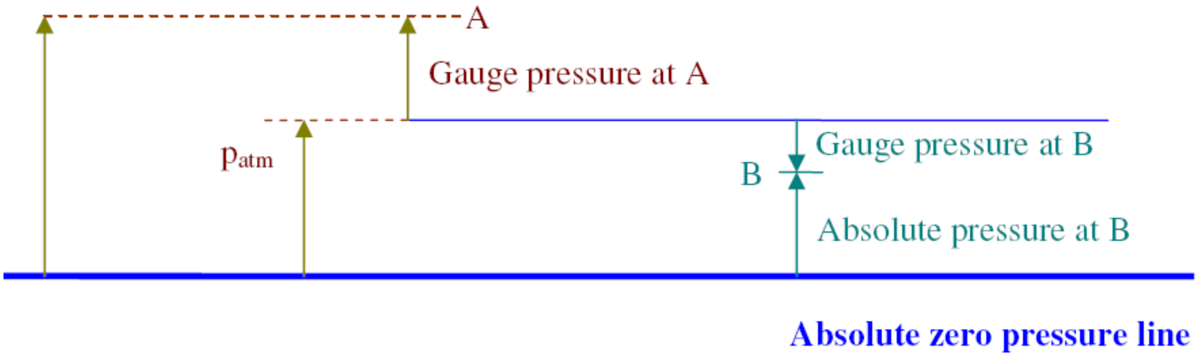
‘bar’ is also a unit of atmospheric pressure 1bar = 100 kPa.

Absolute pressure and Gauge Pressure:

Absolute pressure at a point is the intensity of pressure at that point measured with reference to absolute vacuum or absolute zero pressure.

Absolute pressure at a point can never be negative since there can be no pressure less than absolute zero pressure.

Absolute pressure at ‘A’



Absolute pressure at a point is the intensity of pressure at that point measured with reference to absolute vacuum or absolute zero pressure.

Absolute pressure at a point can never be negative since there can be no pressure less than absolute zero pressure.

If the intensity of pressure at a point is measured with reference to atmospheric pressure, then it is called gauge pressure at that point.

Gauge pressure at a point may be more than the atmospheric pressure or less than the atmospheric pressure. Accordingly gauge pressure at the point may be positive or negative.

Negative gauge pressure is also called vacuum pressure.

From the figure, It is evident that, Absolute pressure at a point = Atmospheric pressure ± Gauge pressure.

NOTE: If we measure absolute pressure at a Point below the free surface of the liquid, then, p = g. Y + patm

If gauge pressure at a point is required, then atmospheric pressure is taken as zero, then, p = g. Y

Pressure Head

It is the depth below the free surface of liquid at which the required pressure intensity is available.

P = gh

h = *P/* g

For a given pressure intensity ‘h’ will be different for different liquids since, ‘g’ will be different for different liquids. Whenever pressure head is given, liquid or the property of liquid like specify gravity, specific weight, mass density should be given.

Eg:

(i) 3m of water

(ii) 10m of oil of S = 0.8.

(iii) 3m of liquid of g = 15 kN/m3

(iv) 760mm of Mercury.

(v) 10m _ not correct.

NOTE:

1. To convert head of a liquid to head of another liquid.

$$p = \gamma_1 h_1$$

$$p = \gamma_2 h_2$$

$$\boxed{\gamma_1 h_1 = \gamma_2 h_2}$$

$$S = \frac{\gamma}{\gamma_{\text{Standard}}}$$

$$S_1 = \frac{\gamma_1}{\gamma_{\text{Standard}}}$$

$$\therefore \gamma_1 = S_1\, \gamma_{\text{Standard}}$$

$$\gamma_{21} = S_2\, \gamma_{\text{Standard}}$$

$$\therefore S_1\ \gamma_{\text{Standard}}\, h_1 = S_2\ \gamma_{\text{Standard}}\, h_2$$

$$\boxed{S_1 h_1 = S_2 h_2}$$

2. Swater x hwater = Sliquid x hliquid 1x hwater = Sliquid x hliquid
h water = Sliquid x hliquid

Pressure head in meters of water is given by the product of pressure head in meters of liquid and specific gravity of the liquid.
Eg: 10meters of oil of specific gravity 0.8 is equal to 10x0.8 = 8 meters of water. Eg: Atmospheric pressure is 760mm of Mercury.
NOTE:
P = g h
kPa *kN/ m*^{3} m

Problem:

1. Calculate intensity of pressure due to a column of 0.3m of (a) water (b) Mercury
(c) Oil of specific gravity-0.8.
a) h = 0.3m of water

$$\gamma = 9.81\ \frac{\mathrm{kN}}{\mathrm{m}^3}$$

$p = ?$

$p = \gamma h$

$p = 2.943\ \mathrm{kPa}$

c) $h = 0.3$ of Hg

$\gamma = 13.6 \times 9.81$

$\gamma = 133.416\ \mathrm{kN/m}^3$

$p = \gamma\ h$

$= 133.416 \times 0.3$

$p = 40.025\ \mathrm{kPa}$

2. Intensity of pressure required at a points is 40kPa. Find corresponding head in (a) water (b) Mercury (c) oil of specific gravity-0.9.

(a) $p = 40\ \mathrm{kPa}$

$$h = \frac{p}{\gamma}$$

$h = 4.077\ \mathrm{m}$ of water

$$\gamma = 9.81\frac{kN}{m^3}$$

$h = ?$

(b) $p = 40\ \mathrm{kPa}$

$\gamma = (13.6\mathrm{x}9.81\ \mathrm{N/m}^3$

$$\gamma = 133.416\ \frac{KN}{m^3}$$

$$h = \frac{p}{\gamma}$$

$h = 0.299\ \mathrm{m}$ of Mercury

$$h = \frac{p}{\gamma}$$

c) $p = 40\ \mathrm{kPa}$

$h = 4.53\ \mathrm{m}$ of oil $S = 0.9$

$\gamma = 0.9 \times 9.81$

$$\gamma = 8.829\ \frac{KN}{m^3}$$

4. Standard atmospheric pressure is 101.3 kPa Find the pressure head in (i) Meters of water (ii) mm of mercury (iii) m of oil of specific gravity 0.8.

(i) $p = \gamma h$

$101.3 = 9.81 \text{ x } h$

$h = 10.3$ m of water

(ii) $p = \gamma h$

$101.3 = (13.6 \text{x} 9.81) \text{ x } h$

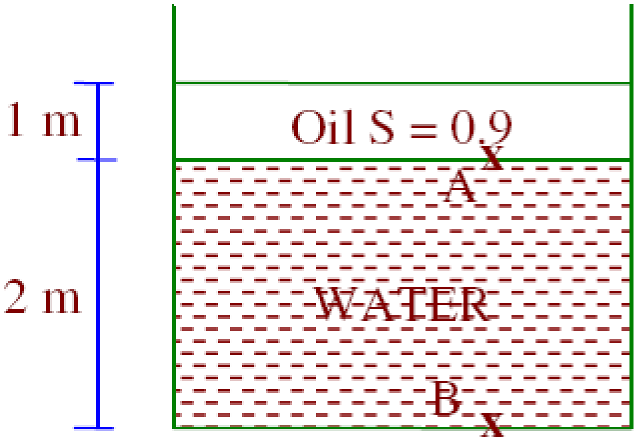
$h = 0.76$ m of mercury

(iii) $p = \gamma h$

$101.3 = (0.8 \text{ x } 9.81 \text{ x } h$

$h = 12.9$ m of oil of $S = 0.8$

5. An open container has water to a depth of 2m and above this an oil of S = 0.9 for a depth of 1m. Find the intensity of pressure at the interface of two liquids and at the bottom of the tank.



$$p_A = \gamma_{a1}\ h_{oil}$$

$$= (0.9\ \text{x}\ 9.81)\ \text{x}\ 1$$

$$p_A = 8.829\ \text{kPa}$$

$$p_B = \gamma_{oil}\ \text{x}h_{oil} + \gamma_{water} + h_{water}$$

$$p_A = 8.829\,\text{kPa} + 9.81\ \text{x}\ 2$$

$$p_B = 28.45\,\text{kPa}$$

6. Convert the following absolute pressure to gauge pressure (a) 120kPa (b) 3kPa (c) 15m of H2o (d) 800mm of Hg.

(a) $p_{abs} = p_{atm} + p_{gauge}$

$\therefore\ p_{gauge} = p_{abs} - p_{atm} = 120 - 101.3 = 18.7$ kPa

(b) $p_{gauge} = 3\text{-}101.3 = -98.3$ kPa

$p_{gauge} = 98.3$ kPa (vacuum)

(c) $h_{abs} = h_{atm} + h_{gauge}$

$15 = 10.3 + h_{gauge}$

$h_{gauge} = 4.7$m of water

(d) $h_{abs} = h_{atm} + h_{gauge}$

$800 = 760 + h_{gauge}$

$h_{gauge} = 40$ mm of mercury

Measurement of Pressure

Various devices used to measure fluid pressure can be classified into,

1. Manometers
2. Mechanical gauges.

Manometers are the pressure measuring devices which are based on the principal of balancing the column of the liquids whose pressure is to be measured by the same liquid or another liquid. Mechanical gauges consist of an elastic element which deflects under the action of applied pressure and this movement will operate a pointer on a graduated scale.

Classification of Manometers:

Manometers are broadly classified into

a) Simple Manometers

b) Differential Manometers.

a) Simple Manometers

Simple monometers are used to measure intensity of pressure at a point.

They are connected to the point at which the intensity of pressure is required. Such a point is called gauge point.

b) Differential Manometers

Differential manometers are used to measure the pressure difference between two points. They are connected to the two points between which the intensity of pressure is required.

Types of Simple Manometers

Common types of simple manometers are

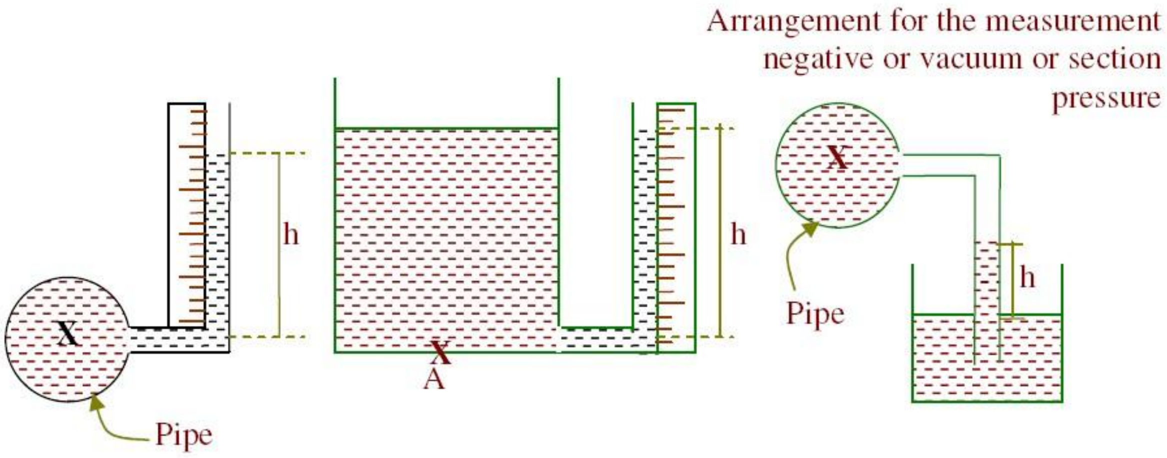
a) Piezometers

b) U-tube manometers

c) Single tube manometers

d) Inclined tube manometers

a) Piezometers:



Piezometer consists of a glass tube inserted in the wall of the vessel or pipe at the level of point at which the intensity of pressure is to be measured. The other end of the piezometer is exposed to air. The height of the liquid in the piezometer gives the pressure head from which the intensity of pressure can be calculated.

To minimize capillary rise effects the diameters of the tube is kept more than 12mm.

Merits

_ Simple in construction

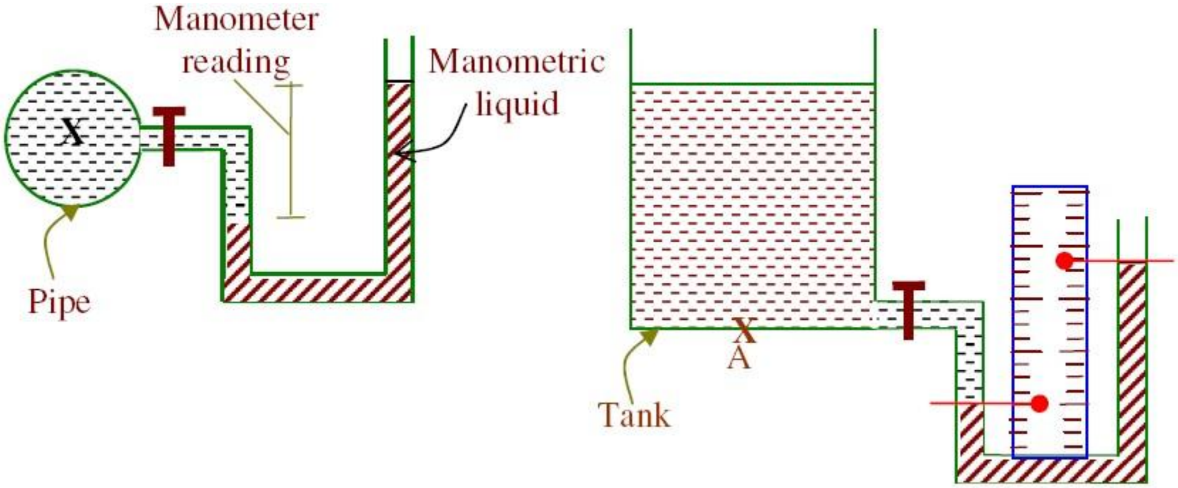
_ Economical

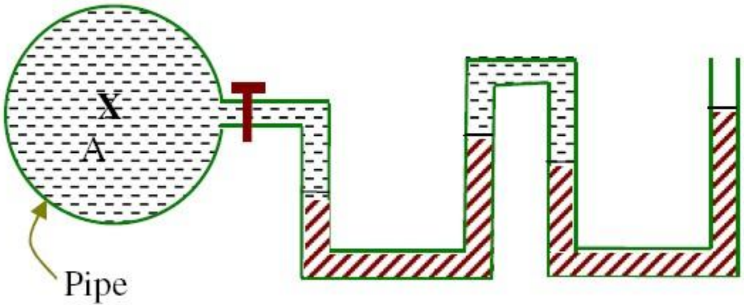
Demerits

_ Not suitable for high pressure intensity.

_ Pressure of gases cannot be measured.

(b) U-tube Manometers:





A U-tube manometers consists of a glass tube bent in U-Shape, one end of which

is connected to gauge point and the other end is exposed to atmosphere. U-tube consists of a liquid of specific of gravity other than that of fluid whose pressure intensity is to be measured and is called manometric liquid.

• **Manometric liquids**

¨ Manometric liquids should neither mix nor have any chemical reaction with the fluid whose pressure intensity is to be measured.

¨ It should not undergo any thermal variation.

¨ Manometric liquid should have very low vapour pressure.

¨ Manometric liquid should have pressure sensitivity depending upon the magnitude of pressure to be measured and accuracy requirement.

• **To write the gauge equation for manometers**

Gauge equations are written for the system to solve for unknown quantities.

Steps:

1. Convert all given pressure to meters of water and assume unknown pressure in meters of waters.

2. Starting from one end move towards the other observing the following points.

¨ Any horizontal movement inside the same liquid will not cause change in pressure.

¨ Vertically downward movement causes increase in pressure and upward motion causes decrease in pressure.

¨ Convert all vertical columns of liquids to meters of water by multiplying them by corresponding specify gravity.

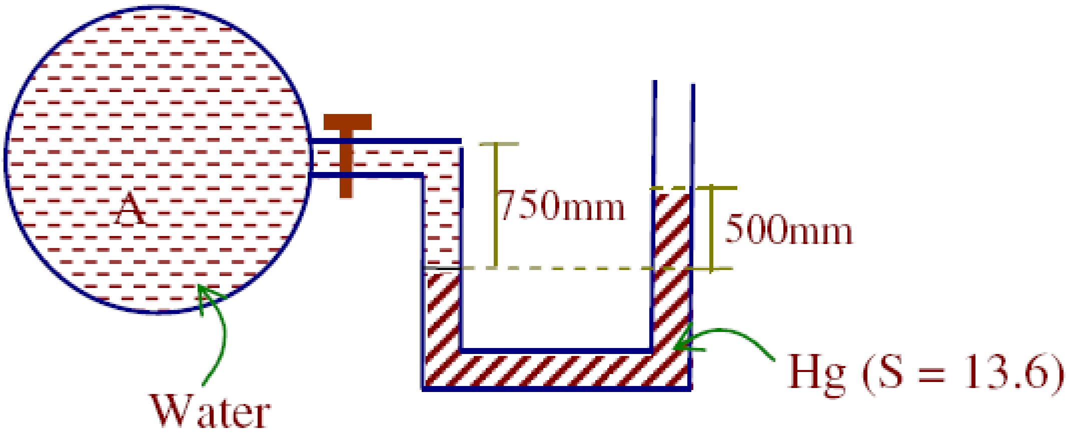
¨ Take atmospheric pressure as zero (gauge pressure computation).

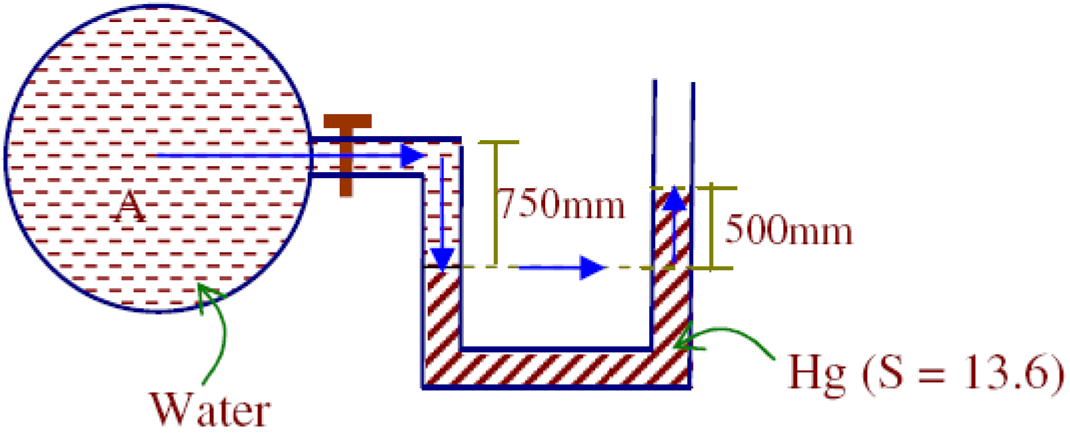
3. Solve for the unknown quantity and convert it into the required unit.

4. If required calculate absolute pressure.

Problem:

1. Determine the pressure at A for the U- tube manometer shown in fig. Also calculate the absolute pressure at A in kPa.





Let 'h_A' be the pressure head at 'A' in 'meters of water'.

$$h_A + 0.75 - 0.5 x 13.6 = 0$$

$$h_A = 6.05 m\ of\ \ water$$

$$p = \gamma h$$

$$= 9.81 x 6.05$$

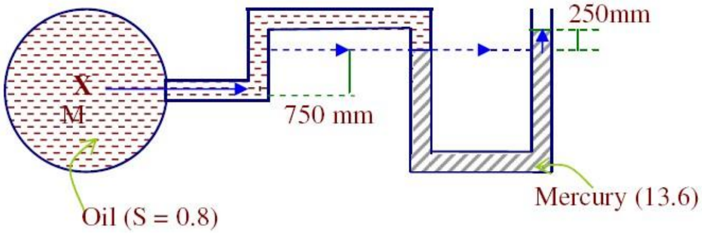
$$p = 59.35\ kPa (gauge\ \ pressure)$$

$$p_{abs} = p_{atm} + p_{gauge}$$

$$= 101.3 + 59.35$$

$$p_{abc} = 160.65\ kPa$$

2. For the arrangement shown in figure, determine gauge and absolute pressure at the point M.



Let 'h_M' be the pressure head at the point 'M' in m of water,

h_M - 0.75 x 0.8 – 0.25 x 13.6 = 0

$h_M =$ 4 m of water

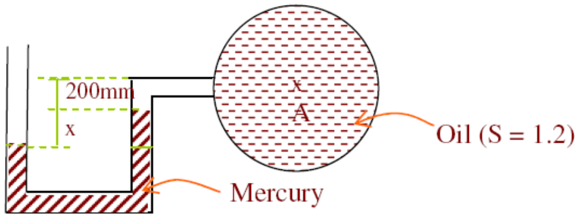
$p = \gamma h$

$p = 39.24 \text{kPa}$

$p_{abs} = 101.3 + 39.24$

$p_{abs} 140.54 \text{kPa}$

3. If the pressure at 'At' is 10 kPa (Vacuum) what is the value of 'x'?



p_A = 10 kPa (Vacuum)

p_A = - 10 kPa

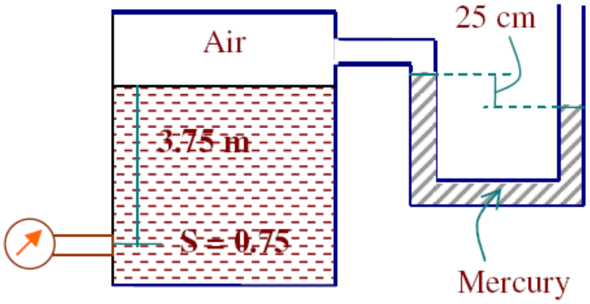
$$\frac{p_A}{\gamma} = \frac{-10}{9.81} = -1.019 \text{ m of water}$$

$$h_A = -1.019 \text{ m of water}$$

$$-1.019 + 0.2 \times 1.2 + x\,(13.6) = 0$$

$$x = 0.0572 \text{ m}$$

4. The tank in the accompanying figure consists of oil of S = 0.75. Determine the pressure gauge reading in *kN/m*$^{2.}$



Let the pressure gauge reading be ‘h’ m of water

$h - 3.75 \times 0.75 + 0.25 \times 13.6 = 0$

h = - 0.5875 m of water

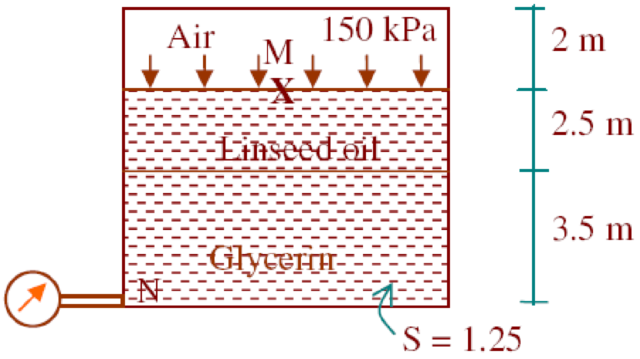
$p = \gamma h$

p = -5.763 kPa

p = 5.763 kPa (Vacuum)

5. A closed tank is 8m high. It is filled with Glycerine up to a depth of 3.5m and linseed oil to another 2.5m. The remaining space is filled with air under a pressure of 150 kPa. If a pressure gauge is fixed at the bottom of the tank what will be its reading.

Also calculate absolute pressure. Take relative density of Glycerine and Linseed oil as 1.25 and 0.93 respectively.



$$P_H = 150\,\text{kPa}$$

$$h_M = \frac{150}{9.81}$$

$$h_M = 15.29\,\text{m of water}$$

Let 'h_N' be the pressure gauge reading in m of water.

$$h_N - 3.5 \times 1.25 - 2.5 \times 0.93 = 15.29$$

$$h_N = 21.99 \text{ m of water}$$

$$p = 9.81 \times 21.99$$

$$p = 215.72 \text{ kPa (gauge)}$$

$$p_{abs} = 317.02 \text{ kPa}$$

DIFFERENTIAL MANOMETERS

Differential manometers are used to measure pressure difference between any two points.

Common varieties of differential manometers are:

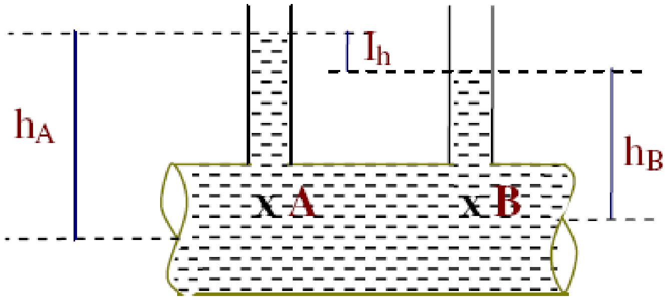
(a) Two piezometers.

(b) Inverted U-tube manometer.

(c) U-tube differential manometers.

(d) Micromanometers.

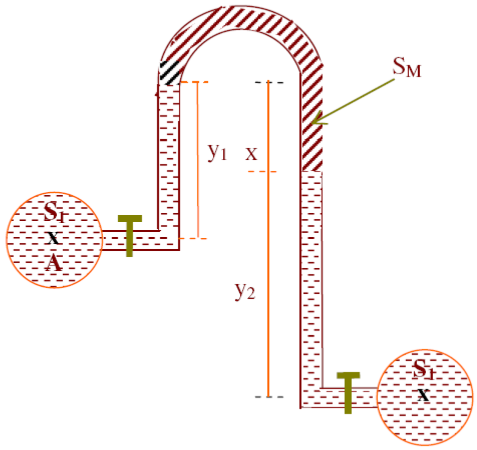
(a) Two Pizometers



The arrangement consists of two pizometers at the two points between which the pressure difference is required. The liquid will rise in both the piezometers. The difference in elevation of liquid levels can be recorded and the pressure difference can be calculated.

It has all the merits and demerits of piezometer.

(b) Inverted U-tube manometers



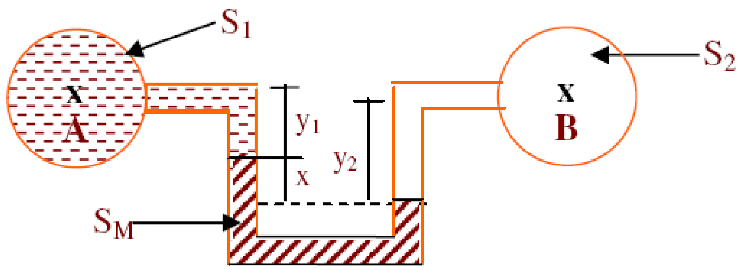
Inverted U-tube manometer is used to measure small difference in pressure between any two points. It consists of an inverted U-tube connecting the two points between which the pressure difference is required. In between there will be a lighter manometric liquid. Pressure difference between the two points can be calculated by writing the gauge equations for the system.

Let ‘hA’ and ‘hB’ be the pr head at ‘A’ and ‘B’ in meters of water

hA – (Y1 S1) + (x SM) + (y2 S2) = hB. hA – hB = S1 y1 – SM x – S2 y2,

pA – pB = g (hA – hB)

(c) U-tube Differential manometers



A differential U-tube manometer is used to measure pressure difference between any two points. It consists of a U-tube containing heavier manometric liquid, the two limbs of which are connected to the gauge points between which the pressure difference is required. U-tube differential manometers can also be used for gases. By writing the gauge equation for the system pressure difference can be determined.

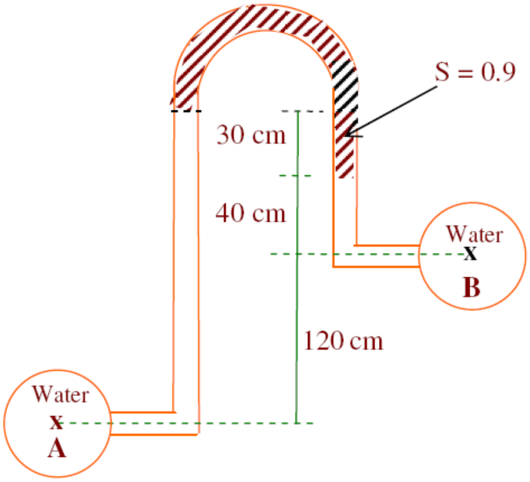
Let ‘hA’ and ‘hB’ be the pressure head of ‘A’ and ‘B’ in meters of water

hA + S1 Y1 + x SM – Y2 S2 = hB hA – hB = Y2 S2 – Y1 S1– x SM

Problems

(1) An inverted U-tube manometer is shown in figure. Determine the pressure difference between A and B in N/m^2

Let hA and hB be the pressure heads at A and B in meters of water.



$h_A - (190 \times 10^{-2}) + (0.3 \times 0.9) + (0.4)\,0.9 = h_B$

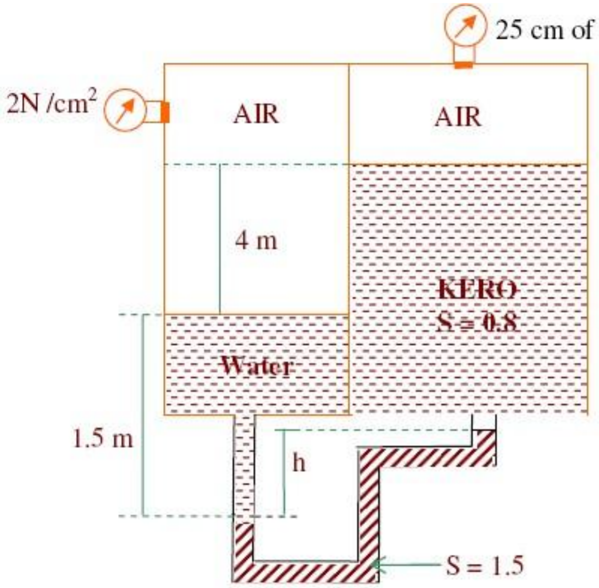
$h_A - h_B = 1.23$ meters of water

$p_A - p_B = \gamma\,(h_A - h_B) = 9.81 \times 1.23$

$p_A - p_B = 12.06$ kPa

$p_A - p_B = 12.06 \times 10^3\ \text{N/m}^2$

2. In the arrangements shown in figure. Determine the ho ‘h’.



25 cm of Mercury (Vacuum)
$= -0.25 \times 13.6$
$= -3.4$ m of water

$2\text{N/cm}^2 = 2 \times 100^2\ \text{N/m}^2 = 20$ kPa

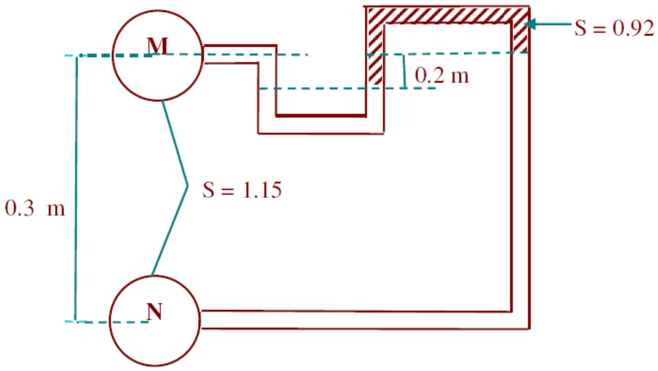
$h = 20\ 9.81$

$h = 2.038$ meters of water

$2.038 + 1.5 - (4 + 1.5 - h)\,0.8 = -3.4$

$h = 3.6$ m

3. Compute the pressure different between ‘M’ and ‘N’ for the system shown in figure.



Let ‘h_M’ and ‘ h_N’ be the pressure heads at M and N in m of water.

$hm + y \text{ x } 1.15 - 0.2 \text{ x } 0.92 + (0.3 - y + 0.2)\ 1.15 = hn$

$hm + 1.15\, y - 0.184 + 0.3 \text{ x } 1.15 - 1.15\, y + 0.2 \text{ x } 1.15 = hn$

$hm + 0.391 = hn$

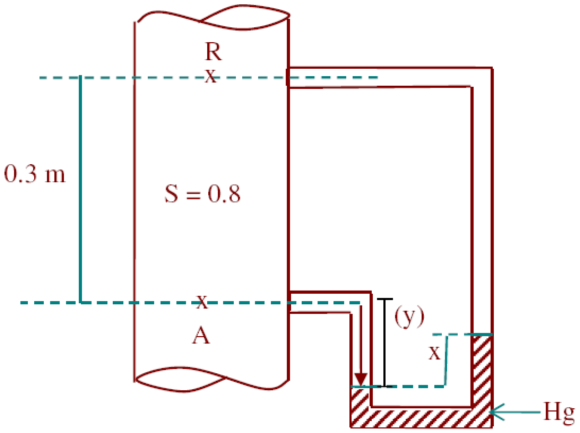
$hn - hm = 0.391$meters of water

$p_n - p_m = \gamma\, (h_N - h_m)$

$= 9.81 \text{ x } 0.391$

$p_n - p_m = 3.835$ kPa

4. Petrol of specify gravity 0.8 flows up through a vertical pipe. A and B are the two points in the pipe, B being 0.3 m higher than A. Connection are led from A and B to a U–tube containing Mercury. If the pressure difference between A and B is 18 kPa, find the reading of manometer.



$p_A - p_B = 18$kPa

$$\frac{P_A - P_B}{\gamma}$$

$$h_A - h_B = \frac{18}{9.81}$$

$h_A - h_B = 1.835 m\ of\ \ water$

$h_A + y \text{ x } 0.8 - x\ 13.6 - (0.3 + y - x)\ 0.8 = h_B$

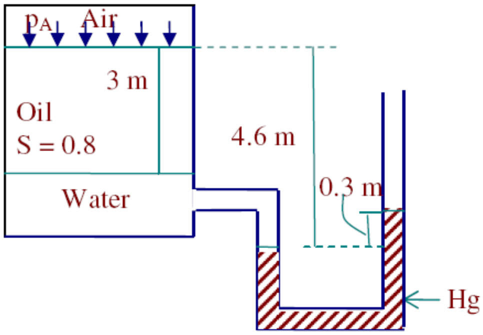
$h_A - h_B = -0.8y + 13.66\, x + 0.24 + 0.8\, y - 0.8\, x$

$h_A - h_B = 12.8x + 0.24$

$1.835 = 12.8x + 0.24$

$x = 0.1246$ m

4. What is the pressure pA in the fig given below? Take specific gravity of oil as 0.8.



$h_A + (3 \times 0.8) + (4.6 - 0.3)(13.6) = 0$

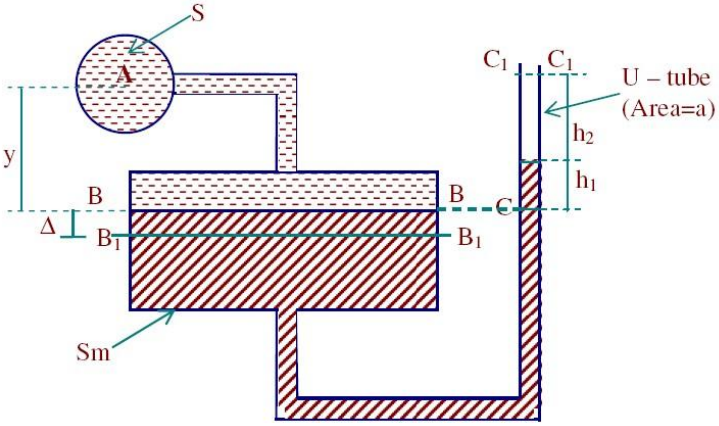
$h_A = 2.24$ m of oil

$p_A = 9.81 \times 2.24$

$p_A = 21.97$ kPa

SINGLE COLUMN MANOMETER:

Single column manometer is used to measure small pressure intensities.



A single column manometer consists of a shallow reservoir having large cross sectional area when compared to cross sectional area of U – tube connected to it. For any change in pressure, change in the level of manometric liquid in the reservoir is small and change in level of manometric liquid in the U- tube is large.

To derive expression for pressure head at A:

BB and CC are the levels of manometric liquid in the reservoir and U-tube before connecting the point A to the manometer.

Let the point A be connected to the manometer. B1B1 and C1 C1 are the levels of manometric liquid. Volume of liquid between BBB1B1 = Volume of liquid between

Let the point A be connected to the manometer. B1B1 and C1 C1 are the levels of manometric liquid. Volume of liquid between BBB1B1 = Volume of liquid between

CCC1C1

$$A\Delta = a\,h_2$$

$$\Delta = \frac{ah_2}{A}$$

Let 'h_A' be the pressure head at A in m of water.

$$h_A + (y + \Delta)\,S - (\Delta + h_1 + h_2)\,Sm = 0$$

$$h_A = (\Delta + h_1 + h_2)\,Sm - (y + \Delta)\,S$$

$$= \Delta\,Sm + \underline{h_1\,Sm} + h_2\,Sm - \underline{yS} - \Delta S$$

$$h_A = \Delta\,(Sm - S) + h_2\,Sm$$

$$h_A = \frac{ah_2}{A}\,(Sm - S) + h_2\,Sm$$

$\therefore$ It is enough if we take one reading to get 'h_2' If '$\frac{a}{A}$' is made very small (by increasing 'A') then the I term on the RHS will be negligible.

$$\text{Then } h_A = h_2\,Sm$$

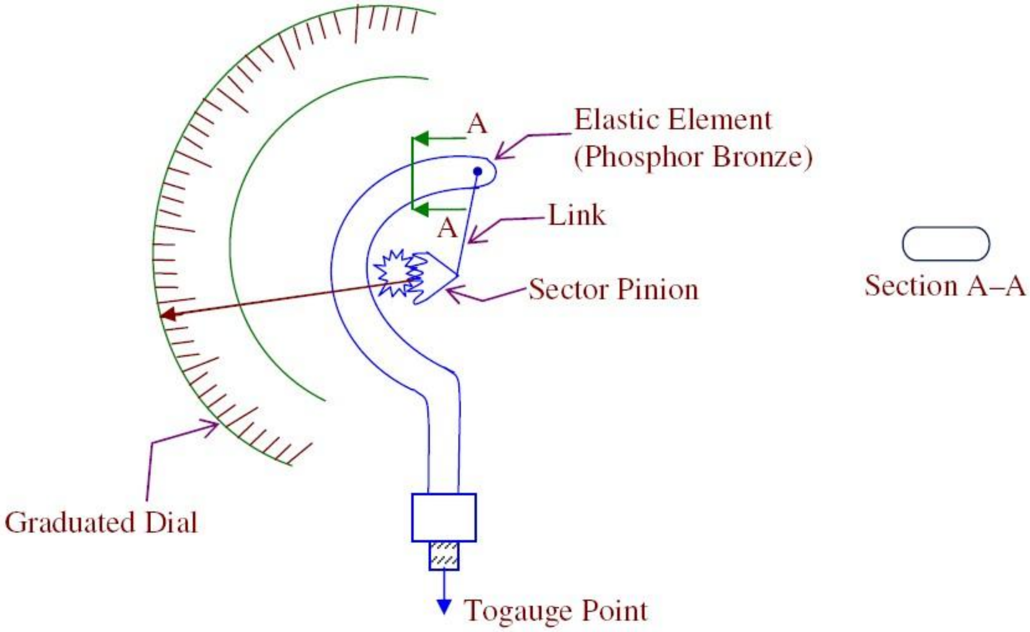
MECHANICAL GAUGES:

Pressure gauges are the devices used to measure pressure at a point.

They are used to measure high intensity pressures where accuracy requirement is less.

Pressure gauges are separate for positive pressure measurement and negative pressure measurement. Negative pressure gauges are called Vacuum gauges.

BASIC PRINCIPLE:



Mechanical gauge consists of an elastic element which deflects under the action of applied pressure and this deflection will move a pointer on a graduated dial leading to the measurement of pressure. Most popular pressure gauge used is Bordon pressure gauge.

The arrangement consists of a pressure responsive element made up of phosphor bronze or special steel having elliptical cross section. The element is curved into a circular arc, one end of the tube is closed and free to move and the other end is connected to gauge point. The changes in pressure cause change in section leading to the movement. The movement is transferred to a needle using sector pinion mechanism. The needle moves over a graduated dial.

UNIT – II

FLUID KINEMATICS AND DYNAMICS

INTRODUCTION

Fluid kinematics refers to the features of a fluid in motion. It only deals with the motion of fluid particles without taking into account the forces causing the motion. Considerations of velocity, acceleration, flow rate, nature of flow and flow visualization are taken up under fluid kinematics.

A fluid motion can be analyzed by one of the two alternative approaches, called **Lagrangian** and**Eulerian**.

In Lagrangian approach, a particle or a fluid element is identified and followed during the course of its motion with time as demonstrated in Fig.1

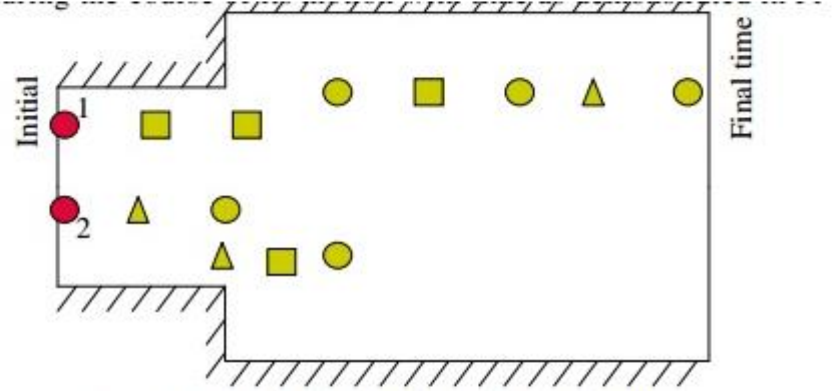


Fig. 1. Lagrangian Approach (Study of each particle with time)

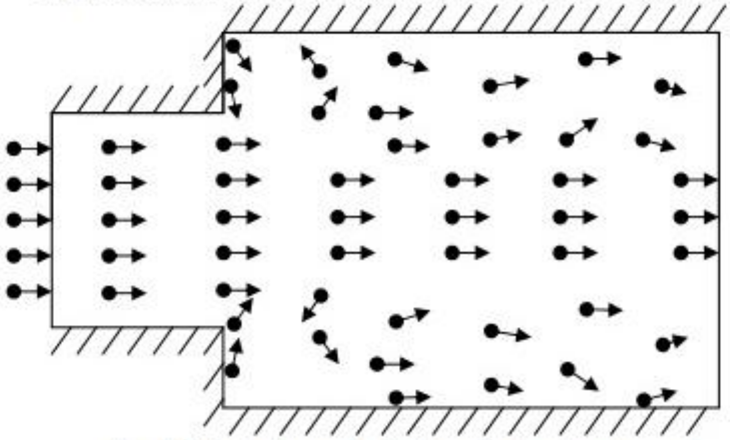


Fig. 2. Eulerian Approach (Study at fixed station in space)

Eg: To know the attributes of a vehicle to be purchased, you can follow the specific vehicle in the traffic flow all along its path over a period of time.

Difficulty in tracing a fluid particle (s) makes it nearly impossible to apply the Lagrangian approach. The alternative approach, called Eulerian approach consists of observing the fluid by setting up fixed stations (sections) in the flow field (Fig. 2).

Motion of the fluid is specified by velocity components as functions of space and time. This is considerably easier than the previous approach and is followed in Fluid Mechanics.

Eg: Observing the variation of flow properties in a channel like velocity, depth etc, at a section.

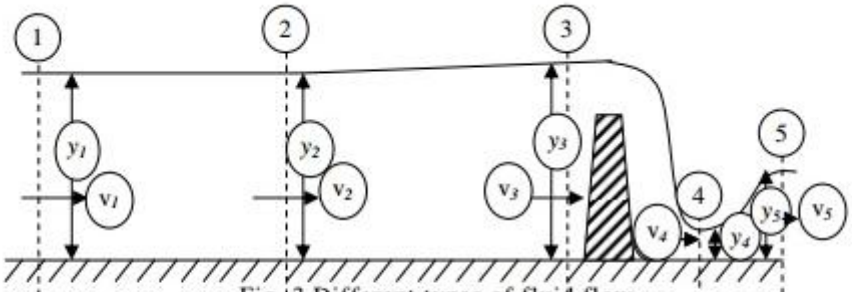


Fig. 3 Different types of fluid flow

Classification of Flows

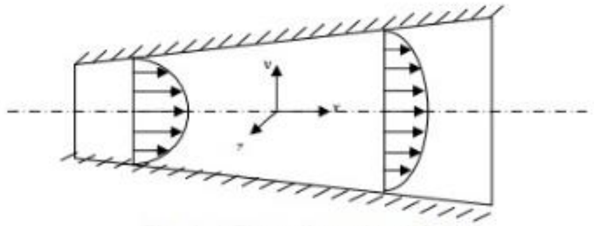


Fig. 4 c) Three dimensional flow

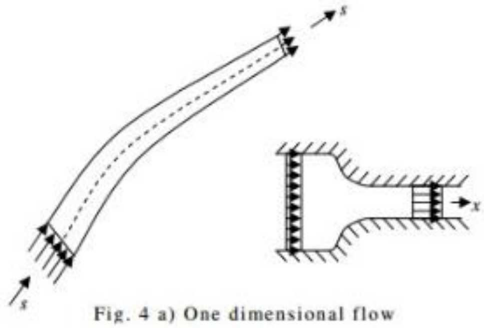


Fig. 4 a) One dimensional flow

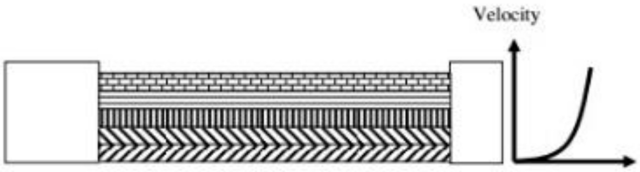


Fig. 5 Laminar flow

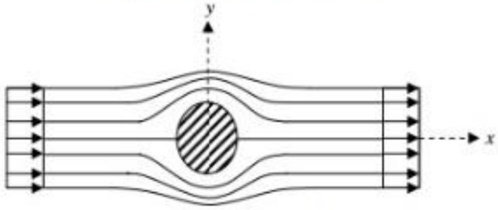


Fig. 4 b) Two dimensional flow

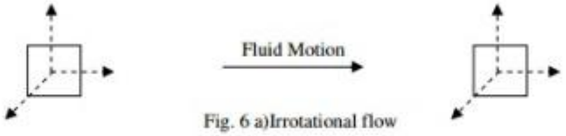


Fig. 6 a)Irrotational flow

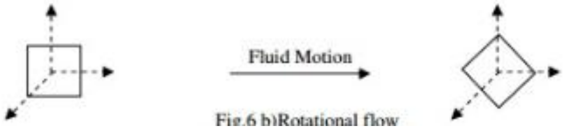


Fig.6 b)Rotational flow

1. Steady and unsteady flows:

A flow is said to be steady if the properties (P) of the fluid and flow do not change with time (t) at any section or point in a fluid flow.

A flow is said to be unsteady if the properties (P) of the fluid and flow change with time (t) at any section or point in a fluid flow.

Eg: Flow observed at a dam section during rainy season, wherein, there will be lot of inflow with which the flow properties like depth, velocity etc.. will change at the dam section over a period of time representing it as unsteady flow.

2. Uniform and non-uniform flows:

A flow is said to be uniform if the properties (P) of the fluid and flow do not change (with direction) over a length of flow considered along the flow at any instant.

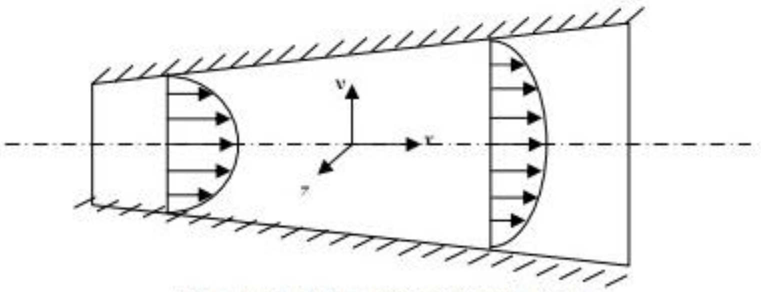


Fig. 4 c) Three dimensional flow

A flow is said to be ***non-uniform*** if the properties (P) of the fluid and flow change (with direction) over a length of flow considered along the flow at any instant.

Eg: Flow observed at any instant, at the dam section during rainy season, wherein, the flow varies from the top of the overflow section to the foot of the dam and the flow properties like depth, velocity etc., will change at the dam section at any instant between two sections, representing it as non-uniform flow.

Consider a fluid flow as shown above in a channel. The flow is said to be steady at sections 1 and 2 as the flow does not change with respect to time at the respective sections (y_1=y_2 *and* v_1=v_2).

The flow between sections 1 and 2 is said to be uniform as the properties does not change between the sections at any instant (y_1 =y_2 and v_1 = v_2).

The flow between sections 2 and 3 is said to be non-uniform flow as the properties vary over the length between the sections.

Non-uniform flow can be further classified as ***Gradually varied flow*** and ***Rapidly varied flow***. As the name itself indicates, ***Gradually varied flow*** is a non-uniform flow wherein the flow/fluid properties vary gradually over a long length (Eg: between sections 2 and 3).

Rapidly varied flow is a non-uniform flow wherein the flow/fluid properties vary rapidly within a very short distance. (Eg: between sections 4 and 5).

Combination of steady and unsteady flows and uniform and non-uniform flows can be classified as***steady-uniform flow*** (Sections 1 and 2)**, *unsteady-uniform flow, steady-non-uniform flow*** (Sections 2 and 3) and ***unsteady-non-uniform flow***
(Sections 4 and 5)**.**

3. *One, two and three dimensional flows:*

Flow is said to be direction and will one-dimensional if the properties vary only along one axis / be constant with respect to other two directions of a three-

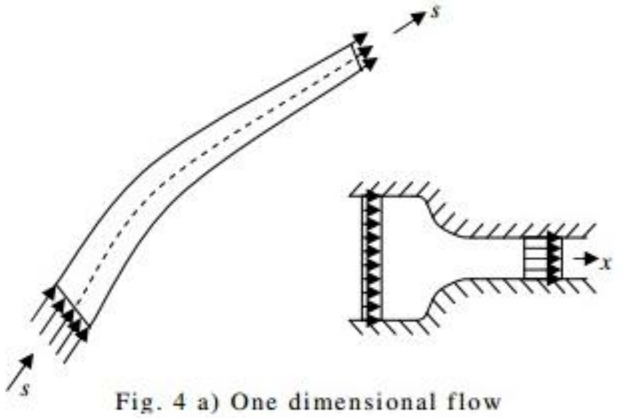


Fig. 4 a) One dimensional flow

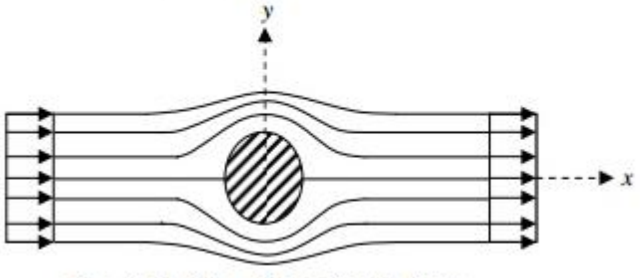


Fig. 4 b) Two dimensional flow

Flow is said to be ***two-dimensional*** if the properties vary only along two axes / directions and will be constant with respect to other direction of a three-dimensional axis system.

Flow is said to be ***three-dimensional*** if the properties vary along all the axes / directions of a three-dimensional axis system.

4. *Laminar and Turbulent flows:*

When the flow occurs like sheets or laminates and the fluid elements flowing in a layer does not mix with other layers, then the flow is said to be laminar. The Reynolds number (R_e) for the flow will be less than 2000.

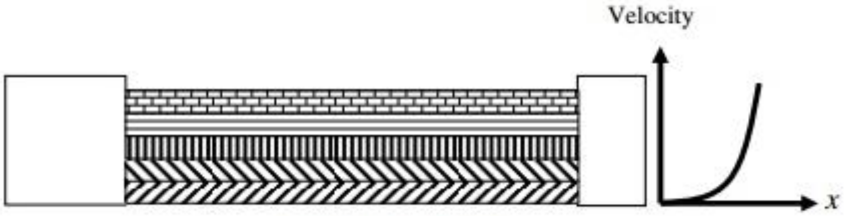


Fig. 5 Laminar flow

When the flow velocity increases, the sheet like flow gets mixed up and the fluid elements mix with other layers there by causing turbulence. There will be eddy currents generated and flow reversal takes place. This flow is said to be Turbulent.

The Reynolds number for the flow will be greater than 4000.
For flows with Reynolds number between 2000 to 4000 is said to be transition flow.

5. *Compressible and Incompressible flows:*

Flow is said to be ***Incompressible*** if the fluid density does not change (constant) along the flow direction and is ***Compressible*** if the fluid density varies along the flow direction

6. *Rotational and Irrotational flows:*

Flow is said to be ***Rotational*** if the fluid elements does not rotate about their own axis as they move along the flow and is ***Rotational*** if the fluid elements rotate along their axis as they move along the flow direction.

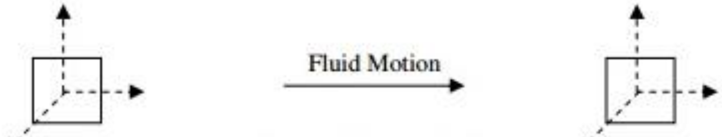


Fig. 6 a)Irrotational flow

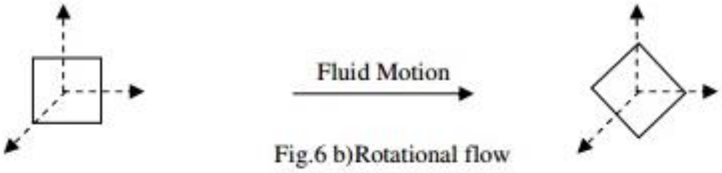


Fig.6 b)Rotational flow

7. Critical, Sub-critical and Super-critical flows:

Froude's Number

It is the ratio of the inertia forces to gravity forces and mathematically

where F_e=Froudes No, *V* is the flow velocity and *d* is the hydraulic mean *gd* depth given by

d-A/T, A is the flow cross-sectional area and *T* is the top width.
T

If the Foude's number is ONE, the flow is ***critical***, Less than ONE, ***Sub-critical*** and Greater than ONE,***Super-critical.***

Rate of flow or Discharge (Q):

Rate of flow or discharge is said to be the quantity of fluid flowing per second across a section of a flow. Rate of flow can be expressed as mass rate of flow or volume rate of flow. Accordingly

Mass rate of flow = Mass of fluid flowing across a section / time Rate of flow = Volume of fluid flowing across a section / time

Types of lines

Path Line: It is the path traced by a fluid particle over a period of time during its motion along the fluid flow.

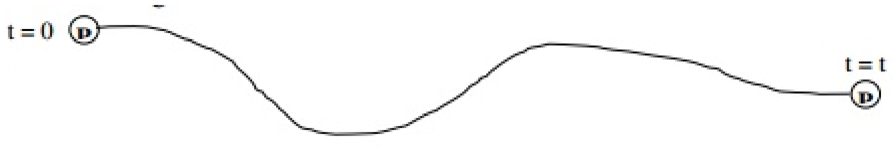
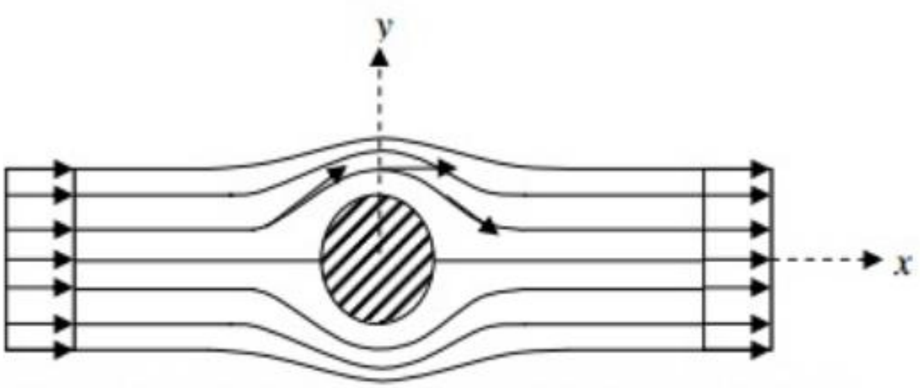


Fig. 7 Path line

Eg: Path traced by an ant coming out from its dwelling

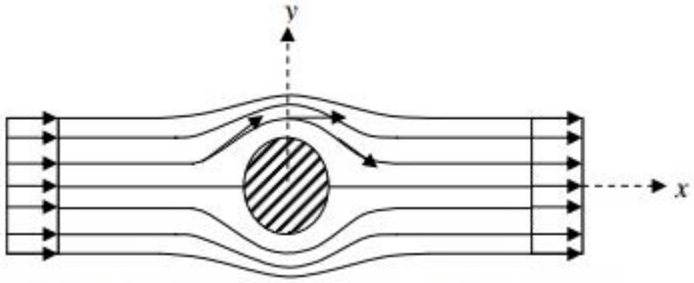
Stream Lines:



velocity of the fluid particle at that point and at that instant.

Stream Lines

It is an imaginary line such that when a tangent is drawn at any point it gives the velocity of the fluid particle at that point and at that instant.



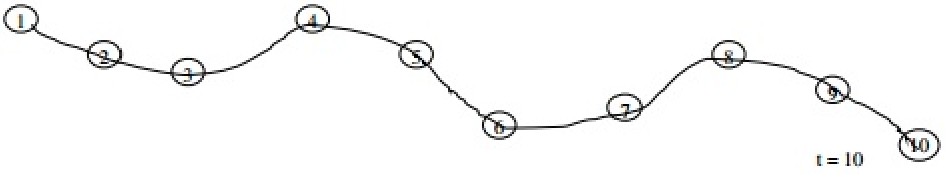
velocity of the fluid particle at that point and at that instant.

Fig. 8 Stream lines

Eg: Path traced by the flow when an obstruction like, a sphere or a stick is kept during its motion. The flow breaks up before the obstruction and joins after it crosses it.

Streak lines

It is that imaginary line that connects all the fluid particles that has gone through a point/section over a period of time in a fluid motion.



Stream tube:

It is an imaginary tube formed by stream line on its surface such that the flow only enters the tub from one side and leaves it on the other side only. No flow takes place across the stream tube. This concept will help in the analysis of fluid motion.

Variation of a Property along any given direction

If *P* is a Property at any point, then the property at any other location along *x* direction at a distance *dx* is given by

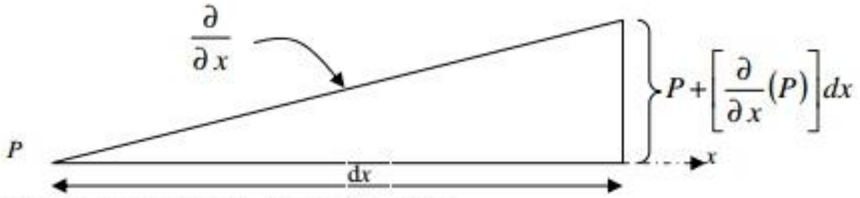


Fig. 12 Variation of a property along x direction

New Property = Old Property + slope x Old Property x distance

Continuity Equation

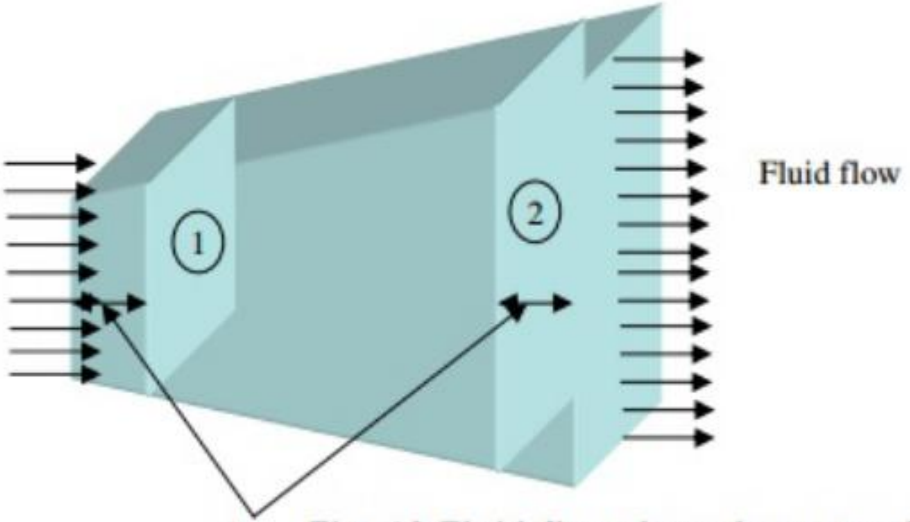


Fig. 13 Fluid flow through a control volume

Continuity Equation in three dimensional or differential forms

Consider a parallelepiped ***ABCDEFGH*** in a fluid flow of density **?** as shown in Fig. Let the dimensions of the parallelepiped be ***dx***, ***dy*** and ***dz*** along ***x***, ***y*** and ***z*** directions respectively. Let the velocity components along ***x, y*** and ***z*** be ***u,*** **v** and **w** respectively.

Similarly mass rate of fluid flow leaving the section EFGH along *x* direction is given by

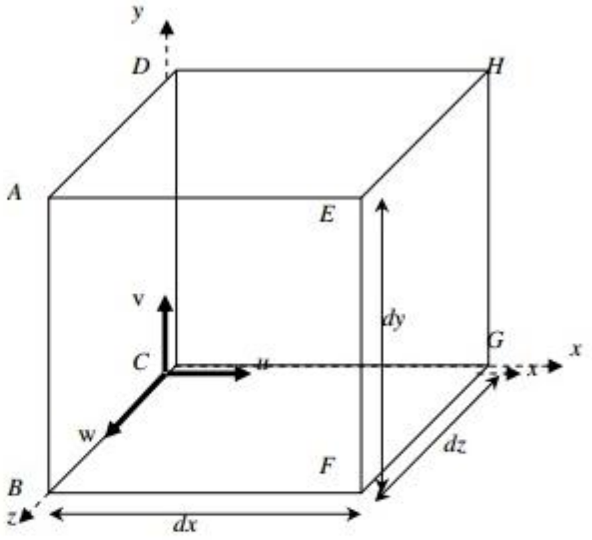


Fig. 14 parallelepiped in a fluid flow

Net gain in mass rate of the fluid along the *x* axis is given by the difference between the mass rate of flow entering and leaving the control volume. i.e. Eq. 1 - Eq. 2

$$\left[\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}\right]=0$$

Velocity

Velocity of a fluid along any direction can be defined as the rate of change of displacement of the fluid along that direction.

u = dx / dt

Where ***dx*** is the distance traveled by the fluid in time ***dt***.

Velocity of a fluid element is a vector, which is a function of space and time.

Let **V** be the resultant velocity of a fluid along any direction and ***u***, **v** and **w** be the velocity components in***x, y*** and ***z*** directions respectively.

Mathematically the velocity components can be written as

u = f (x, y, z, t)

v = f (x, y, z, t)

w = f (x, y, z, t)

Acceleration

Acceleration of a fluid element along any direction can be defined as the rate of change of velocity of the fluid along that direction.

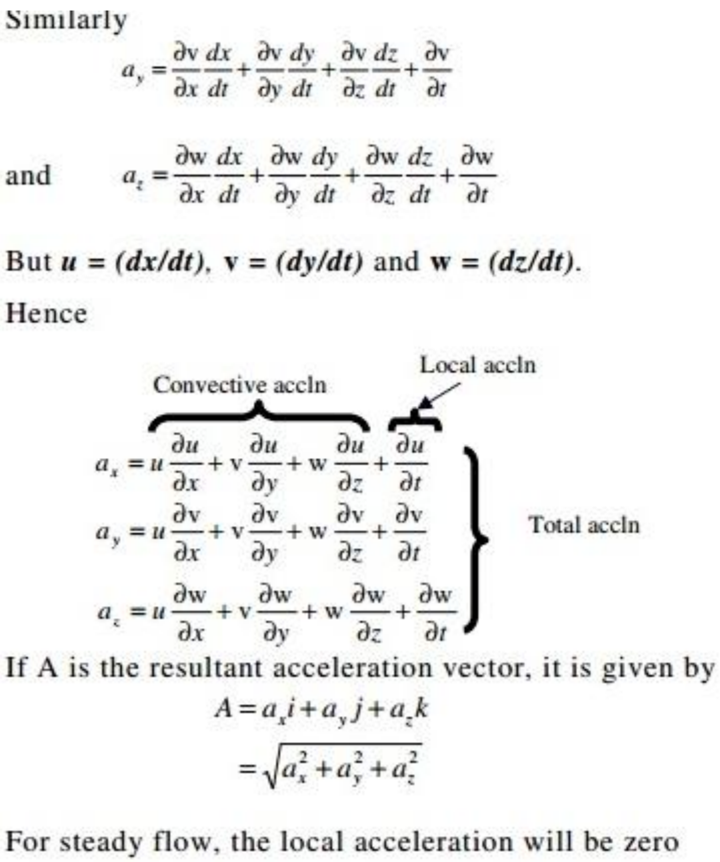
If a_x , a_y and a_z are the components of acceleration along ***x, y*** and ***z*** directions respectively, they can be mathematically written as

a_x = du/ dt.

But ***u = f (x, y, z, t)*** and hence by chain rule, we can write,

ax = ?u dx + ?u dy + ?u dz + ?u ?x dt ?y dt ?z dt ?t

Similarly



Similarly

$$a_y = \frac{\partial v}{\partial x}\frac{dx}{dt} + \frac{\partial v}{\partial y}\frac{dy}{dt} + \frac{\partial v}{\partial z}\frac{dz}{dt} + \frac{\partial v}{\partial t}$$

and $$a_z = \frac{\partial w}{\partial x}\frac{dx}{dt} + \frac{\partial w}{\partial y}\frac{dy}{dt} + \frac{\partial w}{\partial z}\frac{dz}{dt} + \frac{\partial w}{\partial t}$$

But ***u* = *(dx/dt)*, v = *(dy/dt)*** and **w = *(dz/dt)*.**

Hence

$$\left.\begin{aligned} a_x &= \overbrace{u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} + w\frac{\partial u}{\partial z}}^{\text{Convective accln}} + \overbrace{\frac{\partial u}{\partial t}}^{\text{Local accln}} \\ a_y &= u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} + w\frac{\partial v}{\partial z} + \frac{\partial v}{\partial t} \\ a_z &= u\frac{\partial w}{\partial x} + v\frac{\partial w}{\partial y} + w\frac{\partial w}{\partial z} + \frac{\partial w}{\partial t} \end{aligned}\right\} \text{Total accln}$$

If A is the resultant acceleration vector, it is given by

$$A = a_x i + a_y j + a_z k$$
$$= \sqrt{a_x^2 + a_y^2 + a_z^2}$$

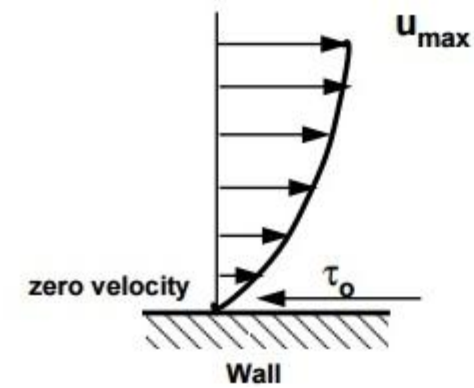
For steady flow, the local acceleration will be zero

UNIT – III

BOUNDARY LAYER THEORY AND CLOSED CONDUIT FLOW

3.1 Boundary Layers

When a fluid flows over a stationary surface, e.g. the bed of a river, or the wall of a pipe, the fluidtouching the surface is brought to rest by the shear stress t_o at the wall. The velocity increases from thewall to a maximum in the main stream of the flow.



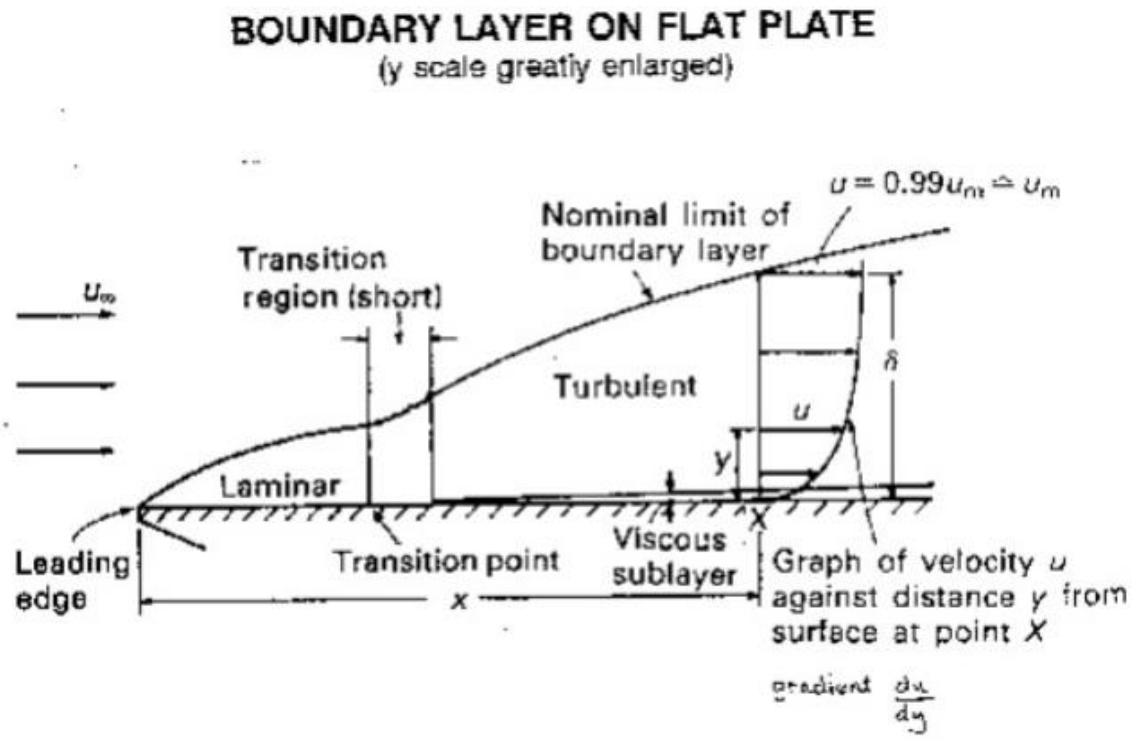
Looking at this two-dimensionally we get the above velocity profile from the wall to the centre of the flow.

This profile doesn't just exit, it must build up gradually from the point where the fluid starts to flow past the surface - e.g. when it enters a pipe.

If we consider a flat plate in the middle of a fluid, we will look at the build up of the velocity profile as the fluid moves over the plate.

Upstream the velocity profile is uniform, (free stream flow) a long way downstream we have the velocity profile we have talked about above. This is the known as **fully developed flow**. But how do we get to that state?

This region, where there is a velocity profile in the flow due to the shear stress at the wall, we call the**boundary layer**. The stages of the formation of the boundary layer are shown in the figure below:



We define the thickness of this boundary layer as the distance from the wall to the point where the velocity is 99% of the 'free stream' velocity, the velocity in the middle of the pipe or river.

boundary layer thickness, d = distance from wall to point where u = 0.99 $u_{mainstream}$

The value of d will increase with distance from the point where the fluid first starts to pass over the boundary - the flat plate in our example. It increases to a maximum in fully developed flow.

Correspondingly, the drag force D on the fluid due to shear stress t_o at the wall increases from zero at the start of the plate to a maximum in the fully developed flow region where it remains constant. We can calculate the magnitude of the drag force by using the momentum equation. But this complex and not necessary for this course.

Our interest in the boundary layer is that its presence greatly affects the flow through or round an object. So here we will examine some of the phenomena associated with the boundary layer and discuss why these occur.

3.2 Formation of the boundary layer

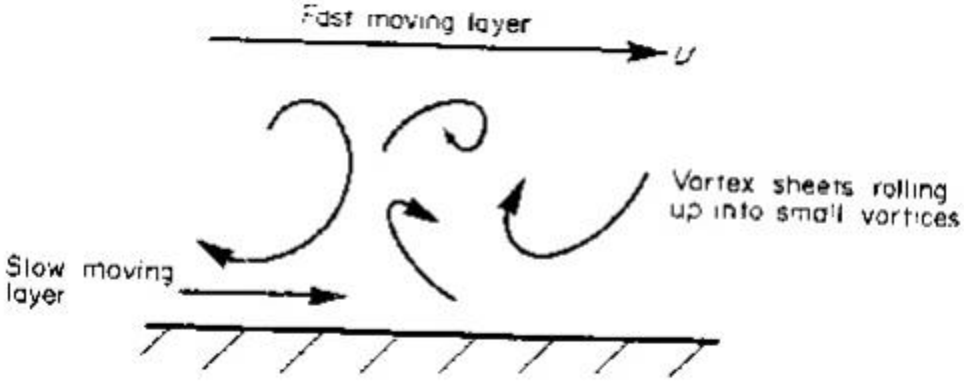
Previously we noted that the boundary layer grows from zero when a fluid starts to flow over a solid surface. As is passes over a greater length more fluid is slowed by friction between the fluid layers close to the boundary. Hence the thickness of the slower layer increases.

The fluid near the top of the boundary layer is dragging the fluid nearer to the solid surface along. The mechanism for this dragging may be one of two types:

The first type occurs when the normal viscous forces (the forces which hold the fluid together) are large enough to exert drag effects on the slower moving fluid close to the solid boundary. If the boundary layer is thin then the velocity gradient normal to the surface, (du/dy), is large so by Newton's law of viscosity the shear stress, = m (du/dy), is also large. The corresponding force may then be large enough to exert drag on the fluid close to the surface.

As the boundary layer thickness becomes greater, so the velocity gradient become smaller and the shear stress decreases until it is no longer enough to drag the slow fluid near the surface along. If this viscous force was the only action then the fluid would come to a rest.

It, of course, does not come to rest but the second mechanism comes into play. Up to this point the flow has been laminar and Newton's law of viscosity has applied. This part of the boundary layer is known as the laminar boundary layer.



This causes the fluid motion to rapidly becomes turbulent. Fluid from the fast moving region moves to the slower zone transferring momentum and thus maintaining the fluid by the wall in motion. Conversely, slow moving fluid moves to the faster moving region slowing it down. The net effect is an increase in momentum in the boundary layer. We call the part of the boundary layer the turbulent boundary layer.

At points very close to the boundary the velocity gradients become very large and the velocity gradients become very large with the viscous shear forces again becoming large enough to maintain the fluid in laminar motion. This region is known as the laminar sub-layer. This layer occurs within the turbulent zone and is next to the wall and very thin - a few hundredths of a mm.

3.3 Surface roughness effect

Despite its thinness, the laminar sub-layer can play a vital role in the friction characteristics of the surface.

This is particularly relevant when defining pipe friction - as will be seen in more detail in the level 2 module. In turbulent flow if the height of the roughness of a pipe is greater than the thickness of the laminar sub-layer then this increases the amount of turbulence and energy losses in the flow. If the height of roughness is less than the thickness of the laminar sub-layer the pipe is said to be smooth and it has little effect on the boundary layer.

In laminar flow the height of roughness has very little effect

3.4 Boundary layers in pipes

As flow enters a pipe the boundary layer will initially be of the laminar form. This will change depending on the ration of inertial and viscous forces; i.e. whether we have laminar (viscous forces high) or turbulent flow (inertial forces high).

From earlier we saw how we could calculate whether a particular flow in a pipe is laminar or turbulent using the Reynolds number.

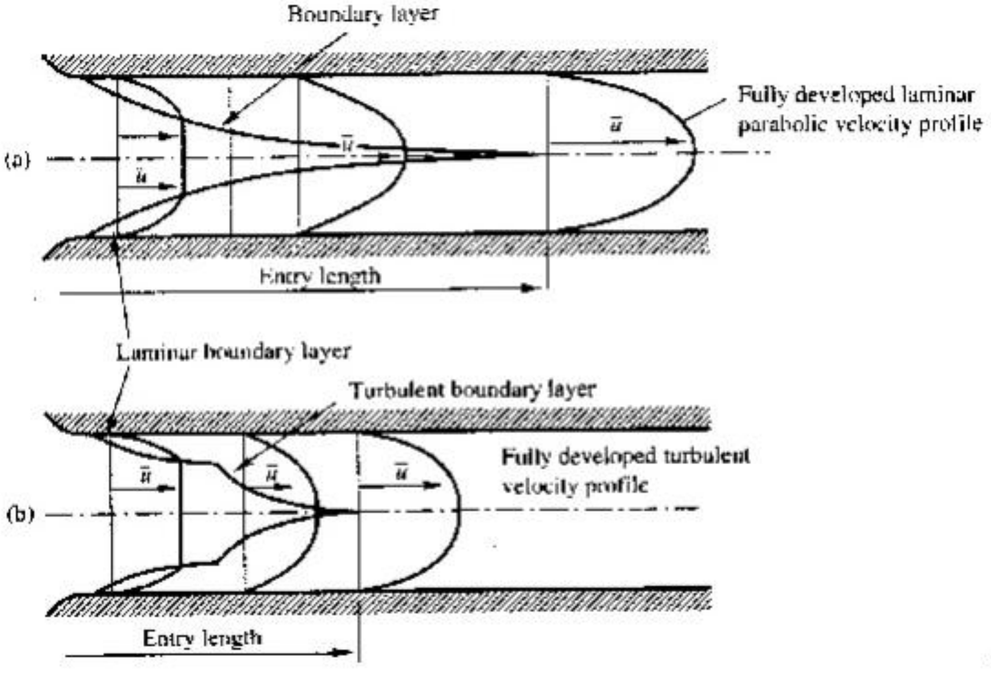
Re = rud / m

(r = density u = velocity m = viscosity d = pipe diameter)

Laminar flow: Re < 2000

Transitional flow: 2000 < Re < 4000

Turbulent flow: Re > 4000



If we only have laminar flow the profile is parabolic - as proved in earlier lectures - as only the first part of the boundary layer growth diagram is used. So we get the top diagram in the above figure.

If turbulent (or transitional), both the laminar and the turbulent (transitional) zones of the boundary layer growth diagram are used. The growth of the velocity profile is thus like the bottom diagram in the above figure.

Once the boundary layer has reached the centre of the pipe the flow is said to be fully developed. (Note that at this point the whole of the fluid is now affected by the boundary friction.)

The length of pipe before fully developed flow is achieved is different for the two types of flow. The length is known as the entry length.

Problem From the given calculate the solution for a laminar boundary layer along a flat plate. Since fully developed laminar flow between two flat plates has a velocity distribution given by a parabola, we will assume that

$$u(x, y) = a(x) + b(x)y + c(x)y^2$$

Physics requires the boundary conditions

$$u(x, 0) = 0 \quad , \quad u(x, \delta) = U \quad , \quad \frac{\partial u(x, \delta)}{\partial y} = 0$$

These three equations determine a, b and c and lead to the result

$$u(x, y) = U\left(2\xi - \xi^2\right) \text{ in which } \xi = \frac{y}{\delta(x)}$$

Thus, the integral on the right sides of

$$\int_0^\delta (U - u)\,u\,dy = U^2 \int_0^\delta \left(1 - 2\xi + \xi^2\right)\left(2\xi - \xi^2\right)dy = U^2\delta \int_0^1 \left(2\xi - 5\xi^2 + 4\xi^3 - \xi^4\right)d\xi$$

$$= \frac{2}{15}U^2\delta(x)$$

$$\tau_0 = \mu\frac{\partial u(x, 0)}{\partial y} = \mu\left(\frac{du}{d\xi}\right)_{\xi = 0}\frac{\partial \xi}{\partial y} = \mu\frac{2U}{\delta}$$

Thus, Eq. (8.7) becomes

$$\frac{\mu}{\rho}\,\frac{2U}{\delta} = \frac{2}{15}U^2\frac{d\delta}{dx}$$

Separating variables gives

$$\int_0^{\delta(x)} \delta\,d\delta = 15\frac{\nu}{U}\int_0^x dx$$

and integration gives

$$\frac{1}{2}\delta^2 = 15\frac{\nu}{U}x$$

This can be written dimensionlessly as

$$\frac{\delta}{x} = \sqrt{\frac{30}{Ux/\nu}} = \frac{5.48}{\sqrt{Re_x}}$$

The force per unit width on one side of the plate is calculated from (8.9).

$$F = \rho \int_0^{\delta(L)} (U-u)\,u\,dy = \rho\frac{2}{15}U^2\delta(L) = \rho\frac{2}{15}U^2\frac{5.48}{\sqrt{Re_L}}\,L$$

This can be put in the more significant form

$$F = C_D A\rho\frac{U^2}{2} \quad , \quad A = L\times 1 \quad , \quad C_D = \frac{1.46}{\sqrt{Re_L}} \quad , \quad Re_L = \frac{UL}{\nu}$$

The exact solution of (5.23 a, b, c) that was obtained by Blasius gave

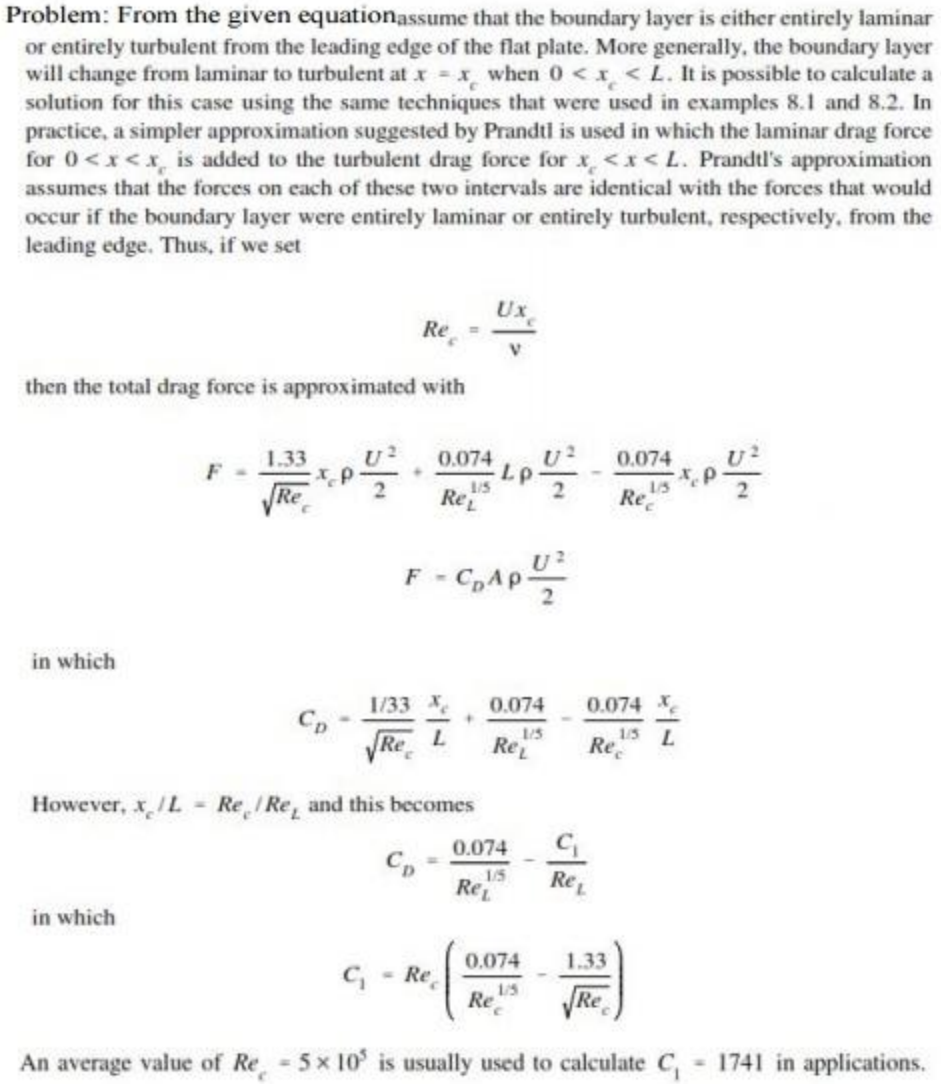
$$\frac{\delta}{x} = \frac{5.0}{\sqrt{Re_x}} \quad , \quad C_D = \frac{1.33}{\sqrt{Re_L}}$$

5. From the given equation calculate an approximate solution for a turbulent boundary layer along a smooth flat plate. We will use the one seventh power law given by Eq. (7.43)

$$u(x,y) = U\xi^{1/7} \quad , \quad \xi = \frac{y}{\delta(x)}$$

Thus, the integral on the right sides

$$\int_0^{\delta}(U-u)\,u\,dy = U^2\delta\int_0^1\left(1-\xi^{1/7}\right)\xi^{1/7}\,d\xi = \frac{7}{72}U^2\delta(x)$$



Problem: From the given equationassume that the boundary layer is either entirely laminar or entirely turbulent from the leading edge of the flat plate. More generally, the boundary layer will change from laminar to turbulent at $x = x_c$ when $0 < x_c < L$. It is possible to calculate a solution for this case using the same techniques that were used in examples 8.1 and 8.2. In practice, a simpler approximation suggested by Prandtl is used in which the laminar drag force for $0 < x < x_c$ is added to the turbulent drag force for $x_c < x < L$. Prandtl's approximation assumes that the forces on each of these two intervals are identical with the forces that would occur if the boundary layer were entirely laminar or entirely turbulent, respectively, from the leading edge. Thus, if we set

$$Re_c = \frac{Ux_c}{\nu}$$

then the total drag force is approximated with

$$F = \frac{1.33}{\sqrt{Re_c}} x_c \rho \frac{U^2}{2} + \frac{0.074}{Re_L^{1/5}} L \rho \frac{U^2}{2} - \frac{0.074}{Re_c^{1/5}} x_c \rho \frac{U^2}{2}$$

$$F = C_D A \rho \frac{U^2}{2}$$

in which

$$C_D = \frac{1/33}{\sqrt{Re_c}} \frac{x_c}{L} + \frac{0.074}{Re_L^{1/5}} - \frac{0.074}{Re_c^{1/5}} \frac{x_c}{L}$$

However, $x_c / L = Re_c / Re_L$ and this becomes

$$C_D = \frac{0.074}{Re_L^{1/5}} - \frac{C_1}{Re_L}$$

in which

$$C_1 = Re_c \left(\frac{0.074}{Re_c^{1/5}} - \frac{1.33}{\sqrt{Re_c}} \right)$$

An average value of $Re_c = 5 \times 10^5$ is usually used to calculate $C_1 = 1741$ in applications.

FLOW THROUGH CIRCULAR CONDUITS

This page has an in dept dealing of laminar flow through pipes, boundary layer concept, hydraulic and energy gradient, friction factor, minor losses, and flow through pipes in series and parallel.

Boundary layer is the region near a solid where the fluid motion is affected by the solid boundary. In the bulk of the fluid the flow is usually governed by the theory of ideal fluids. By contrast, viscosity is important in the boundary layer. The division of the problem of flow past an solid object into these two parts, as suggested by Prandtl in 1904 has proved to be of fundamental importance in fluid mechanics.

This concept of hydraulic gradient line and total energy line is very useful in the study of flow This concept of hydraulic gradient line and total energy line is very useful in the study of flow of fluids through pipes. f fluids through pipes.

HYDRAULIC GRADIENT AND TOTAL ENERGY LINE

1.Hydraulic Gradient Line

It is defined as the line which gives the sum of pressure head (p/w) and datum head (z) of a flowing fluid in a pipe with respect to some reference line or it is the line which is obtained by joining the top of all vertical ordinates, showing the pressure head (p/w) of a flowing fluid in a pipe from the centre of the pipe. It is briefly written as H.G.L (Hydraulic Gradient Line).

2.Total Energy Line

It is defined as the line which gives the sum of pressure head, datum head and kinetic head of a flowing fluid in a pipe with respect to some reference line. It is also defined as the line which is obtained by joining the tops of all vertical ordinates showing the sum of pressure head and kinetic head from the centre of the pipe. It is briefly written as T.E.L (Total Energy Line).

BOUNDARY LAYER

Concepts

The variation of velocity takes place in a narrow region in the vicinity of solid boundary. The fluid layer in the vicinity of the solid boundary where the effects of fluid friction i.e., variation of velocity are predominant is known as the boundary layer.

1 FLOW OF VISCOUS FLUID THROUGH CIRCULAR PIPE

For the flow of viscous fluid through circular pipe, the velocity distribution across a section, the ratio of maximum velocity to average velocity, the shear stress distribution and drop of pressure fora given length is to be determined. The flow through circular pipe will be viscous or laminar, if the Reynold’s number is less than 2000.

2 DEVELOPMENT OF LAMINAR AND TURBULENT FLOWS IN CIRCULAR PIPES

1.Laminar Boundary Layer

At the initial stage i.e, near the surface of the leading edge of the plate, the thickness of boundary layer is the small and the flow in the boundary layer is laminar though the main stream flows turbulent. So, the layer of the fluid is said to be laminar boundary layer.

2.Turbulent Boundary Layer

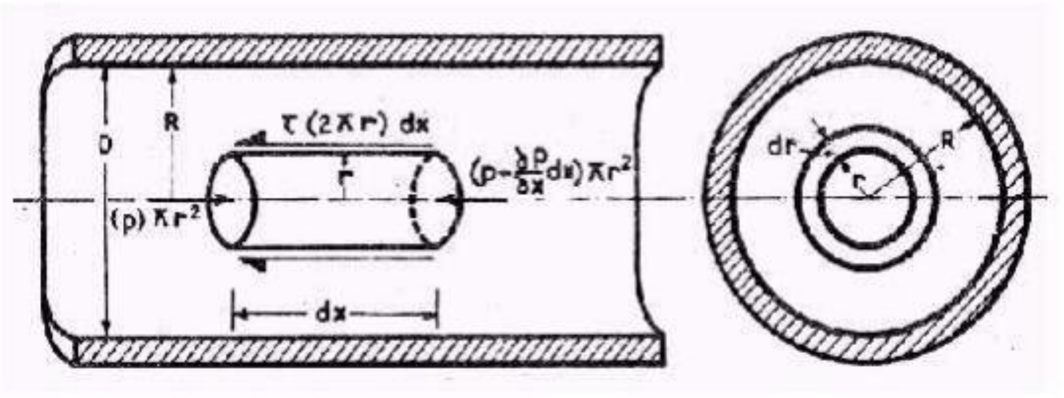
The thickness boundary layer increases with distance from the leading edge in the down-stream direction. Due to increases in thickness of boundary layer, the laminar boundary layer becomes unstable and the motion of the fluid is disturbed. It leads to a transition from laminar to turbulent boundary layer.

3 BOUNDARY LAYER GROWTH OVER A FLAT PLATE

Consider a continuous flow of fluid along the surface of a thin flat plate with its sharp leading edge set parallel to the flow direction as shown in figure 2.7.The fluid approaches the plate with uniform velocity U known as free stream velocity at the leading edge. As soon as the fluid comes in contact the leading edge of the plate,its velocity is reduced to zero as the fluid particles adhere to the plate boundary thereby satisfying no-slip condition.

FLOW THROUGH CIRCULAR PIPES-HAGEN POISEUILLE'S EQUATION

Due to viscosity of the flowing fluid in a laminar flow,some losses of head take place.The equation which gives us the value of loss of head due to viscosity in a laminar flow is known as Hagen-Poiseuille's law.



$$p1-p2=32\mu UL/D^2$$

$$=128\mu QL/\pi D4$$

DARCY'S EQUATION FOR LOSS OF HEAD DUE TO FRICTION IN PIPE

A pipe is a closed conduit through which the fluid flows under pressure.When the fluid flows through the piping system,some of the potential energy is lost due to friction.

$$hf=4fLv^2/2gD$$

MOODY'S DIAGRAM

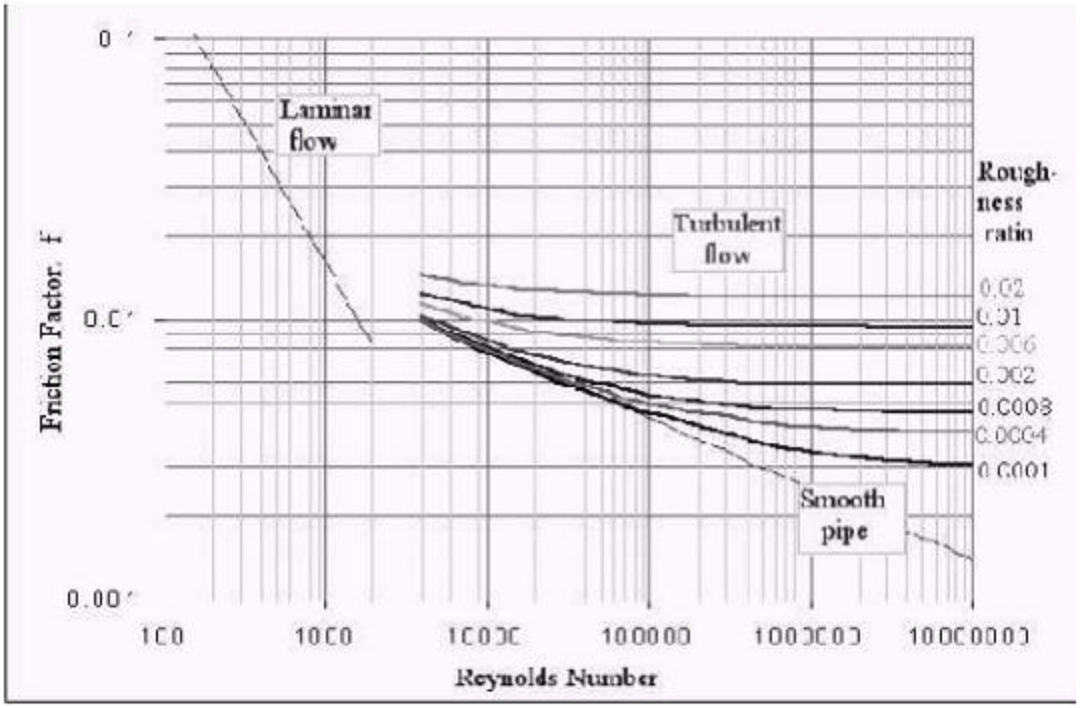
Moody's diagram is plotted between various values of *friction factor(f)*,*Reynolds* *number(*Re) and *relative roughness*(R/K) as shown in figure 2.6.For any turbulent flowproblem,the values of friction factor(f) can therefore be determined from Moody's diagram,if the numerical values of R/K for the pipe and Re of flow are known.

The Moody's diagram has plotted from the equation

$$1/\sqrt{f}-2.0\log_{10}(R/K)=1.74-2.0\log_{10}[1+18.7/(R/K/Re/f)]$$

Where,R/K=relative roughness

f=friction factor and Re=Reynolds number.



CLASSIFICATION OF BOUNDARY LAYER THICKNESS

1. Displacements thickness(δ^*)
2. Momentum thickness(θ)
3. Energy thickness(δe)

BOUNDARY LAYER SEPARATION

The boundary layer leaves the surface and gets separated from it. This phenomenon is known as *boundary layer separation.*

LOSSESS IN PIPES

When a fluid flowing through a pipe, certain resistance is offered to the flowing fluid, it results in causing a loss of energy.

The loss is classified as:

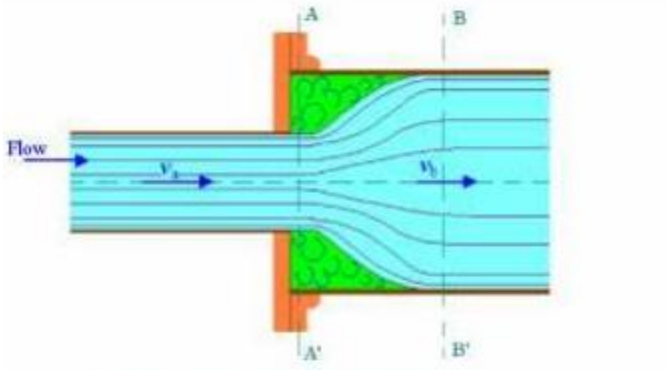
1. Major losses
2. Minor losses

Major Losses in Pipe Flow

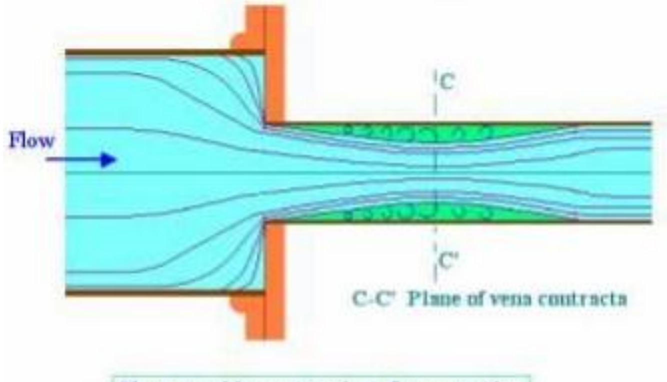
The major loss of energy is caused by friction in pipe. It may be computed by Darcy-weisbach equation.

Minor Losses in Pipe Flow

The loss of energy caused on account of the change in velocity of flowing fluid is called minor loss of energy.



Flow at sudden enlargement of cross section



Flow at sudden contraction of cross section

FLOW THOUGH PIPES IN SERIES AND PARALLEL

Pipes in Series

The pipes of different diamers and lengths which are connected with one another to form a single pipeline.

Pipes in Parallel

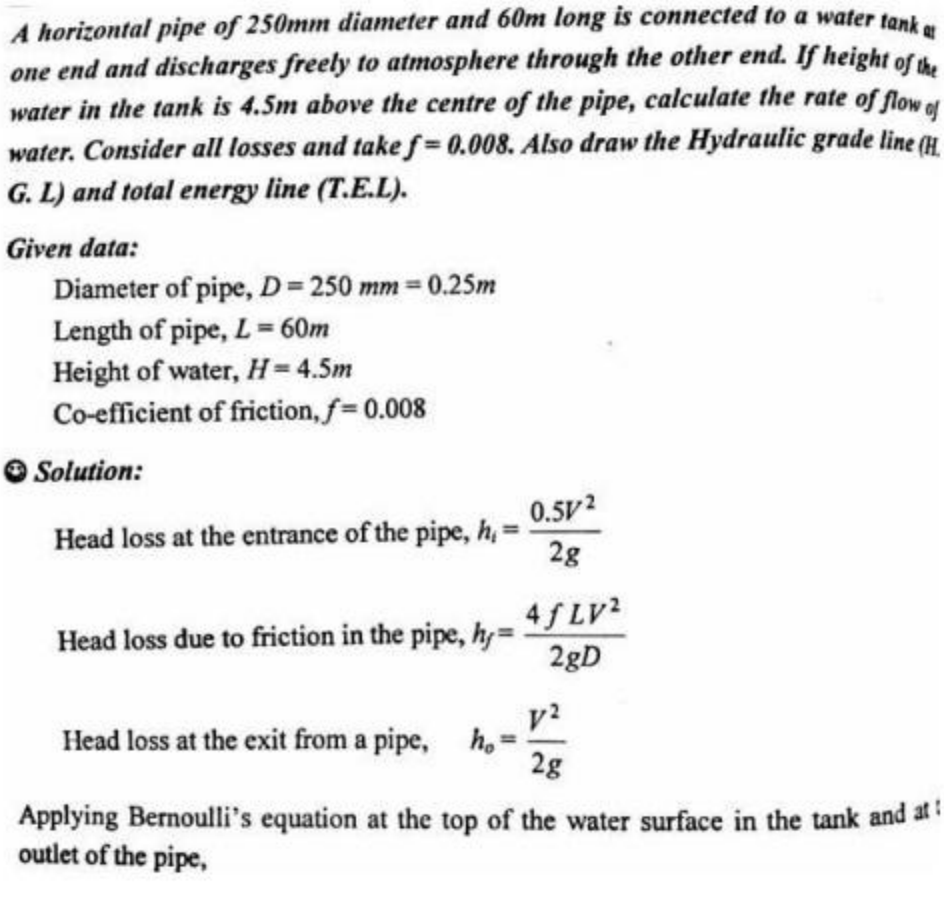
When a main pipeline divides into two or more parallel pipes which again join together to form a single pipe and continuous as a main line

GLOSSARY

HGL –Hydraulic gradient line
TEL – Total energy line.

Applications

1. To find out friction factor in the flow through pipe.
2. To find out the losses in losses in the pipes.



A horizontal pipe of 250mm diameter and 60m long is connected to a water tank at one end and discharges freely to atmosphere through the other end. If height of the water in the tank is 4.5m above the centre of the pipe, calculate the rate of flow of water. Consider all losses and take f = 0.008. Also draw the Hydraulic grade line (H. G. L) and total energy line (T.E.L).

Given data:

Diameter of pipe, $D = 250\ mm = 0.25m$
Length of pipe, $L = 60m$
Height of water, $H = 4.5m$
Co-efficient of friction, $f = 0.008$

Solution:

Head loss at the entrance of the pipe, $h_i = \dfrac{0.5V^2}{2g}$

Head loss due to friction in the pipe, $h_f = \dfrac{4\,f\,LV^2}{2gD}$

Head loss at the exit from a pipe, $h_o = \dfrac{V^2}{2g}$

Applying Bernoulli's equation at the top of the water surface in the tank and at
outlet of the pipe,

$$\frac{p_1}{w}+\frac{V_1^2}{2g}+z_1=\frac{p_2}{w}+\frac{V_2^2}{2g}+z_2+\text{All losses}$$

$$0+0+4.5=0+\frac{V_2^2}{2g}+0+\frac{0.5V^2}{2g}+\frac{4\,f\,LV^2}{2gD}+\frac{V^2}{2g}$$

But the velocity in the pipe $V = V_2$

$$4.5=\frac{V^2}{2g}\left[1+0.5+\frac{4fL}{D}+1\right]$$

$$=\frac{V^2}{2g}\left[1+0.5+\frac{4\times0.008\times60}{0.25}+1\right]$$

$$4.5=\frac{V^2}{2g}\times(10.18)$$

$$V=\sqrt{\frac{4.5\times2\times9.81}{10.18}}=2.945\,m/s$$

Rate of flow, $Q = A\times V$

$$=\frac{\pi}{4}\times(0.25)^2\times2.945=\mathbf{0.1445\,m^3/s}\qquad \textbf{Ans.}$$

Hydraulic Gradient Line (H. G. L.) gives the sum of $\left(\frac{p}{w}+z\right)$ with reference to the datum line. Hence, H. G. L. is obtained by subtracting $\frac{V^2}{2g}$ from total energy available at that point.

Head loss at the entrance of the pipe, $h_i=\frac{0.5\times(2.945)^2}{2\times9.81}=0.221\,m$

Head loss due to friction, $h_f=\frac{4\,f\,LV^2}{2gD}=\frac{4\times0.008\times60\times(2.945)^2}{2\times9.81\times0.25}=3.3949\,m$

Head loss at exit of the pipe, $h_o=\frac{V^2}{2g}=\frac{(2.945)^2}{2\times9.81}=0.442\,m$

Total energy available at the entrance of the pipe

$$= h - h_i = 4.5 - 0.221 = 4.279m$$

The piezometric head $\left(\frac{p}{w} + z\right)$ at the entrance= Total energy at entrance $-\frac{V^2}{2g}$ =

entrance of the pipe $= 4.2749 - \frac{(2.945)^2}{2\times9.81} = 3.833m$

Similarly, total energy at exit of the pipe,

$$= h - (h_i + h_f + h_o)$$

$$= 4.5 - (0.221 + 3.3949 + 0.442) \; 0.442m$$

The piezometer head $\left(\frac{p}{w} + z\right)$ available at exit of the pipe

$$= 0.442 - \frac{V^2}{2g} = 0.442 - \frac{(2.945)^2}{2\times9.81} = 0m$$

Total energy line (T.E.L):

1. Point A lies on the free surface of water since total energy at A = $\frac{p}{w} + \frac{V^2}{2g} + z = 0 + 0 + 4.5 = 4.5m$.
2. A point B is noted at a distance AB = $h_i = 0.221$ *m* because the total energy at entrance of the pipe B = Total energy at A − $h_i = 4.5 - 0.221 = 4.279$ *m*.
3. Total energy available at the exit of the pipe. i.e., at C is already found out as 0.442 *m*. Therefore, a point C is placed at a distance 0.442 *m* from the centre line as shown in Figure 2.3.
4. A, B and C are joined by straight lines. Then ABC represents the total energy line.

Hydraulic gradient line (H.G.L):

HGL gives the piezomteric head i.e., (sum of $\frac{p}{w} + z$) with refernce to the datum line.

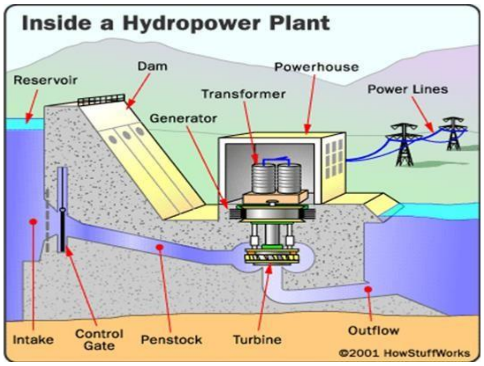
1. Piezometric head at the entrance of the pipe is already found as 3.836 *m*. A point D is placed at a distance of 3.836 *m* from the datum.

UNIT – IV

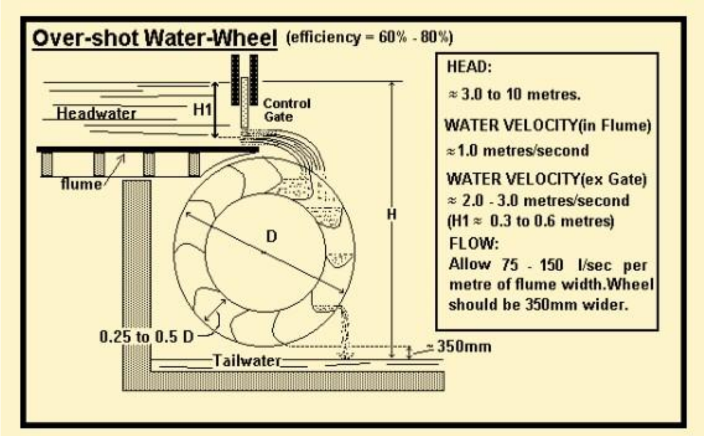
TURBOMACHINERY

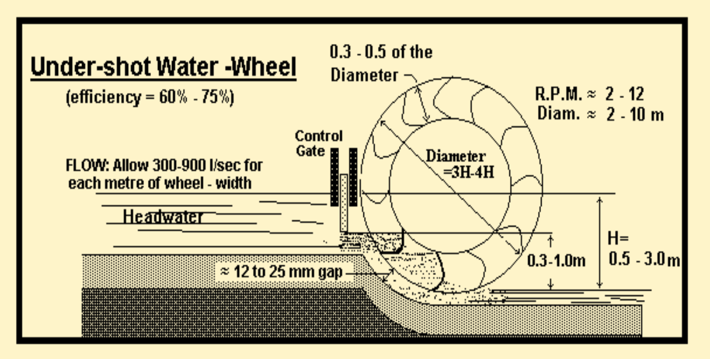
Introduction and Working principle of hydraulic turbines

Hydraulic turbines are the machines which converts the hydraulic energy of water into mechanical energy. Therefore, these may be considered as hydraulic motors or prime movers.
Pump: it converts mechanical energy into hydraulic energy. The mechanical energy developed by the turbine is used in running an electric generator which is directly coupled to the shaft of the turbine. The electric generator thus generates electric power which is known as hydroelectric power.
Electric Motor: Electric motor coverts electrical energy to mechanical energy.



DEVELOPMENT OF TURBINES





- In the early days of water, pump development water wheels made of wood are widely used which uses either (falling water) potential energy or kinetic energy of the flowing stream of water. The wheel consists of series of straight vanes on its periphery, water was permitted to enter at the top and imbalance created by the weight of the water causes wheel to rotate (over shot wheel uses potential energy, under short wheel uses kinetic energy). Since, the low efficiency and low power generation and these could not be directly coupled to modern fast electric generators for the purpose of power generation. Therefore, the water wheels are completely replaced by modern hydraulic turbines, which will run at any head and desired speed enabling the generator to be coupled directly.
- In general turbine consists of wheel called runner or rotor having a number of specially developed vanes or blades or buckets. The water possessing large amount of hydro energy when strikes the runner, it does the work on runner and causes it to rotate.

Classification of Hydraulic Turbines

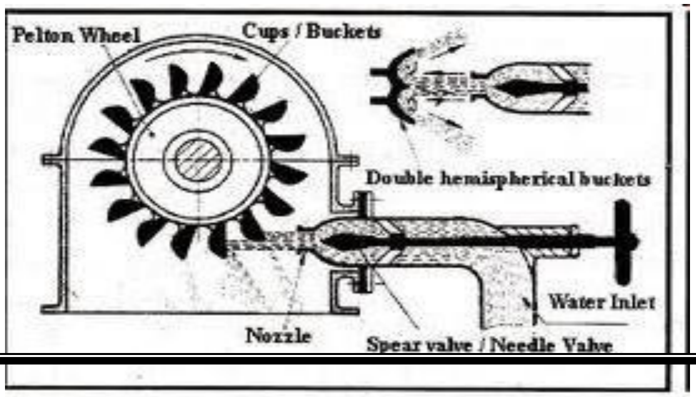
1. According to the type of energy at the inlet
2. According to the direction of flow through runner
3. According to head at inlet
4. According to specific speed of turbine
5. According to Position of the shaft

1. According to the type of energy at the inlet

a) Impulse turbine:

- All the available energy of the water is converted into kinetic energy by passing it through a contracting nozzle provided at the end of penstock

Ex: Pelton wheel turbine, Turgo-impulse turbine, Girard turbine, Bank turbine, Jonval turbine etc.



Reaction Turbine:

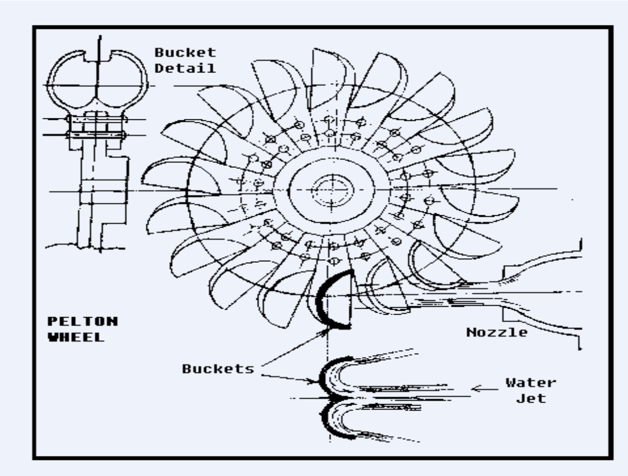
- At the entrance of the runner, only a part of the available energy of water is converted into kinetic energy and a substantial part remains in the form of pressure energy.
- As the water flow through the turbine pressure energy converts into kinetic energy gradually. Therefore the pressure at inlet of runner is higher than the pressure at outlet and it varies through out the passage of the turbine.
- For this gradual change of pressure to the possible the runner must be completely enclosed in a air-tight casing and the passage is entirely full of water throughout the operation of turbine
- The difference of pressure between the inlet and outlet of the runner is called reaction
- pressure and hence the turbines are known as reaction turbines.
- Ex: Francis turbine, Kaplan turbine, Thomson Turbine, Fourneyron turbine, Propeller turbine, etc

2. According to the direction of flow through runner:

a) Tangential flow turbine b) Radial flow turbine
c) Axial flow turbine d) Mixed flow turbine

a) Tangential flow turbine:

The water flows along the tangent to the path of rotation of the runner Ex: Pelton wheel turbine



b) Radial flow Turbine

- The water flows in the radial direction through the runner.
- Inward radial flow turbine: The water enters the outer circumference and flows radially inwards towards the centre of the runner.
- Ex: Old Francis turbine, Thomson turbine, Girard turbine etc
- Outward radial flow turbine: The water enters at the centre and flows radially outwards towards the outer periphery of the runner.
- Ex: Fourneyron turbine.

c) Axial flow turbine**:**

- The water flow through runner wholly and mainly along the direction parallel to the axis of rotation of the runner.
- Ex: Kaplan turbine, Jonval, Girard axial flow turbine, Propeller turbine, etc

d) Mixed flow turbines

The water enters the runner at the outer periphery in the radial direction and leaves it at the centre of the axial direction parallel to the rotation of the runner.

Ex: Modern Francis turbine.

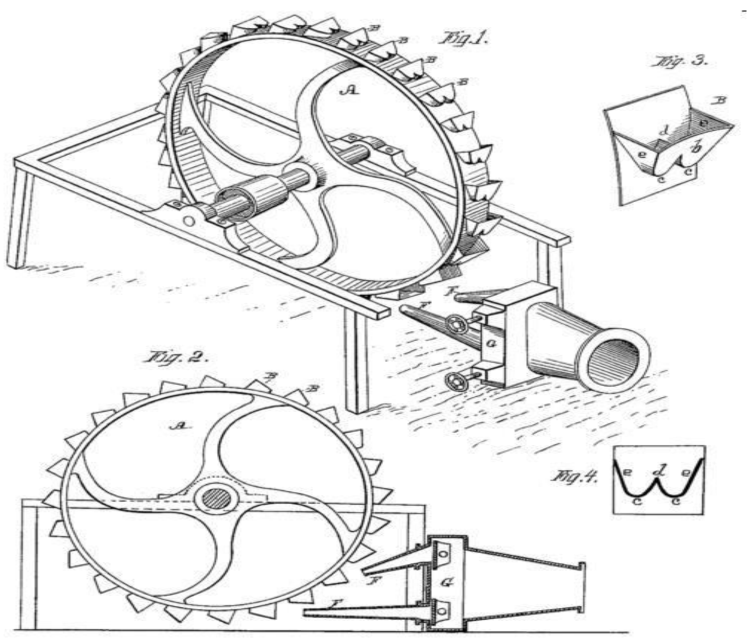
a) High head turbines: These turbines work under very high heads 255m - 1770m and above. Requires relatively less quantity of water.
Ex: Pelton wheel turbine or impulse turbine.
b) Medium head turbines: These turbines are capable of working under medium heads ranging from 60m - 250m These turbines requires large quantity of water.
Ex: Francis Turbine
c) Low head turbines: these turbines are capable of working under the heads less than 60mts. These turbines requires large quantity of water.
Ex: Kaplan turbine, propeller turbine.

a) Low specific speed turbines: specific speed turbine varies from 8.5 to 30.
Ex: Pelton wheel turbine
b) Medium specific speed turbines: specific speed varies from 50 to 340 Ex: Francis turbine.
c) High specific speed turbines: specific speed varies from 255-860. Ex: Kaplan and propeller turbine.

5) According to the position of the shaft:

a) Horizontal disposition of shaft

PELTON WHEEL TURBINE



- This is named after Lester A. Pelton, American engineer who contributed much to its development in about 1880. It is well suited for operating under high heads.
- It's an impulse, high head, low specific speed and tangential flow turbine.
- The runner consists of a circular disc with a number of buckets evenly spaced around its periphery.

- The buckets have a shape of double semi-ellipsoidal cups. Each bucket is divided into 2 symmetrical parts by sharp edged ridge known as splitter.
- One or more nozzles are mounted so that each directs a jet along a tangential to the pitch circle of runner or axis of blades.
- The jet of water impinges on the splitter, which divides jet into equal halves, each of which after flowing around the smooth inner surface of the bucket leaves at its outer edge.

- The buckets are so shaped that the angle at the outlet lip varies from 10 to 20 degrees. So that the jet of outer deflects through 160 to 170. The advantage of having double cup-shaped bucket is that

  the axial thrust neutralizes each other being equal and opposite and having bearing supporting the wheel shaft are not supported to any axial thrust or end thrust.

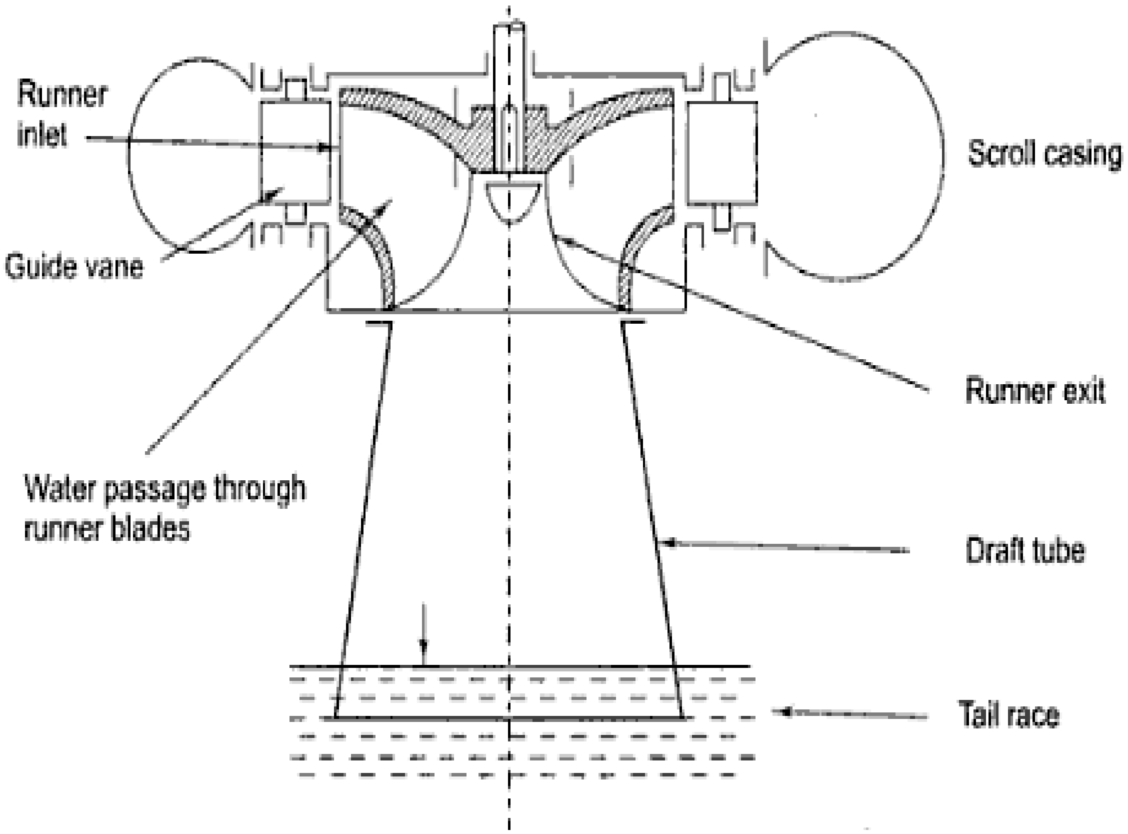
- The back of the bucket is shaped that as it swings downward into the jet no water is wasted by splashing.
- At the lower tips of the bucket a notch is cut which prevents the jet striking the preceding bucket and also avoids the deflection of water towards the centre of the wheel.
- For low heads buckets are made of C.I, for high heads buckets are made of Cast Steel ,bronze, stainless steel.

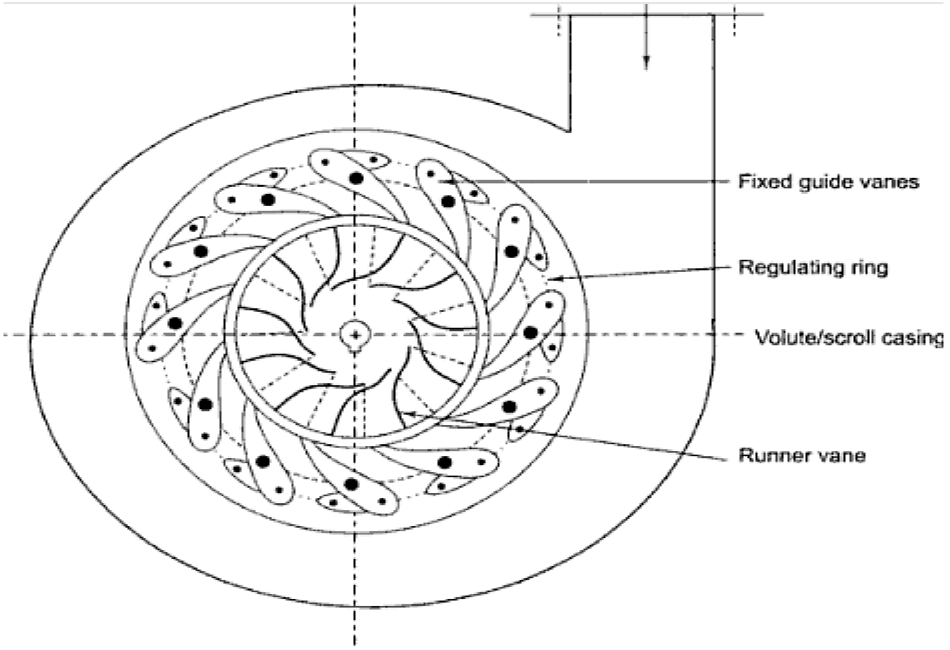
- In order to control the quantity of water striking the runner, the nozzle is fitted at the end of the penstock is provided with a spear valve having streamlined head which is fixed at the end of the rod.
- When the shaft of pelton wheel is horizontal, not more than to two jets are used if the shaft vertical six number of jets are possible.

- A casing is made of C.I or fabricated steel plates is usually provided for a pelton wheel to prevent splashing of water, to lead water to the tail race and also act as safeguard against accidents.
- Large pelton wheels are usually equipped with a small break nozzle which when opened directs a jet of water on the back of the buckets, therby bringing the wheel quickly to rest after it is shut down, otherwise it takes considerable time to come to rest.

REACTION TURBINES:

- In reaction turbines, the available energy of water at inlet of the turbine is sum of pressure energy and kinetic energy and during the flow of water through the runner a part of pressure energy is converted into kinetic energy, such type of turbine is reaction turbine. Ex: Francis Turbine, Kaplan Turbine, Propeller Turbine, etc

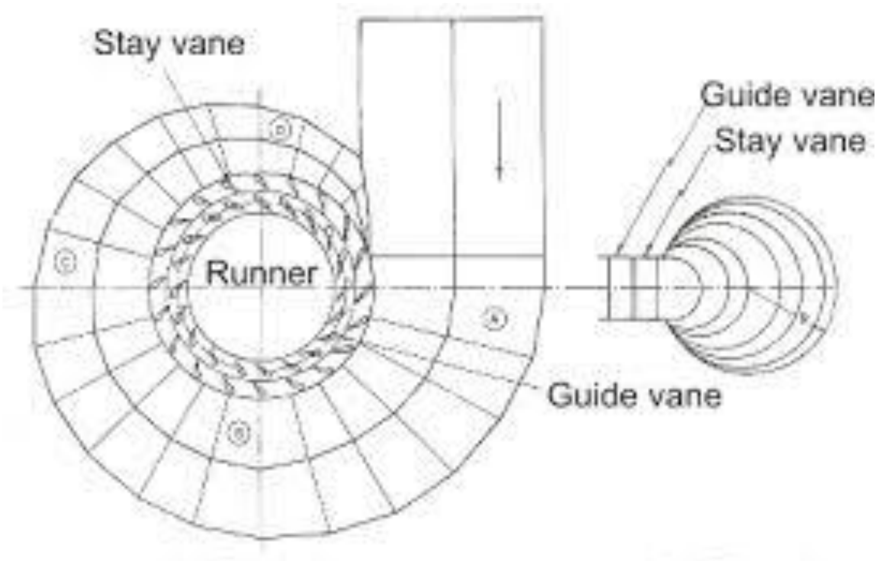

Runner inlet
Guide vane
Water passage through runner blades
Scroll casing
Runner exit
Draft tube
Tail race


Fixed guide vanes
Regulating ring
Volute/scroll casing
Runner vane

Sectional view of Francis Turbine

SCROLL CASING

- The water from the penstock enters the scroll casing or spiral casing which completely surrounds the runner. The purpose of casing is to provide even distribution of water around the circumference of the runner and to maintain constant velocity of water so distributed.



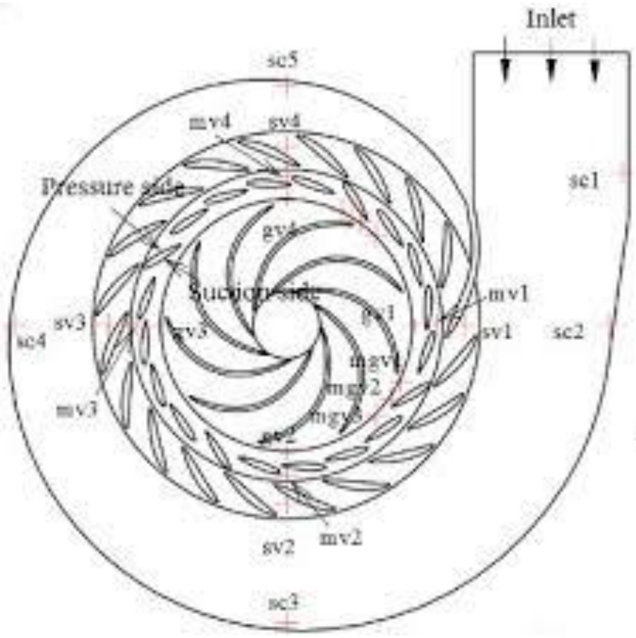
(a) Plan view (b) Elevation

In order to maintain constant velocity of water through out its path around the runner, the cross-sectional area of casing is gradually decreased. The casing is made of cast steel or plate steel.

STAY RING

-From the scroll casing the water passes through a speed ring or stray ring. Stay ring consists of outer and lower ring held together by series of fixed vanes called stay vanes.

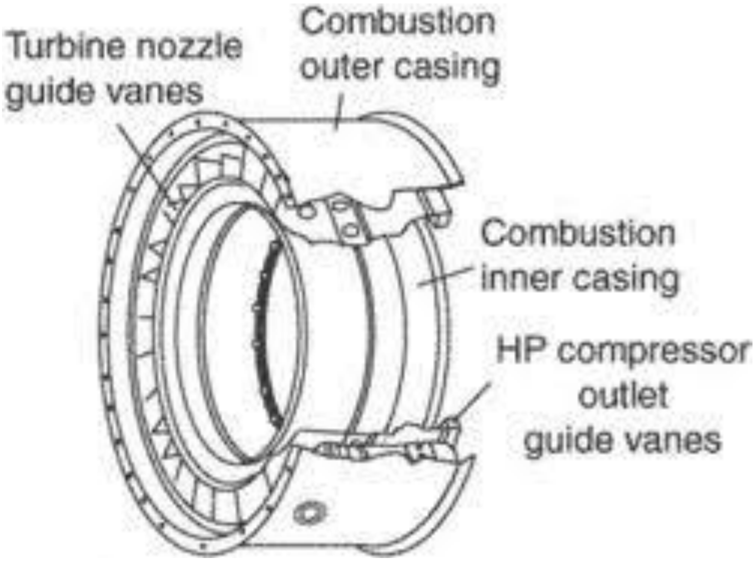
- Number of stay vanes usually half of the number of guide vanes. Stay vane performs two functions, one is to direct the water from the scroll casing to the guide vanes and other is to rest the load imposed upon it by the internal pressure of water and the weight of the turbine and electrical generator and transmits the same to the foundation. Speed ring is made of C.I or C.S.



GUIDE VANES:

-From the stay ring water passes through a series of guide vanes provided around the periphery of the runner. The function of guide vanes is to regulate the quantity of water supplied to the runner and to direct the water on to the runner with design angle.

- The guide vanes are airfoil shaped and made of C.S or S.S or P.S. Each guide vane is provided with two stems; the upper stem passes through head cover and lower stem seats in bottom ring. By a system of levers and links all the guide vanes may be turned about their stems, so as to alter the width of the passage between the adjacent guide vanes, thereby allowing a variable quantity of water to strike the runner. The guide vanes are operated either by means of a wheel or automatically by a governor.



RUNNER:

-The runner of a Francis turbine consists of a series of a curved vanes (from 16 to 24) evenly arranged around the circumference in the annular space between two plates.

-The vanes are so shaped that water enters the runner radially at the outer periphery and leaves it axially at the inner periphery.

-The change in the direction of flow of water from radial to axial, as it passes through the runner, produces a circumferential force on the runner which makes the runner to rotate and thus contributes to the useful output of the runner.

-Runner vanes are made of SS and other parts are made of CI or CS

- The runner is keyed to a shaft which is usually of forged steel. The torque produced by the runner is transmitted to the generator through the shaft which is usually connected to the generator shaft by a bolted flange connection.

and requires large quantity of water to develop large amount of power. Since it is a reaction turbine, it operates in an entirely closed conduit from head race to tail race.

The main components of a Kaplan turbine

Scroll Casing

Guide vanes Mechanism

Hub with vanes or runner of turbine, and

Draft Tube

The function of above components is same as that of Francis turbine

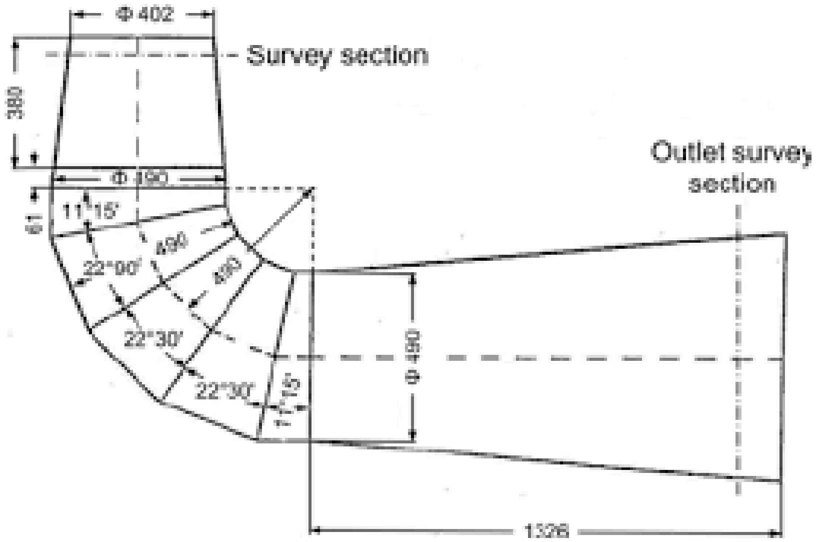
The water from the penstock enters the scroll casing and then moves to the guide vanes. From the guide vanes, the water turns through 900 and flows axially through the runner.

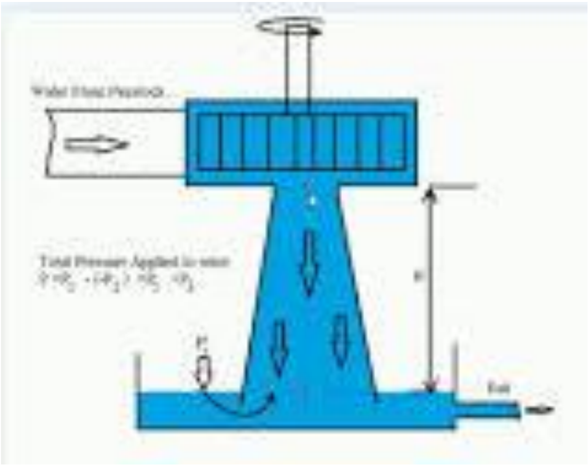
The runner of a Kaplan turbine has four or six blades (eight in exceptional cases). The blades attached to a hub are so shaped that water flows axially through the runner.

The adjustment of the runner blades is usually carried out automatically by means of a servomotor operating inside the hollow coupling of turbine and generator shaft.

When both guide vane angle and runner blade angle may varied, a high efficiency can be maintained. Even at part load, when a lower discharge is flowing through the runner, a high efficiency can be attained in case of Kaplan turbine.

Simultaneously the guide vane and runner vane angles are adjusted the water under all the working conditions flows through the runner blades without shock. as such the eddy losses which inevitable in Francis turbine and propeller turbines are almost completely eliminated in a Kaplan turbine.





UNIT-V:

CENTRIFUGAL PUMPS & RECIPROCATING PUMPS

CENTRIFUGAL PUMPS:

A pump is a hydraulic machine which converts mechanical energy into hydraulic energy or pressure energy.

A centrifugal pump is also known as a Rotodynamic pump or dynamic pressure pump. It works on the principle of centrifugal force. In this type of pump the liquid is subjected to whirling motion by the rotating impeller which is made of a number of backward curved vanes. The liquid enters this impeller at its center or the eye and gets discharged into the casing enclosing the outer edge of the impeller. The rise in the pressure head at any point/outlet of the impeller is Proportional to the square of the tangential velocity of theliquid at that point.

Hence at the outlet of the impeller where the radius is more the rise In pressure head will be more and the liquid will be discharged at the outlet with a high pressure head. Due to this high pressure head, the liquid can be lifted to a higher level. Generally centrifugal pumps are made of the radial flow type only. But there are also axial flow or propeller pumps which are particularly adopted for low heads. Advantages of centrifugal pumps:-

1. Its initial cost is low

2. Efficiency is high.
3. Discharge is uniform and continuous
4. Installation and maintenance is easy.
5. It can run at high speeds, without the risk of separation of flow

As the water reaches the delivery pipe a considerable part of kinetic energyis converted into pressure energy. However, the eddies are not completely avoided , therefore some loss of energy takes place due to the continually increasing quantity of water through the volute chamber.

In the case of a diffuser pump the guide wheel containing a series of guide vanes or diffuser is the additional component. The diffuser blades which provides gradually enlarging passages surround the impeller periphery. They serve to augment the process of pressure built up that is normally achieved in the volute casing. Diffuser pumps are also called turbine pumps in view of their resemblance to a reaction turbine.

Multistage pumps and vertical shaft deep-well pumps fall under this category. Centrifugal pumps can normally develop pressures upto 1000kpa (100m). If higher pressures are required there are three options.a) Increase of impeller diameter. b)Increase of Rpm. c)Use of two or more impellers in series.

The pump looks clumsy in option (a). The impeller material is heavily stressed in option (b)The third choice is the best and is generally adopted, the impellers which are usually of the same size are mounted on the same shaft. The unit is called a multistage pump. It discharges the same quantity of fluid as a single stage pump but the head developed is high.

There are centrifugal pumps upto 54 stages. However, generally not more than 10 stages are required. In the case of the double suction impeller, two impellers are set back to back. The two suction eyes together reduce the intake. The two suction eyes together reduce the intake velocity reduce the risk of cavitations.

Mixed flow type double suction axial flow pumps besides are capable of developing higher heads. For convenience of operation and maintenance, horizontal shaft settings are the preferred setups for centrifugal pumps. The exceptions are deep-well turbine pumps and axial flow pumps,these have vertical shafts.

Restricted space conditions usually require a vertical shaft setting. Centrifugal impellers usually have vanes fitted between the shroudes or plate. The crown plate has the suction eye and the base plate is mounted on a sleeve which is keyed to the shaft.

An impeller without the crown plate is called the non-clog or semi- open impeller. In an open impeller both crown plate and the base plate are absent.

Only clear liquids, can be safely pumped by a shrouded impeller pump. The semi-open impeller is useful for pumping liquids containing suspended solids, such as sewage, molasses or paper pulp. The open-vane impeller pump is employed for dredging operations in harbours and rivers.

Shrouded and semi open impellers may be made of cast iron Or cast steel. Open vane impellers are usually made of forged steel. If the liquid pumped are corrosive, brass, bronze or gun metal are the best materials for making the impellers.

A radial flow impeller has small specific speeds (300 to 1000) & is suitable for discharging relatively small quantities of flow against high heads.

The direction of flow at exit of the impeller is radial. The mixed flow type of impellers has a high specific speed (2500 to 5000), has large inlet diameter D and impeller width B to handle relatively large discharges against medium heads. The axial flow type or propeller impellers have the highest speed range (5000 to 10,000). They are capable of pumping large discharges against small heads. The specific speed of radial pump will be $10<Ns<80$, Axial pump $100<Ns<450$, Mixed flow pump $80<Ns<160$.
Components of a centrifugal pump

The main components of a centrifugal pump are:

i. Impeller
ii. Casing
iii. Suction pipe
iv. Foot valve with strainer,
v. Delivery pipe vi) Delivery valve.

Impeller is the rotating component of the pump. It is made up of a series of curved vanes. The impeller is mounted on the shaft connecting an electric motor.

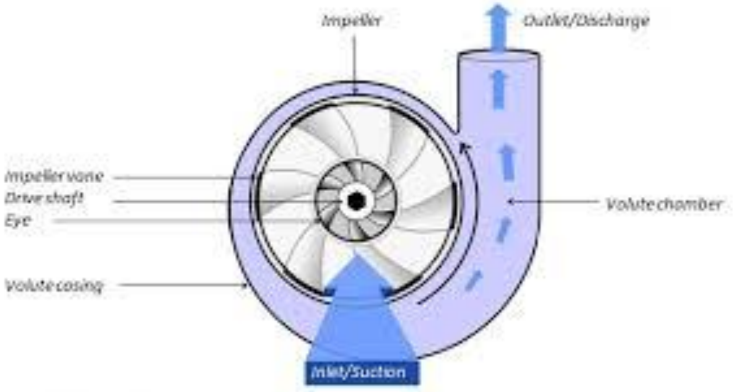
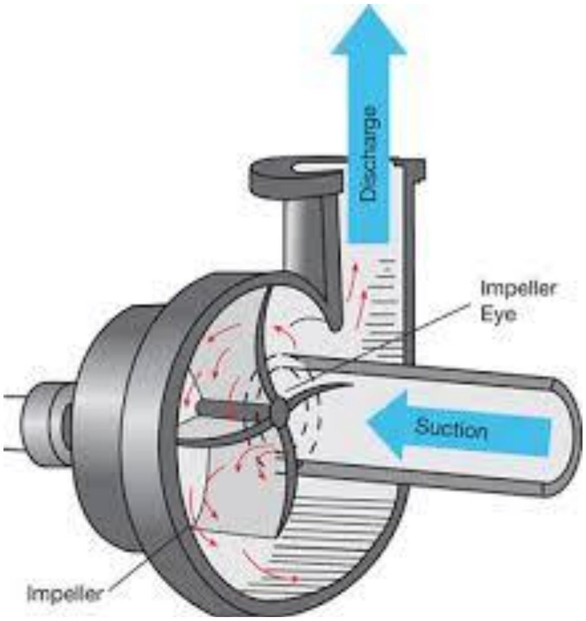


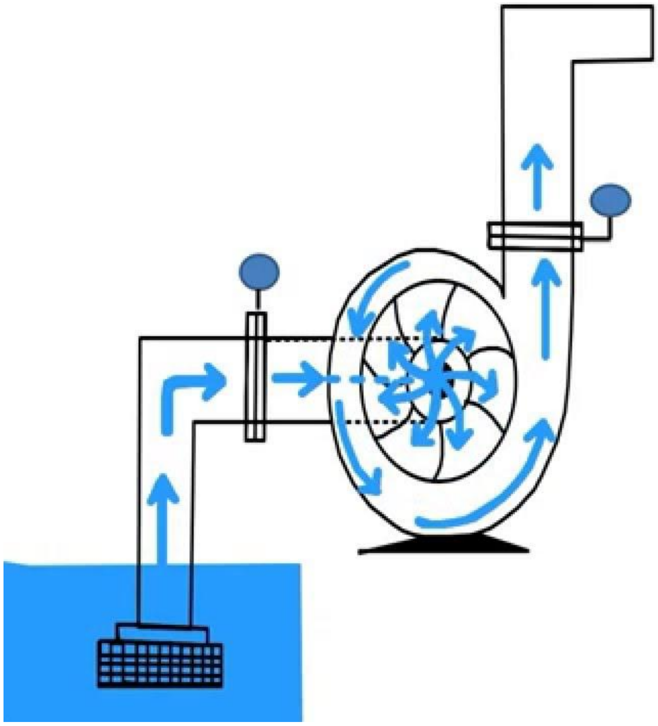
Figure 2. Volute case design

Casing is an air tight chamber surrounding the impeller. The shape of the casing is designed in such a way that the kinetic energy of the impeller is gradually changed to potential energy. This is achieved by gradually increasing the area of cross section in the direction of flow.



Suction pipe It is the pipe connecting the pump to the sump, from where the liquid has to be lifted up.

Foot valve with strainer the foot valve is a non-return valve which permits the flow of the liquid from the sump towards the pump. In other words the foot valve opens only in the upward direction.



The strainer is a mesh surrounding the valve, it prevents the entry of debris and silt into the pump. Delivery pipe is a pipe connected to the pump to the overhead tank. Delivery valve is a valve which can regulate the flow of liquid from the pump.

Priming of a centrifugal pump

Priming is the process of filling the suction pipe, casing of the pump and the delivery pipe upto the delivery valve with the liquid to be pumped.

If priming is not done the pump cannot deliver the liquid due to the fact that the head generated by the Impeller will be in terms of meters of air which will be very small (because specific weight of air is very much smaller than that of water).

Priming of a centrifugal pump can be done by any one of the following methods:

i. Priming with suction/vacuum pump.
ii) Priming with a jet pump.
iii) Priming with separator.
iv) Automatic or self priming.

Heads on a centrifugal pump:

Suction head (hs):it is the vertical distance between the liquid level in the sump and the centre line of the pump. It is expressed as meters.

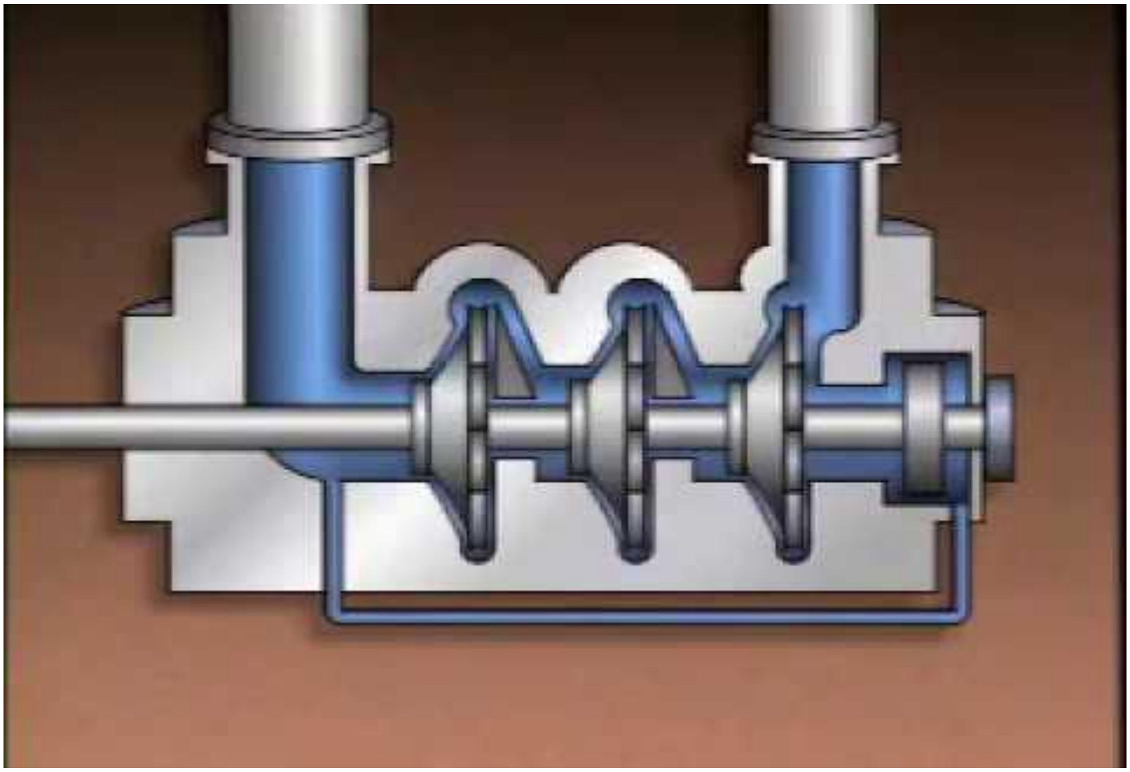
Delivery head (hd):It is the vertical distance between the centre line of the pump and the liquid level in the overhead tank or the supply point. It is expressed in meters.

Static head (Hs):It is the vertical difference between the liquid levels In the overhead tank and the sump, when the pump is not working. It is expressed as meters.

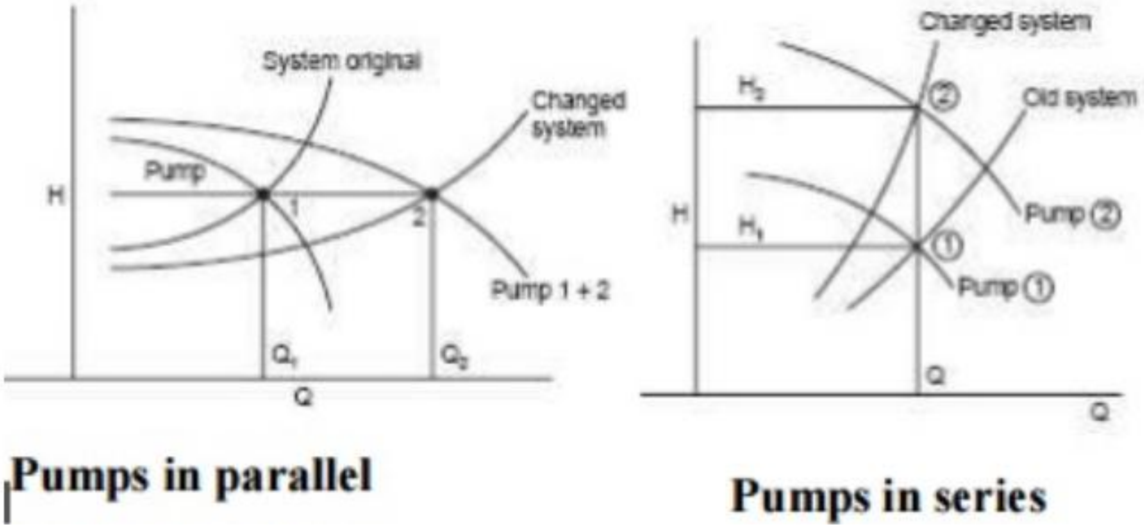
Therefore, $HS= (hs+ hd)$

Friction head (hf): It is the sum of the head loss due to the friction in the suction and delivery pipes. The friction loss in both the pipes is calculated using the Darcys equation, $hf=(fLV2/2gD)$.

Total head (H): It is the sum of the static head Hs, friction head (hf) and the velocity head in the delivery pipe (Vd 2/2g). Where, Vd=velocity in the delivery pipe.



Operation of Pumps in Series and Parallel:



Pumps in parallel

Pumps in series

Operation of Pumps in Series and Parallel

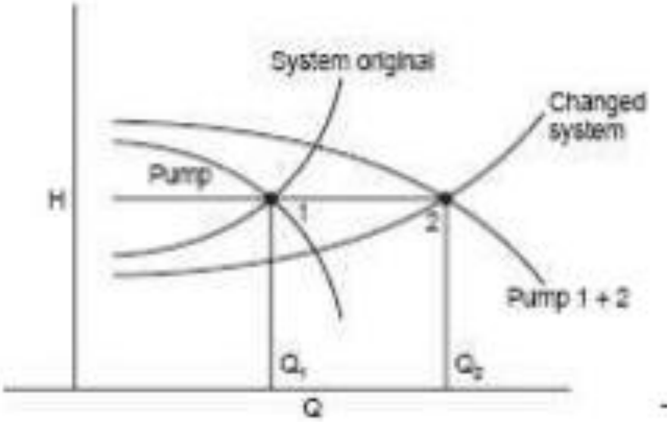
Pumps are chosen for particular requirement. The requirements are not constant as per example the pressure required for flow through a piping system. As flow increases, the pressure required increases. In the case of the pump as flow increases, the head decreases. The operating condition will be the meeting point of the two curves representing the variation of head required by the system and the variation of head of the pump. This is shown in Figure.

The operating condition decides about the capacity of the pump or selection of the pump. If in a certain setup, there is a need for increased load; either a completely new pump may be chosen. This may be costlier as well as complete revamping of the setup. An additional pump can be the alternate choice. If the head requirement increases the old pump and the new pump can operate in series.

In case more flow is required the old pump and the new pump will operate in parallel. There are also additional advantages in two pump operation. When the Pump-load characteristics load is low one of the pump can operate with a higher efficiency when the load increases then the second pump can be switched on thus improving part load efficiency. The characteristics of parallel operation is depicted in Figure

1 Pumps in parallel

The original requirement was $Q1$ at $H1$. Pump 1 could satisfy the same and operating point is at when the flow requirement and the system characteristic is changed such that $Q2$ is required at head $H1$, then two pumps of similar characteristics can satisfy the requirement.

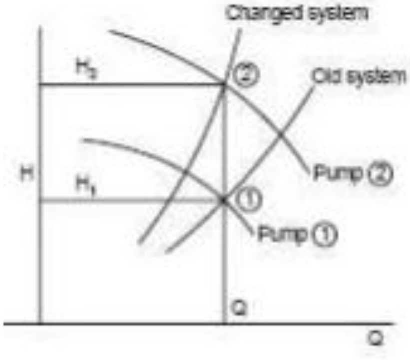


Pumps in parallel

Providing a flow volume of *Q*2 as head *H*1. It is not necessary that similar pumps should be used. Suitable control system for switching on the second pump should be used in such a case. When the head requirement is changed with flow volume being the same, then the pumps should work in series. The characteristics are shown in Figure.

2 Pumps in series

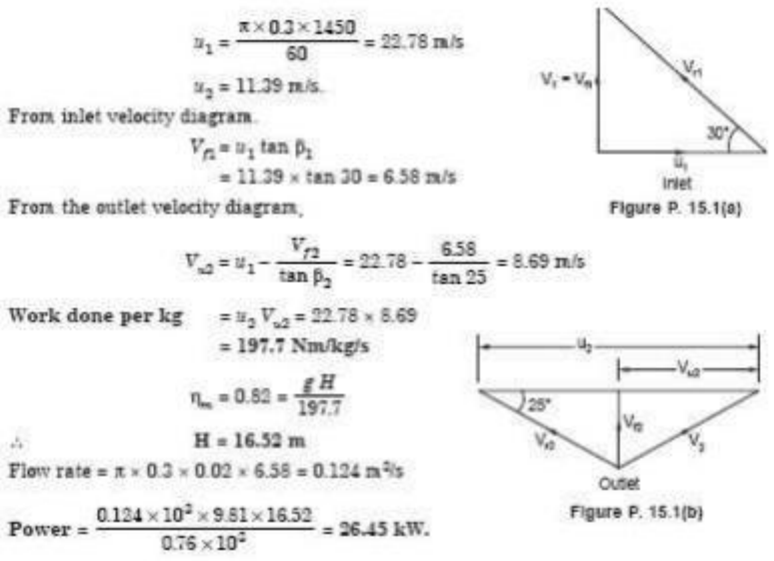
The flow requirement is *Q*. Originally head requirement was *H*1 met by the first pump alone. The new requirement is flow rate *Q* and head *H*2. This can be met by adding in series the pump2, which meets this requirement. It is also possible to meet changes in both head and flow requirements by the use of two pumps. Suitable control system should be installed for such purposes.



Pumps in series

Problem 1:The following details refer to a centrifugal pump. Outer diameter : 30 cm. Eye diameter : 15 cm. Blade angle at inlet : 30 o . Blade angle at outlet : 25 o . Speed 1450 rpm. The flow velocity remains constant. The whirl at inlet is zero. Determine the work done per kg. If the manometric efficiency is 82%, determine the working head. If width at outlet is 2cm, determine the power o =

76%.



$$u_1 = \frac{\pi \times 0.3 \times 1450}{60} = 22.78 \text{ m/s}$$

$$u_2 = 11.39 \text{ m/s.}$$

From inlet velocity diagram.

$$V_{f1} = u_1 \tan \beta_1$$

$$= 11.39 \times \tan 30 = 6.58 \text{ m/s}$$

From the outlet velocity diagram,

$$V_{u2} = u_1 - \frac{V_{f2}}{\tan \beta_2} = 22.78 - \frac{6.58}{\tan 25} = 8.69 \text{ m/s}$$

Work done per kg $= u_2 V_{u2} = 22.78 \times 8.69$

$= 197.7$ Nm/kg/s

$$\eta_m = 0.82 = \frac{g\,H}{197.7}$$

$$\therefore \quad H = 16.52 \text{ m}$$

Flow rate $= \pi \times 0.3 \times 0.02 \times 6.58 = 0.124 \text{ m}^3\text{/s}$

$$\text{Power} = \frac{0.124 \times 10^3 \times 9.81 \times 16.52}{0.76 \times 10^3} = 26.45 \text{ kW.}$$

Figure P. 15.1(a)

Figure P. 15.1(b)

Net Positive Suction Head (NPSH)

The pump manufacturer's specified margin of suction pressure above the boiling point of the liquid being pumped, is required to prevent cavitation. This pressure is called the 'Net Positive Suction Head' pressure (NPSH).

In order to ensure that a NPSH pressure is maintained, the Available NPSH should be higher than that required. The NPSH depends on the height and density of the liquid and the pressure above it.

Cavitation

Cavitations is a problem condition which may develop while a centrifugal pump is operating. This occurs when a liquid boils inside the pump due to insufficient suction head pressure. Low suction head causes a pressure below that of vaporization of the liquid, at the eye of the impeller. The resultant gas which forms causes the formation and collapse of 'bubbles' within the liquid. This, because gases cannot be pumped together with the liquid, causes violent fluctuations of pressure within the pump casing and is seen on the discharge gauge.

These sudden changes in pressure cause vibrations which can result in serious

damage to the pump and, of course, cause pumping inefficiency.

To overcome cavitations:

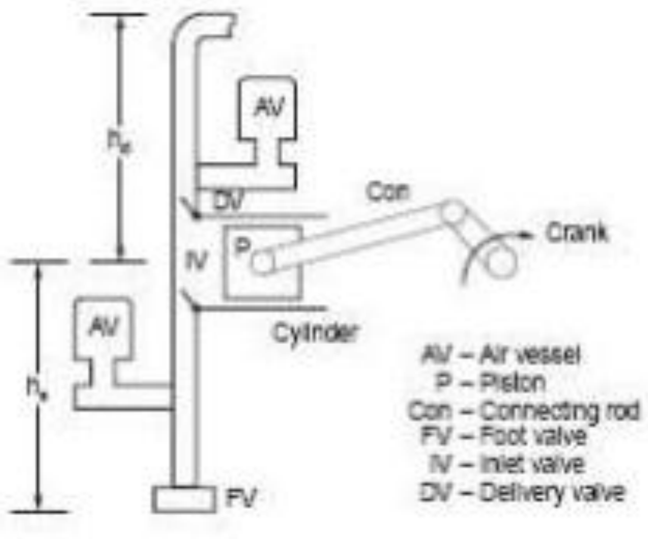
1. Increase suction pressure if possible.

2. Decrease liquid temperature if possible.
3. Throttle back on the discharge valve to decrease flow-rate.
4. Vent gases off the pump casing.

Multistage Pump

If centrifugal pump consists of two or more impellers the pump is called Multistage pump. To produce a high head impellers are connected in series .To produce high discharge impellers are connected in parallel.

Reciprocating Pumps:



Introduction

There are two main types of pumps namely the dynamic and positive displacement pumps. Dynamic pumps consist of centrifugal, axial and mixed flow pumps. In these cases pressure is developed by the dynamic action of the impeller on the fluid.

Momentum is imparted to the fluid by dynamic action. This type was discussed in the previous chapter. Positive displacement pumps consist of reciprocating and rotary types. These types of pumps are discussed in this chapter. In these types a certain volume of fluid is taken in an enclosed volume and then it is forced out against pressure to the required application.

Comparison

Dynamic pumps

1. Simple in construction.
2. Can operate at high speed and hence compact.
3. Suitable for large volumes of discharge at moderate pressures in a single stage.
4. Lower maintenance requirements.
5. Delivery is smooth and continuous.

Positive displacement pumps

1. More complex, consists of several moving parts.
2. Speed is limited by the higher inertia of the moving parts and the fluid.
3. Suitable for fairly low volumes of flow at high pressures.
4. Higher maintenance cost.
5. Fluctuating flow.

2. Description And Working

The main components are:

1. Cylinder with suitable valves at inlet and delivery.
2. Plunger or piston with piston rings.
3. Connecting rod and crank mechanism.
4. Suction pipe with one way valve.
5. Delivery pipe.

6. Supporting frame.

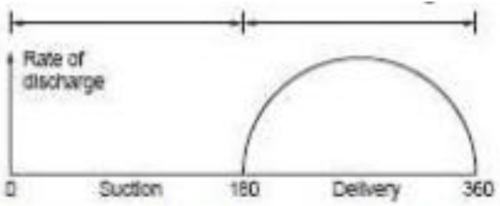
7. Air vessels to reduce flow fluctuation and reduction of acceleration head and friction head.

The action is similar to that of reciprocating engines. As the crank moves outwards, the piston moves out creating suction in the cylinder. Due to the suction water/fluid is drawn into the cylinder through the inlet valve. The delivery valve will be closed during this outward stroke.

During the return stroke as the fluid is incompressible pressure will developed immediately which opens the delivery valve and closes the inlet valve. During the return stroke fluid will be pushed out of the cylinder against the delivery side pressure. The functions of the air vessels will be discussed in a later section. The volume delivered per stroke will be the product of the piston area and the stroke length.

In a single acting type of pump there will be only one delivery stroke per revolution. Suction takes place during half revolution and delivery takes place during the other half. As the piston speed is not uniform (crank speed is uniform) the discharge will vary with the position of the crank. The discharge variation is shown in figure.

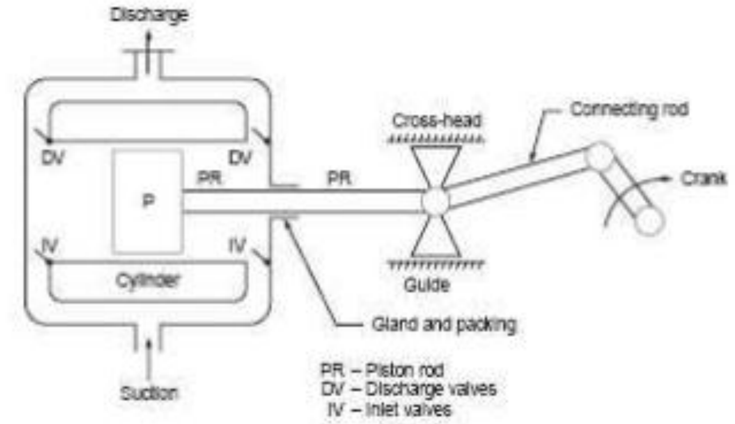
In a single acting pump the flow will be fluctuating because of this operation.



Flow variation during crank movement of single acting pump

Fluctuation can be reduced to some extent by double acting pump or multicylinder pump. The diagrammatic sketch of a double acting pump is shown in figure In this case the piston cannot be connected directly with the connecting rod.

A gland and packing and piston rod and cross- head and guide are additional components. There will be nearly double the discharge per revolution as compared to single acting pump.When one side of the piston is under suction the other side will be delivering the fluid under pressure. As can be noted, the construction is more complex.



Diagrammatic view of a double action pump

Flow Rate and Power

Theoretical flow rate per second for single acting pump is given by,

Theoretical flow rate per second for single acting pump is given by,

$$\therefore Q_{SA} = \frac{L\,A\,N}{60}\ \text{m}^3/\text{s} \tag{16.3.1}$$

Where L is the length of stroke, A is the cylinder or piston area and N is the revolution per minute. It is desirable to express the same in terms of crank radius and the angular velocity as simple harmonic motion is assumed.

$$\omega = \frac{2\pi N}{60},\ N = \frac{60\,\omega}{2\pi},\ r = \frac{L}{2}$$

$$Q_{SA} = \frac{2r\,.\,A \times 60\,\omega}{2\pi \times 60} = \frac{A\omega r}{\pi}\ \text{m}^3/\text{s} \tag{16.3.1a}$$

In double acting pumps, the flow will be nearly twice this value. If the piston rod area is taken into account, then

$$Q_{DA} = \frac{A\,L\,N}{60} + (A - A_{pr})\frac{L\,N}{60}\ \text{m}^3/\text{s} \tag{16.3.2}$$

Compared to the piston area, the piston rod area is very small and neglecting this will lead to an error less than 1%.

$$Q_{DA} = \frac{2A\,L\,N}{60} = \frac{2A\,\omega\,r}{\pi}\ \text{m}^3/\text{s}.$$

Slip

There can be leakage along the valves, piston rings, gland and packing which will reduce the discharge to some extent. This is accounted for by the term slip.

Percentage o Slip = Qa -Qn / Qa x 100

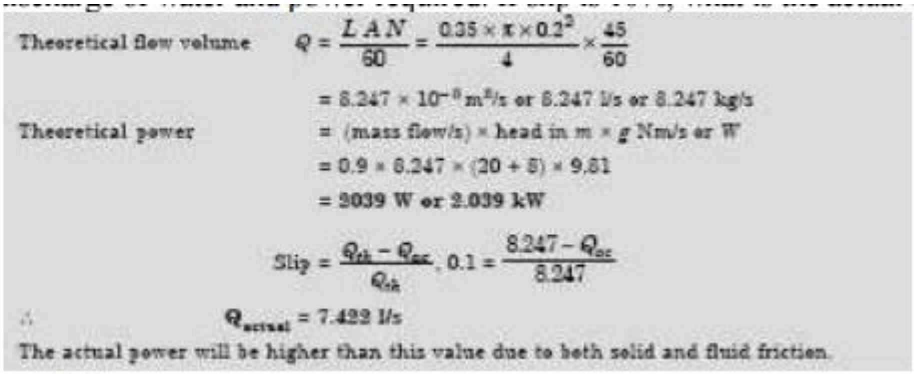
Where Qth is the theoretical discharge given by equation and Qac is the measured discharge. If actual discharge is greater than theoretical discharge negative value is found

this negative value is called negative slip.

Coefficient of discharge

It has been found in some cases that Qac > Qth, due to operating conditions. In this case the slip is called negative slip. When the delivery pipe is short or the delivery head is small and the accelerating head in the suction side is high, the delivery valve is found to open before the end of suction stroke and the water passes directly into the delivery pipe. Such a situation leads to negative slip.

Problem.1 A single acting reciprocating pump has a bore of 200 mm and a stroke of 350 mm and runs at 45 rpm. The suction head is 8 m and the delivery head is 20 m. Determine the theoretical discharge of water and power required. If slip is 10%, what is the actual flow rate ?



Theoretical flow volume $Q = \frac{LAN}{60} = \frac{0.35 \times \pi \times 0.2^2}{4} \times \frac{45}{60}$

$= 8.247 \times 10^{-3}\ m^3/s$ or 8.247 l/s or 8.247 kg/s

Theoretical power $=$ (mass flow/s) × head in m × g Nm/s or W

$= 0.9 \times 8.247 \times (20 + 8) \times 9.81$

$= 2039$ W or 2.039 kW

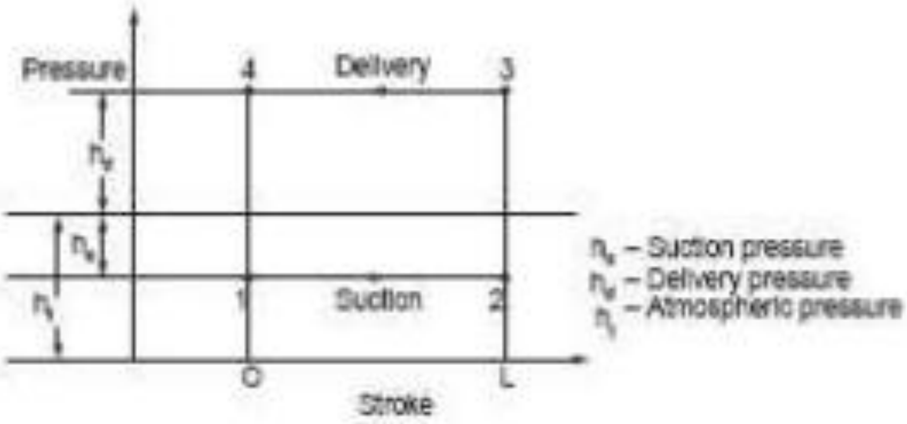
$$\text{Slip} = \frac{Q_{th} - Q_{ac}}{Q_{th}},\ 0.1 = \frac{8.247 - Q_{ac}}{8.247}$$

$\therefore$ $Q_{actual} = 7.422$ l/s

The actual power will be higher than this value due to both solid and fluid friction.

Indicator Diagram

The pressure variation in the cylinder during a cycle consisting of one revolution of the crank. When represented in a diagram is termed as indicator diagram. The same is shown in figure.



Indicator diagram for a crank revolution

Figure represents an ideal diagram, assuming no other effects are involved except the suction and delivery pressures. Modifications due to other effects will be discussed later in the section. Point 1 represents the condition as the piston has just started moving during the suction stroke.

1-2 represents the suction stroke and the pressure in the cylinder is the suction pressure below the atmospheric pressure. The point 3 represents the condition just as the piston has started moving when the pressure increases to the delivery pressure. Along 3-4 representing the delivery stroke the pressure remains constant. The area enclosed represents the work done during a crank revolution to some scale.

Acceleration Head

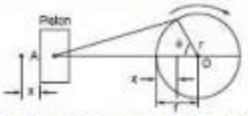
The piston in the reciprocating pump has to move from rest when it starts the suction stroke. Hence it has to accelerate. The water in the suction pipe which is also not flowing at this point has to be accelerated. Such acceleration results in a force which when divided by area results as pressure.

When the piston passes the mid point, the velocity gets reduced and so there is retardation of the piston together with the water in the cylinder and the pipe. This again results in a pressure. These pressures are called acceleration pressure and is denoted as head of fluid (h = P/?g) for convenience.

Referring to the figure shown below the following equations are written.

in a pressure. These pressures are called acceleration pressure and is denoted as head of fluid ($h = P/\rho g$) for convenience.

Referring to the figure shown below the following equations are written.



Piston Crank Configuration

Let ω be the angular velocity.

Then at time t, the angle travelled $\theta = \omega t$

Distance $x = r - r\cos\theta = r - r\cos\omega t$

Velocity at this point,

$$v = \frac{dx}{dt} = \omega r \sin \omega t$$

The acceleration at this condition

$$\dot{x} = \frac{dv}{dt} = \omega^2 r \cos \omega t$$

This is the acceleration in the cylinder of area A. The acceleration in the pipe of area a is=A/a w2rcosot.This head is imposed on the piston in addition to the static head at that condition.This results in the modification of the indicator diagram as shown in figure.

Accelerating force = mass × acceleration

$$\text{mass in the pipe} = \rho\, al \text{ kg} = \frac{\gamma al}{g}$$

$$\therefore \quad \text{Acceleration force} = \frac{\gamma al}{g} \times \frac{A}{a} \omega^2 r \cos \omega t$$

Pressure = force/area

$$= \frac{ral}{g} \cdot \frac{1}{a} \cdot \frac{A}{a} \omega^2 r \cos \omega t$$

$$= \frac{rl}{g} \cdot \frac{A}{a} \omega^2 r \cos\theta$$

Head = Pressure/γ

$$h_a = \frac{l}{g} \cdot \frac{A}{a} \omega^2 r \cos\theta$$

This is the acceleration in the cylinder of area A. The acceleration in the pipe of area a is=A/a w2rcosot.This head is imposed on the piston in addition to the static head at that condition.This results in the modification of the indicator diagram as shown in figure.

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(i) Beginning of suction stroke: $\theta = 0$, $\cos\theta = 1$

$$\therefore \qquad h_{as} = \frac{l_s}{g}\cdot\frac{A}{a_s}\cdot\omega^2 r$$

This is over and above the static suction head. Hence the pressure is indicated by 1′ in the diagram.

(ii) Middle of stroke: $\theta = 90$ $\therefore$ $h_{as} = 0$. There is no additional acceleration head.

(iii) End of stroke: $\theta = 180$. $\cos\theta = -1$

$$\therefore \qquad h_{as} = -\frac{l_s}{g}\cdot\frac{A}{a_s}\cdot\omega^2 r$$

This reduces the suction head. Hence the pressure is indicated at 2′ in the diagram.

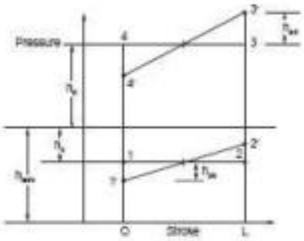
Similarly during the beginning of the delivery stroke

$$\theta = 0,\ \cos\theta = 1$$

$$h_{ad} = \frac{l_d}{g}\cdot\frac{A}{a_d}\cdot\omega^2 r$$

This head is over and above the static delivery pressure. The pressure is indicated by point 3′ in the diagram. At the middle stroke $h_{ad} = 0$. At the end of the stroke $h_{ad} = -\frac{l_d}{g}\cdot\frac{A}{a_d}\cdot\omega^2 r$.

This reduces the pressure at this condition and the same is indicated by 4′, in the diagram.



Modified indicator diagram due to acceleration head

The effect of acceleration head are:

The effect of acceleration head are:

No change in the work done. pressure at 1?is around 2.5 m of head of water (absolute). Which is directly related to speed, the speed of operation of reciprocating pumps is limited. Later it will be shown than the installation of an air vessel alleviates this problem to some extent.

Work done by the Pump

For single acting

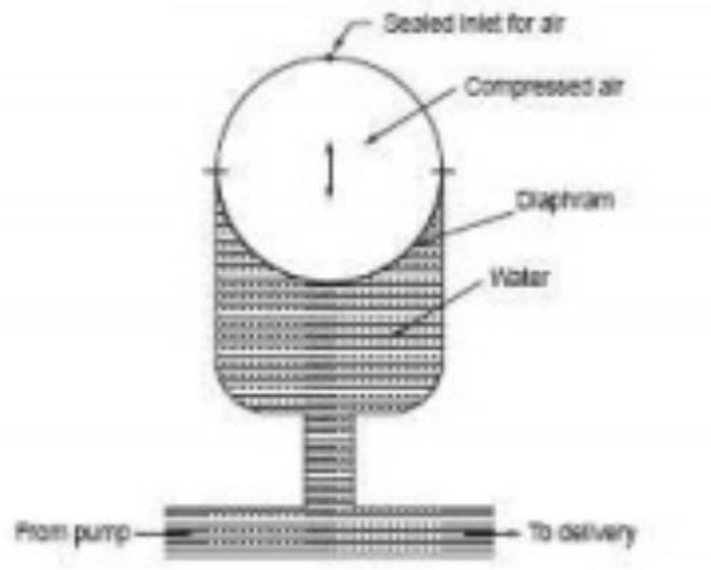
W= gALN(hs+hd+0.67hfs+0.67hfd)/60

For Double acting

W=2gALN(hs+hd+0.67hfs+0.67hfd)/60

Where hfs, hfd =loss of head due to acceleration in the suction and delivery Pipe.

Air Vessels



Air vessel is a strong closed vessel as shown in figure. The top half contains compressed air and the lower portion contains water or the fluid being pumped. Air and water are separated by a flexible diaphragm which can move up or down depending on the difference in pressure between the fluids. The air charged at near total delivery pressure/suction pressure from the top and sealed. The air vessel is connected to the pipe lines very near the pump, at nearly the pump level.

On the delivery side, when at the beginning and up to the middle of the delivery stroke the head equals hs + hf + ha , higher than the static and friction heads. At this time part of the water from pump will flow into the air vessel and the remaining will flow through the delivery pipe. This will increase the compressed air pressure. At the middle stroke position the head will be sufficient to just cause flow.

The whole of the flow from pump will flow to the delivery pipe. At the second half of the stroke the head will be equal to hs + hf - ha. At the position the head will be not sufficient to cause flow. The compressed air pressure will act on the water and water charged earlier into the air vessel will now flow out.

Similar situation prevails on the suction side. At the start and up to the middle of the suction stroke the head at the pump is higher than static suction head by the amount of acceleration head. The flow will be more and part will flow into the air vessel. The second half of the stroke water will flow out of the air vessel.

In this process the velocity of water in the delivery pipe beyond the air vessel is uniform, and lower than the maximum velocity if air vessel is not fitted. Similar situation prevails in the suction side also.

The effect is not only to give uniform flow but reduce the friction head to a considerable extent saving work. Without air vessel the friction head increases, reaches a maximum value at the mid stroke and then decreases to zero. With air vessel the friction head is lower and is constant throughout the stroke. This is due to the constant velocity in the pipe.

The advantages of installing air vessels are:

(i) The flow fluctuation is reduced and a uniform flow is obtained.

(ii) The friction work is reduced.

(iii) The acceleration head is reduced considerably.

(iv) Enables the use of higher speeds.

Types of positive displacement pump

- Rotary pumps
- Reciprocating (piston) pumps
- Gear pumps

1.Rotary Pumps

In Rotary pumps, movement of liquid is achieved by mechanical displacement of liquid produced by rotation of a sealed arrangement of intermeshing rotating parts within the pump casing.

2.The gear pump Construction and Operation:

In this pump, intermeshing gears or rotors rotate in opposite directions, just like the gears in a vehicle or a watch mechanism. The pump rotors are housed in the casing or stator with a very small clearance between them and the casing. (The fluid being pumped will lubricate this small clearance and help prevent friction and therefore wear of the rotors and casing).

In this type of pump, only one of the rotors is driven. The intermeshing gears rotate the other rotor. As the rotors rotate, the liquid or gas, (this type of machine can also be used as a compressor), enters from the suction line and fills the spaces between the teeth of the gears and becomes trapped forming small 'Slugs' of fluid between the teeth.

The slugs are then carried round by the rotation of the teeth to the discharge side of the pump.

At this point, the gears mesh together and, as they do so, the fluid is displaced from each cavity by the intermeshing teeth.

Since the fluid cannot pass the points of near contact of the intermeshed teeth nor between the teeth and casing, it can only pass into the discharge line.

As the rotation continues, the teeth at the suction end are opened up again and the same amount of fluid will fill the spaces and the process repeated. The liquid at the discharge end is constantly being displaced (moved forward).

Thus gear pumps compel or force a fixed volume of fluid to be displaced for each revolution of the rotors giving the 'Positive Displacement' action of the pump.

Gear pumps are generally operated at high speed and thus give a fairly pulse-free discharge flow and pressure. Where these pumps are operated at slower speeds, as in pumping viscous liquids, the output tends to pulsate due to the meshing of the teeth. Any gas or air drawn into the pump with the liquid, will be carried through with the liquid and will not cause cavitation. This action of the pump means that it's a 'Self Priming' pump. The discharge pressure may however, fluctuate.

The output from this type of pump is directly proportional to the speed of operation. If the speed is doubled, the output will be doubled and the pressure will have very little effect. (At higher pressures, due to the fine clearances between the teeth and between the casing and the rotors, a small leakage back to the suction side will occur resulting in a very small drop in actual flow rate. The higher the discharge pressure, the more likely that internal leakage will occur).

Rotary pumps are widely used for viscous liquids and are self-lubricating by the fluid being pumped. This means that an external source of lubrication cannot be used as it would contaminate the fluid being pumped. However, if a rotary pump is used for dirty liquids or slurries, solid particles can get between the small clearances and cause wear of the teeth and casing. This will result in loss of efficiency and expensive repair or replacement of the pump.

Rotary Pumps

The rotary pump is good for handling viscous liquids, nut because of the close tolerances needed, it can not be manufactured large enough to compete with centrifugal pumps for coping with very high flow rates.

Rotary pumps are available in a variety of configurations.

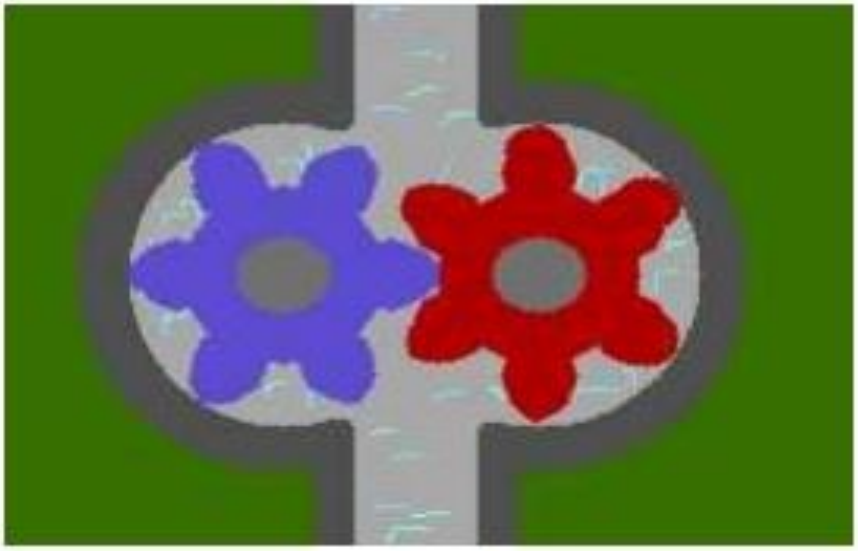
- Double lobe pump

- Trible lobe pumps

- Gear pump

- Gear Pumps

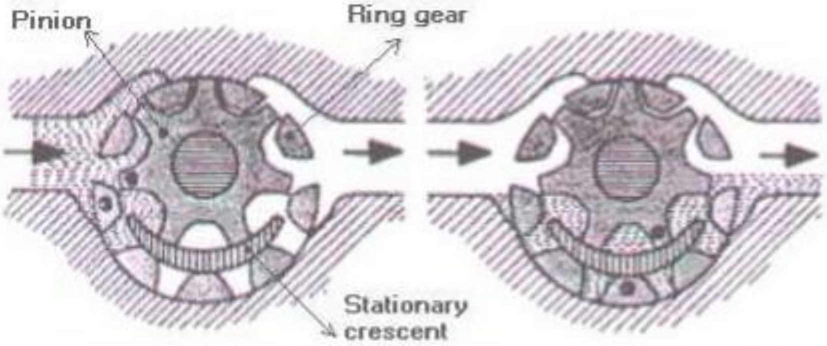
- Spur Gear or Extern al-gear pump



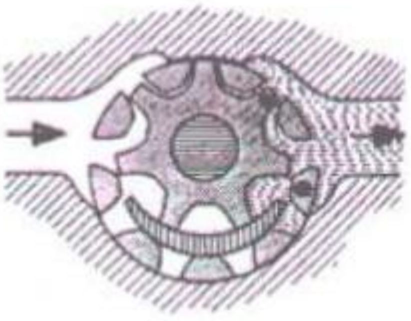
External-gear pump (called as gear pump) consists essen tially of two intermeshing gears which are identical and which are surrounded by a closely fitting casing. One of the gears is driven directly by the prime mover while the other is allowed to rotate freel y. The fluid enters the spaces between the teeth and the casing and moves with the tee th along the outer periphery until it reaches the outlet where it is expelled from the pu mp.

External-gear p umps are used for flow rates up to about 400 m3/hr working against pressures as high as 170 atm. The volumetric efficiency of gear pumps is in the order of 96 percen t at pressures of about 40 atm but decreases a s the pressure rises.

Internal-gear Pump



(1) Liquid inlet (2) Passage of liquid



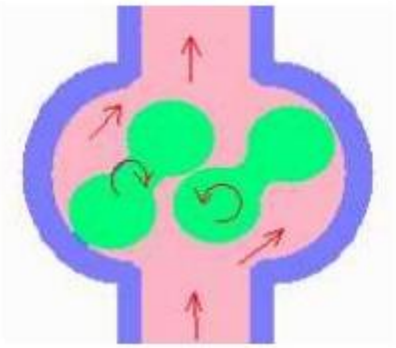
(3) Liquid outlet

The above figure shows the operation of a internal gear pump. In the internal-gear pump a spur gear, or pinion, meshes with a ring gear with internal teeth. Both gears are inside the casing. The ring gear is coaxial with the inside of the casing, but the pinion, which is externally driven, is mounted eccentrically with respect to the center of the casing. A stationary metal crescent fills the space between the two gears. Liquid is carried from inlet to discharge by both gears, in the spaces between the gear teeth and the crescent.

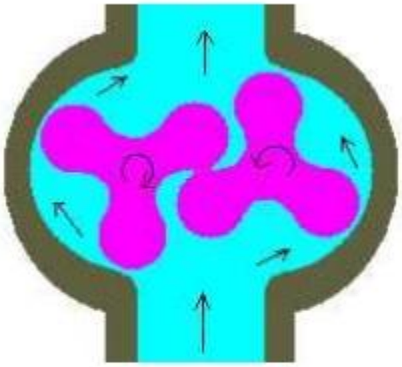
Lobe pumps

In principle the lobe pump is similar to the external gear pump; liquid flows into the region created as the counter-rotating lobes unmesh. Displacement volumes are formed between the surfaces of each lobe and the casing, and the liquid is displaced by meshing of the lobes. Relatively large displacement volumes enable large solids (nonabrasive) to be handled. They also tend to keep liquid velocities and shear low, making the pump type suitable for high viscosity, shear-sensitive liquids.

Two lobe pump



Three lobe pump



The choice of two or three lobe rotors depends upon solids size, liquid viscosity, and tolerance of flow pulsation. Two lobe handles larger solids and high viscosity but pulsates more. Larger lobe pumps cost 4-5 times a centrifugal pump of equal flow and head.

The above figure shows the operation of a internal gear pump. In the internal-gear pump a spur gear, or pinion, meshes with a ring gear with internal teeth. Both gears are inside the casing. The ring gear is coaxial with the inside of the casing, but the pinion, which is externally driven, is mounted eccentrically with respect to the center of the casing. A stationary metal crescent fills the space between the two gears. Liquid is carried from inlet to discharge by both gears, in the spaces between the gear teeth and the crescent.

Selection of Pumps

The following factors influence the choice of pump for a particular operation:

1. The quantity of liquid to be handled: This primarily affects the size of the pump and determines whether it is desirable to use a number of pumps in parallel.

2. The head against which the liquid is to be pumped. This will be determined by the difference in pressure, the vertical height of the downstream and upstream reservoirs and by the frictional losses which occur in the delivery line. The suitability of a centrifugal pump and the number of stages required will largely be determined by this factor.

3. The nature of the liquid to be pumped. For a given throughput, the viscosity largely determines the frictional losses and hence the power required. The corrosive nature will determine the material of construction both for the pump and the packing. With suspensions, the clearance in the pump must be large compared with the size of the particles.

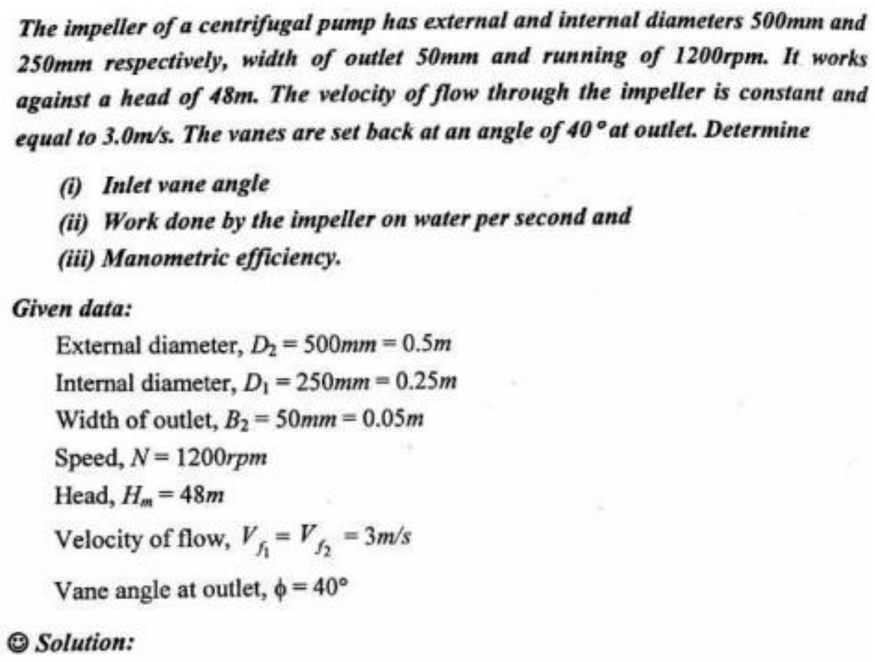
4. The nature of power supply. If the pump is to be driven by an electric motor or internal combustion engine, a high-speed centrifugal or rotary pump will be preferred as it can be coupled directly to the motor.

5. If the pump is used only intermittently, corrosion troubles are more likely than with continuous working.

Applications

The handling of liquids which are particularly corrosive or contain abrasive solids in suspension, compressed air is used as the motive force instead of a mechanical pump.

PROBLEMS:



The impeller of a centrifugal pump has external and internal diameters 500mm and 250mm respectively, width of outlet 50mm and running of 1200rpm. It works against a head of 48m. The velocity of flow through the impeller is constant and equal to 3.0m/s. The vanes are set back at an angle of 40° at outlet. Determine

- ***(i) Inlet vane angle***
- ***(ii) Work done by the impeller on water per second and***
- ***(iii) Manometric efficiency.***

Given data:

External diameter, $D_2 = 500mm = 0.5m$

Internal diameter, $D_1 = 250mm = 0.25m$

Width of outlet, $B_2 = 50mm = 0.05m$

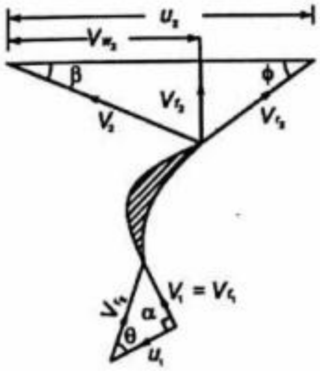
Speed, $N = 1200rpm$

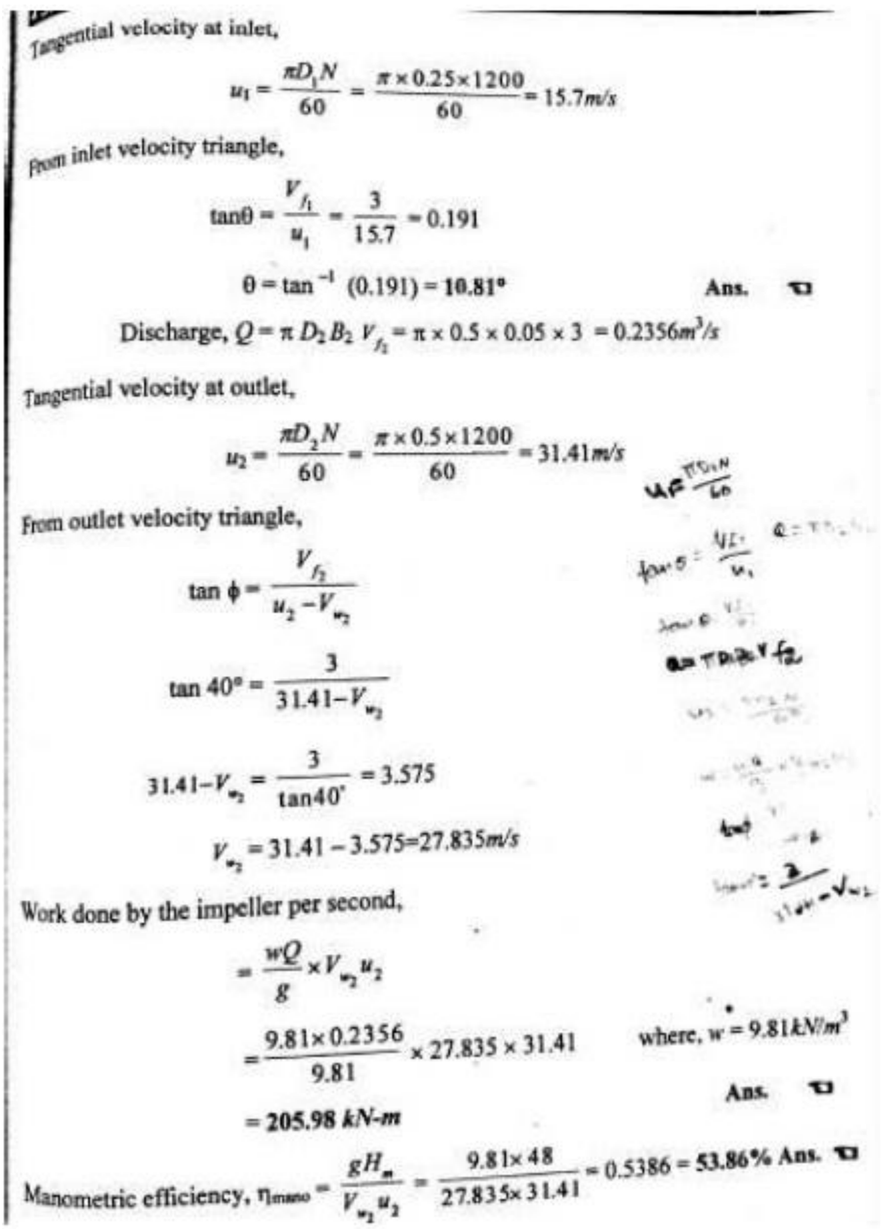
Head, $H_m = 48m$

Velocity of flow, $V_{f_1} = V_{f_2} = 3m/s$

Vane angle at outlet, $\phi = 40°$

☺ ***Solution:***





Tangential velocity at inlet,

$$u_1 = \frac{\pi D_1 N}{60} = \frac{\pi \times 0.25 \times 1200}{60} = 15.7 m/s$$

From inlet velocity triangle,

$$\tan\theta = \frac{V_{f_1}}{u_1} = \frac{3}{15.7} = 0.191$$

$$\theta = \tan^{-1}(0.191) = \mathbf{10.81^\circ}$$ **Ans.**

Discharge, $Q = \pi D_2 B_2 V_{f_2} = \pi \times 0.5 \times 0.05 \times 3 = 0.2356 m^3/s$

Tangential velocity at outlet,

$$u_2 = \frac{\pi D_2 N}{60} = \frac{\pi \times 0.5 \times 1200}{60} = 31.41 m/s$$

From outlet velocity triangle,

$$\tan\phi = \frac{V_{f_2}}{u_2 - V_{w_2}}$$

$$\tan 40^\circ = \frac{3}{31.41 - V_{w_2}}$$

$$31.41 - V_{w_2} = \frac{3}{\tan 40^\circ} = 3.575$$

$$V_{w_2} = 31.41 - 3.575 = 27.835 m/s$$

Work done by the impeller per second,

$$= \frac{wQ}{g} \times V_{w_2} u_2$$

$$= \frac{9.81 \times 0.2356}{9.81} \times 27.835 \times 31.41$$ where, $w = 9.81 kN/m^3$

$$= \mathbf{205.98\ kN\text{-}m}$$ **Ans.**

Manometric efficiency, $\eta_{mano} = \frac{gH_m}{V_{w_2} u_2} = \frac{9.81 \times 48}{27.835 \times 31.41} = 0.5386 = \mathbf{53.86\%}$ **Ans.**

$u = \frac{\pi D_1 N}{60}$

$\tan\theta = \frac{V_{f1}}{u_1}$

$Q = \pi D_2 B_2 V_{f2}$

$\tan\phi = \frac{3}{31.41 - V_{w2}}$

Priming of a centrifugal Pump:

The operation of filling the suction pipe, casing and a portion of delivery pipe with the liquid to be raised, before starting the pump is known as Priming

It is done to remove any air, gas or vapour from these parts of pump.

If a Centrifugal pump is not primed before starting air pockets inside impeller may give rise to vortices and causes discontinuity of flow.

Losses in Centrifugal pump:

Hydraulic Losses:

Shock or eddy losses at the entrance to and exit from the

impeller Losses due to friction in the impeller

Friction and eddy losses in the guide vanes/diffuser and casing

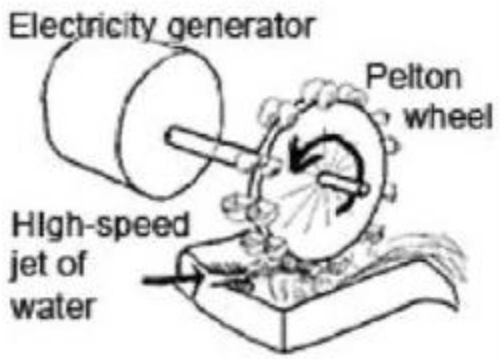
Mechanical Losses:

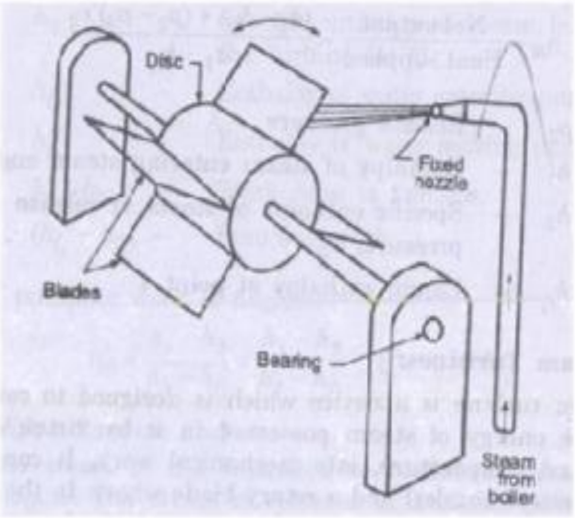
- Losses due to disc friction between the impeller and the liquid which fills the clearance spaces between the impeller and casing

- Losses pertaining to friction of the main bearing and glands.

Specific speed of Centrifugal Pump:

It is the speed in revolutions per minute at which a geometrically similar impeller would deliver one cubic meter of liquid per second against a delivery head of one meter.





APPROACHES FOR RATE-CONTROLLED DELIVERY

Rate control can be achieved by several different technologies similar to those used for “conventional” drugs. Insulin is an excellent example. A spectrum of options is available and accepted: different types of suspensions and continuous infusion systems are marketed. Moreover, chemical approaches can be used to change protein characteristics. Polyoxyethylene glycol attachment to proteins changes their circulation half-life in blood dramatically. Figure 17 shows an example of this approach.

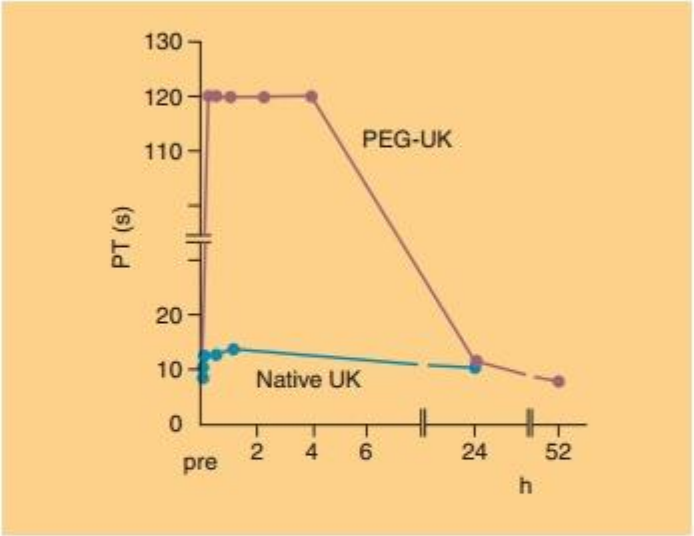
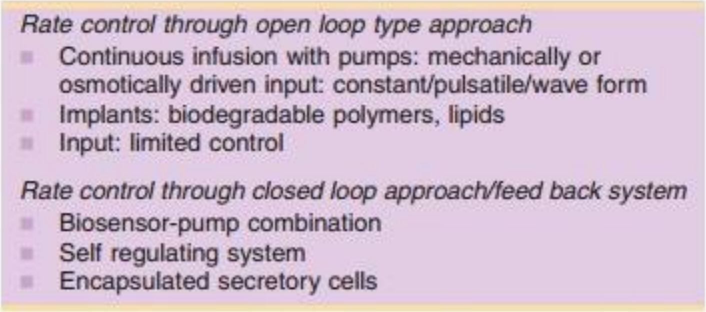


Figure 17 Influence of chemical grafting of poly-ethyleneglycol (*PEG*) on the ability of urokinase (*UK*) to affect the prothrombin time (*PT*) in vivo in beagles with time. *Source*: Adapted from Tomlinson, 1987.

In general, proteins are administered as an aqueous solution. Only recombinant vaccines and most insulin formulations are delivered as (colloidal) dis-persions. At the present time, insulin is routinely and clinically applied through some form of controlled release system other than through continuous infusion. As experience with biotech drugs grows, more advanced technologies will definitely be introduced to optimize the therapeutic benefit of the drug. Table 9 lists some of the technologically feasible options. They are briefly touched upon below.



Rate control through open loop type approach

- Continuous infusion with pumps: mechanically or osmotically driven input: constant/pulsatile/wave form
- Implants: biodegradable polymers, lipids
- Input: limited control

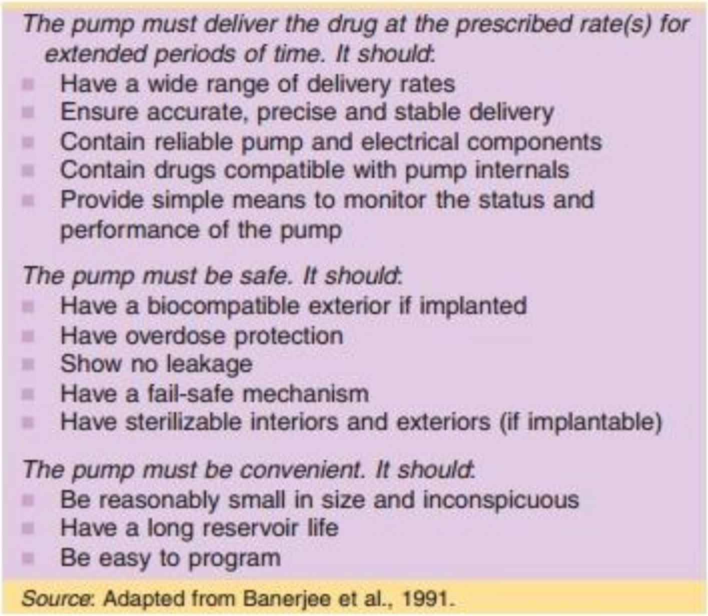
Rate control through closed loop approach/feed back system

- Biosensor-pump combination
- Self regulating system
- Encapsulated secretory cells

Table 9 Controlled release systems for parenteral delivery.

Open-Loop Systems: Mechanical Pumps

Mechanically driven pumps are common tools to administer drugs intravenously in hospitals (continuous infusion, open-loop type). They are available in different kinds of sizes/prices, portable or not, inside/outside the body, etc. Table 10 presents a checklist of issues to be considered when selecting the proper pump.



The pump must deliver the drug at the prescribed rate(s) for extended periods of time. It should:

- Have a wide range of delivery rates
- Ensure accurate, precise and stable delivery
- Contain reliable pump and electrical components
- Contain drugs compatible with pump internals
- Provide simple means to monitor the status and performance of the pump

The pump must be safe. It should:

- Have a biocompatible exterior if implanted
- Have overdose protection
- Show no leakage
- Have a fail-safe mechanism
- Have sterilizable interiors and exteriors (if implantable)

The pump must be convenient. It should:

- Be reasonably small in size and inconspicuous
- Have a long reservoir life
- Be easy to program

Source: Adapted from Banerjee et al., 1991.

Table 10 ■ Characteristics of the ideal pump.

Controlled administration of a drug does not necessarily imply a constant input rate. Pulsatile or variable-rate delivery is the desired mode of input for a number of protein drugs, and for these drugs pumps should provide flexible input rate characteristics. Insulin is a prime example of a protein drug, where there is a need to adjust the input rate to the needs of the body. Today by far most experience with pump systems in an ambulatory setting has been gained with this drug. The pump system may fail because of energy failure, problems with the syringe, accidental needle withdrawal, leakage of the catheter and problems at the injection or implantation site (Banerjee et al., 1991). Moreover, long-term drug stability may become a problem. The protein should be stable at 37 C or ambient temperature (internal and external device, respectively) between two refills. Finally, even with high tech pump systems, the patient still has to collect data to adjust the pump rate. This implies invasive sampling from body fluids on a regular basis, followed by calculation of the required input rate. This problem would be solved if the concept of closed-loop systems would be realized (feedback systems, see below).

Open-Loop Systems: Osmotically Driven Systems

The subcutaneously implantable, osmotic mini-pump developed by ALZA (Alzet minipump, Fig. 18) (Banerjee et al., 1991)) has proven to be useful in animal experiments where continuous, constant infu-sion is required over prolonged periods of time. The rate determining process is the influx of water through the rigid, semi-permeable external mem-brane. The incoming water empties the drug-contain-ing reservoir (solution or dispersion) surrounded by a flexible impermeable membrane. The release rate depends on the characteristics of this semi-permeable membrane and on osmotic pressure differences over this membrane (osmotic agents inside the pump). Zero-order release kinetics exists as long as the osmotic pressure difference over the semi-permeable membrane is maintained constant.

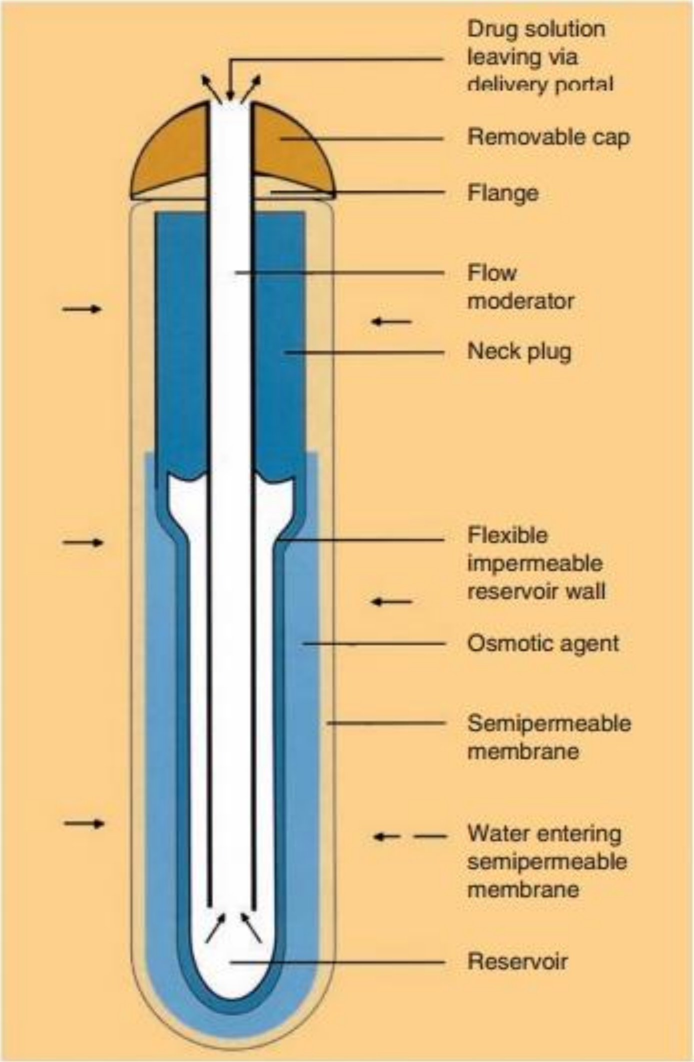


Figure 18 Cross section of functioning Alza Alzet osmotic

The protein solution (or dispersion) must be physically and chemically stable at body temperature over the full term of the experiment. Moreover, the protein solution must be compatible with the pump parts to which it is exposed. A limitation of the system is the fixed release rate, which is not always desired (see above). These devices have currently not been used on a regular basis in the clinic.

Open Loop Systems: Biodegradable Microspheres

Polylactic acid–polyglycolic acid (PLGA)-based deliv-ery systems are being used extensively for the delivery of therapeutic peptides, in particular lutei-nizing hormone-releasing hormone (LHRH) agonists such as leuprolide in the therapy of prostate cancer. The first LHRH agonist controlled release formula-tions were implants containing leuprolide with dose ranges of 1–3 months. Later, microspheres loaded with leuprolide were introduced and dosing intervals were prolonged to up to 6 months. Critical success factors for the design of these controlled release systems are: (i) the drug has to be highly potent (only a small dose is required over the dosing interval), (ii) a sustained presence in the body is required, and (iii) no adverse reactions at the injection site should occur.

New strategies for controlled release of thera-peutic proteins are presently under development. For example, Figures 19 and 20 describe a dextran-based microsphere technology for SC or IM administration that often has an almost 100% protein encapsulation efficiency.

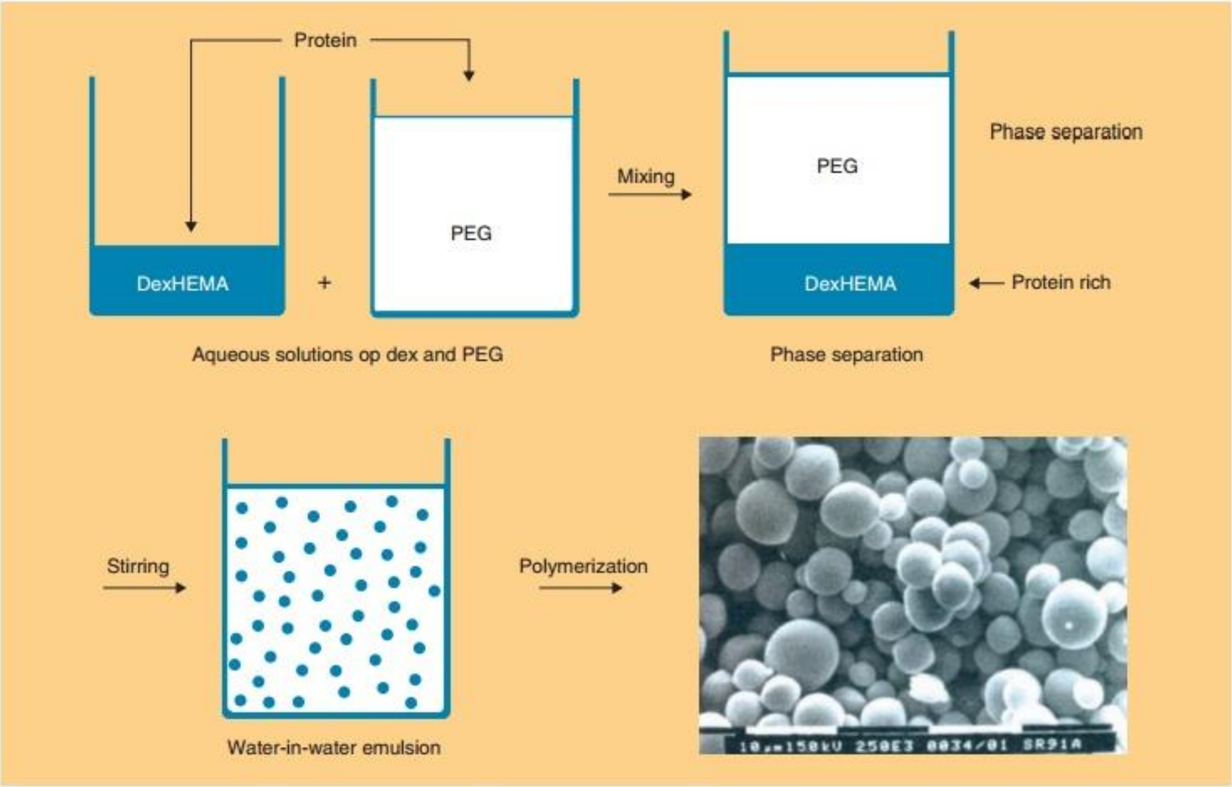


Figure 19 Schematic representation of the microsphere preparation process for the controlled release of therapeutic proteins from dextran (DexHEMA = modified dextran = dextran hydroxyethylmethacrylate) microspheres. No organic solvents are involved and encapsulation efficiency (percentage of therapeutic protein ending up in the microspheres) is routinely > 90%. Polymerization: cross-linking of dextran chains through the HEMA units. *Source*: Adapted from Stenekes, 2000.

used in the preparation protocol. Thus, a direct interaction of the dissolved protein with an organic phase (as seen in many polymeric microsphere preparation schemes) is avoided. This minimizes denaturation of the protein. Figure 20 shows that by selecting the proper cross-linking conditions one has a degree of control over the release kinetics. Release kinetics are mainly dependent on degradation kinetics of the dextran matrix and size of the protein molecule (Stenekes, 2000). Another approach for prolonged and controlled release of therapeutic proteins is to use microspheres based on another biodegradable hydro-gel material. PolyActiveTM is a block-copolymer consisting of polyethylene glycol (PEG) blocks and polybutylene terephthalate blocks (van Dijkhuizen-Radersma et al., 2004). Results of a dose finding study in humans with PolyActiveTM microspheres loaded with interferon-a are shown in Figure 21.

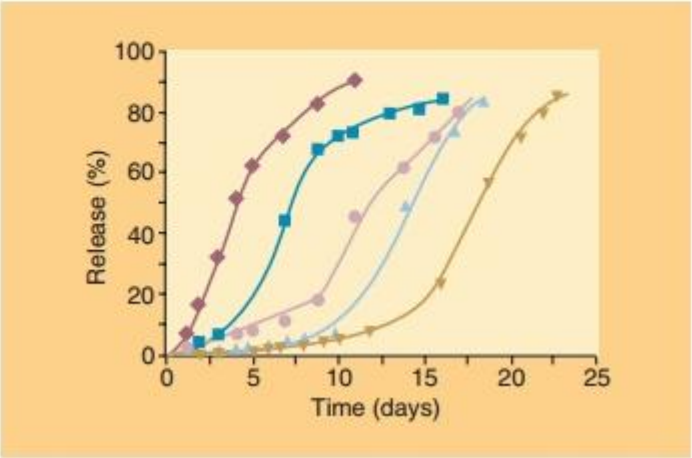


Figure 20 ■ Cumulative release of IgG from degrading DexHEMA microspheres in time in vitro at pH 7, 37°C. Water content of the dextran microspheres upon swelling: about 60%: DS 3 (■) and water content of about 50%: DS 3 (♦), DS 6 (●), DS 8 (A) and DS 11 (▲). The values are the mean of 2 independent measurements that deviated typically less than 5% from each other. *Abbreviation*: DS, degree of cross-linking. *Source*: Adapted from Stenekes, 2000.

Closed Loop Systems: Biosensor-Pump Combinations

If input rate control is desired to stabilize a certain body function, then this function should be monitored. Via an algorithm and connected pump settings, this data should be converted into a drug-input rate. These systems are called closed-loop systems as compared to the open-loop systems discussed above. If there is a known relationship between plasma level and phar-macological effect, these systems contain (Fig. 22):

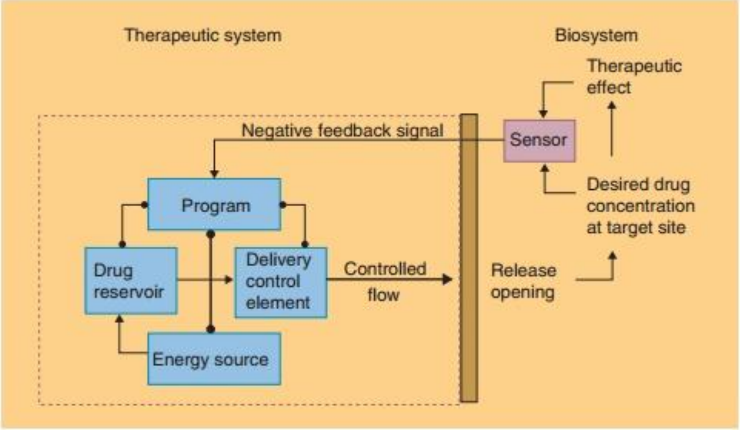


Figure 22 ■ Therapeutic system with closed control loop. (1) a biosensor, measuring the plasma level of the protein, (2) an algorithm, to calculate the required input rate for the delivery system, and (3) a pump system, able to administer the drug at the required rate over prolonged periods of time. *Source*: Adapted from Heilman, 1984

1. a biosensor, measuring the plasma level of the protein;

2. an algorithm, to calculate the required input rate for the delivery system;

3. a pump system, able to administer the drug at the required rate over prolonged periods of time.

The concept of a closed-loop delivery of proteins still has to overcome many conceptual and practical problems. A simple relationship between plasma level and therapeutic effect does not always exist. There are many exceptions known to this rule, for instance, “hit and run” drugs can have long lasting pharmacological effects after only a short exposure time. Also, drug effect–blood level relation-ships may be time dependent, as in the case of down regulation of relevant receptors on prolonged stimu-lation. Finally, if circadian rhythms exist, these will be responsible for variable PK/PD relationships as well.

If the above expressed PK/PD concerns do not apply, as with insulin, technical problems form the

second hurdle in the development of closed-loop systems. It has not been possible yet to design biosensors that work reliably in vivo over prolonged periods of time. Biosensor stability, robustness and absence of histological reactions still pose problems.

Protein Delivery by Self-Regulating Systems

Apart from the design of biosensor-pump combina-tions, two other developments should be mentioned when discussing closed-loop approaches: self-regulat-ing systems and encapsulated secretory cells. At the present time, both concepts are still under develop-ment (Heller, 1993).

In self-regulating systems, drug release is con-trolled by stimuli in the body. By far most of the research is focused on insulin release as a function of local glucose concentrations in order to stabilize blood glucose levels in diabetics. Two approaches for controlled drug release are being followed: (i) competitive desorption and (ii) enzyme-substrate reactions. The competitive desorption approach is schematically depicted in Figure 23.

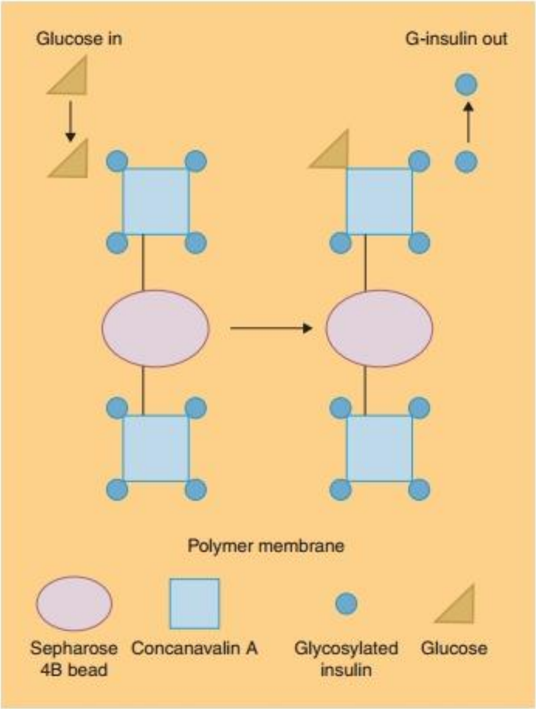


Figure 23 Schematic design of the Con A immobilized bead/G (*glycosylated*)-insulin/membrane self-regulating insulin delivery system. *Source*: Adapted from Kim et al., 1990.

It is based on the competition between glycosy-lated-insulin and glucose for concanavalin (Con A) binding sites. Con A is a plant lectin with a high affinity for certain sugars. Con A attached to sepharose beads and loaded with glycosylated-insulin (a bioactive form of insulin) is implanted in a pouch with a semiperme-able membrane: permeable for insulin and glucose, but impermeable for the sepharose beads carrying the toxic Con A.