Chapter 1
PROPERTIES OF FLUID & PRESSURE MEASUREMENT

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1. Introduction

Fluid mechanics is a branch of engineering science which deals with the behavior of fluids (liquid or gases) at rest as well as in motion.

2. Properties of Fluids

2.1 Density or Mass Density

-Density or mass density of fluid is defined as the ratio of the mass of the fluid to its volume. Mass per unit volume of a fluid is called density.

-It is denoted by the symbol ‘ρ’ (rho).

-The unit of mass density is kg per cubic meter i.e. kg/m3.

-Mathematically,

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

-The value of density of water is 1000 kg/m3, density of Mercury is 13600 kg/m3.

2.2 Specific Weight or Weight Density

-Specific weight or weight density of a fluid is defined as the ratio of weight of a fluid to its volume.

-Thus weight per unit volume of a fluid is called weight density.

-It is denoted by the symbol ‘w’.

-Mathematically,

$$w = \frac{Weight\ of\ fluid}{Volume\ of\ fluid} = \frac{\text{Mass of fluid X Acceleration due to gravity}}{\text{Volume of fluid}} = \frac{\text{m X g}}{V}$$

$$w = \rho\ g$$

-The value of specific weight of water is 9.81 X 1000 = 9810 N/m3 in SI unit.

2.3 Specific Volume

-Specific volume of a fluid is defined as the volume of a fluid occupied by a unit mass of fluid.

-Thus specific volume is volume per unit mass of fluid.

-It is expressed as m3/kg.

-Thus specific volume is the reciprocal of mass density.

- Mathematically,

$$v = \frac{Volume\ of\ fluid}{Mass\ of\ fluid}$$

2.4 Specific Gravity or Relative Density

-Specific gravity is define as the ratio of the density (or weight density) of a fluid to the density (or weight density) of a standard fluid.

-For liquids, standard fluid is taken water and for gases, standard fluid is taken air.

-Specific gravity is also called relative density.

-It is dimensionless quantity and is denoted by symbol S.

- Mathematically,

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

-Specific gravity of Mercury is 13.6 and water is 1.

2.5 Dynamic Viscosity

-Viscosity is defined as the property of fluid which offers resistance to the movement of one layer of fluid over another adjacent layer of fluid.

-When two layers of a fluid distance 'dy' apart, move one over the another at different velocities, say u and u + du as shown in fig., the viscosity together with relative velocity causes a shear stress acting between the fluid layers.

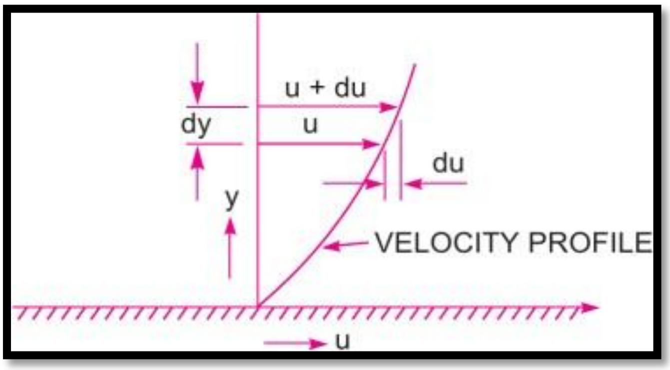


Fig. Velocity variation near a solid boundary

-The top layer causes a shear stress on the adjacent lower layer while the lower layer causes shear stress on the adjacent top layer. This shear stress is proportional to the rate of change of velocity with respect to y.

-It is denoted by symbol τ (Tau).

$$\tau \ \alpha \ \frac{du}{dy}$$

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

-Where μ (called mu) is the constant of proportionality and is known as the co- efficient of Dynamic viscosity or only viscosity. (du/dy) represents the rate of shear strain or rate of shear deformation or velocity gradient.

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

-Viscosity is also defined as the shear stress required producing unit rate of shear strain.

Unit- **SI Unit**- Ns/ m^2 or Pa.s, **CGS Unit**- dyne.s/cm^2 or posie.

1 Poise = 0.1 Ns/ m^2

Newton's Law of Viscosity-

-Its states that the shear stress (τ) on a fluid element layer is directly proportional to the rate of shear strain. The constant of proportionality is called the co-efficient of viscosity.

-Mathematically,

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

Variation of Viscosity with Temperature-

-The viscosity of fluid is due to two contributing factors, namely

1. Cohesion between the fluid molecules
2. Transfer of momentum between the molecules

-In the case of gases the interspace between the molecules is larger and so the intermolecular cohesion is negligible. Hence temperature increases viscosity also increases.

- The intermolecular cohesive force decreases with rise of temperature and hence with the increase in temperature the viscosity of a liquid decreases.

2.6 Kinematic viscosity

It is define as the ratio between the dynamic viscosity and density of fluid.

It is denoted by the Greek symbol υ (called 'nu').

Thus mathematically,

Kinematic viscosity = $\frac{Dynamic\ Viscosity}{Density}$ $\upsilon = \frac{\mu}{\rho}$

***Unit* – SI Unit** – m^2/s, **CGS Unit**- cm^2/s or stoke.

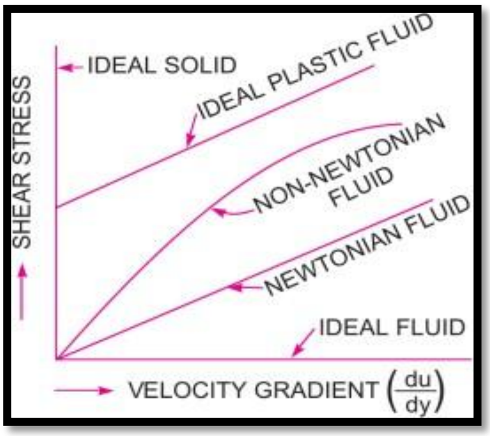
1 stoke = 10^{-4} m^2/s

Classification of fluid

The fluid may be classified into the following five types:

1. Ideal fluid 2. Real fluid 3. Newtonian fluid 4. Non-Newtonian fluid 5. Ideal plastic fluid.

1. Ideal Fluid- A fluid, which is incompressible and is having no viscosity, is known as ideal fluid. Ideal fluid is only an imaginary fluid because all the fluids, which exit, have some viscosity.



2. Real Fluid- A fluid which possesses viscosity is known as real fluid. All the fluids in practice are real fluids.

3. Newtonian fluid- A real fluid, in which the shear stress is directly proportional to the rate of shear strain (or velocity gradient), is known as the Newtonian fluid.

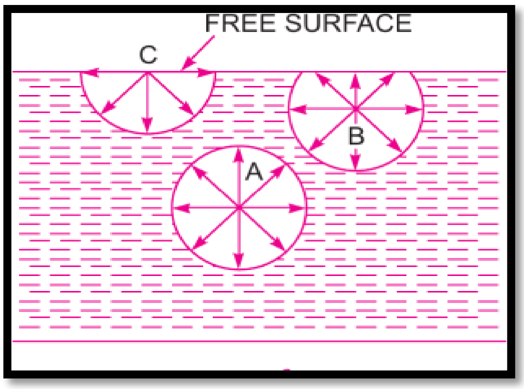
Example: Water, Air, Thin motor oil

4. Non-Newtonian Fluid - A real fluid, in which the shear stress is not proportional to the rate of shear strain (or velocity gradient), is known as the non-Newtonian fluid.

Example: Tooth Paste

5. Ideal-Plastic Fluid- A fluid, in which shear stress is more than the yield value and shear stress is proportional to the rate of shear strain(or velocity gradient), is known as ideal plastic fluid.

2.7 Surface tension



-Surface tension is defined as the tensile force acting on the surface of a liquid in contact with a gas or on the surface between two immiscible liquid such that the contact surface behaves like a membrane under tension.

-It is denoted by Greek letter σ (sigma).

-SI unit of surface tension is N/m, and **MKS unit** is kgf/m.

- Consider three molecules A, B, C of a liquid in a mass of liquid. The molecule A is attracted in all directions equally by the surrounding molecules of the liquid. Thus resultant force acting on molecule A is zero. But molecule B, which is situated near the free surface, is acted upon by upward and downward forces which are unbalanced. Thus a net resultant force on molecule B is acting in the downward direction. The molecule C, Situated on the free surface of liquid, does experience resultant downward force. All the molecules on the free surface of the liquid act like a very thin film under tension of the surface of the liquid act as through it is an elastic membrane under tension.

1. Surface Tension on Liquid Droplet – P =$\frac{4\sigma}{d}$

Where, P= Pressure developed inside droplet.

σ = Surface tension and d = diameter of droplet.

2. Surface Tension on a Hollow Bubble- P =$\frac{8\sigma}{d}$

3. Surface Tension on a Liquid Jet- P =$\frac{2\sigma}{d}$

2.8 Capillarity or Meniscus Effect

-Capillarity is defined as a phenomenon of rise or fall of s liquid surface in a small tube relative to the adjacent general level of liquid when tube is held vertically in the liquid.

-The rise of the liquid surface is known as capillarity rise while the fall of liquid surface is known as capillarity depression or fall.

-It is expressed in terms of cm or mm of liquid.

-Its value depends upon the specific weight of the liquid, diameter of the tube and surface tension of the liquid.

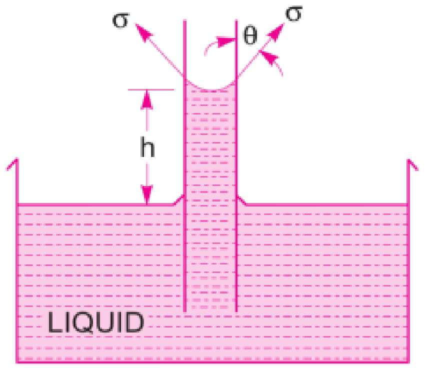


Fig. Capillary Rise

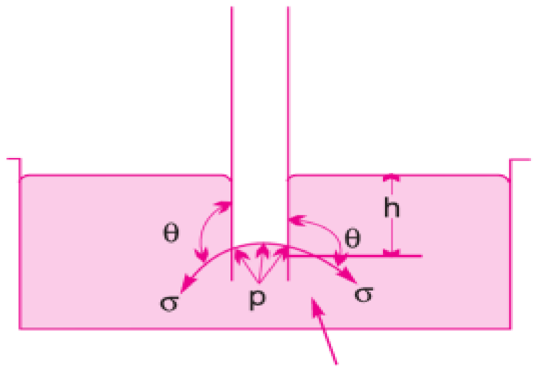


Fig. Capillary fall

- Expression for Capillarity Rise or fall,

$$h = \frac{4\,\sigma\cos\theta}{\rho\, g\, d}$$

-Where, h = Capillarity Rise or fall,

σ = Surface tension

ϴ = Angle of contact between glass and tube.

Value of ϴ for mercury and glass tube is 128^0 and water and glass tube is 0^0.

ρ= Density of fluid

d = Diameter of capillary tube

2.9 Vapor Pressure and Cavitation

-A change from a liquid state to gaseous state is known as vaporization.

-Vaporization (which is depending upon the prevailing pressure and temperature condition) occur because of continuous escaping of the molecules through the free liquid surface.

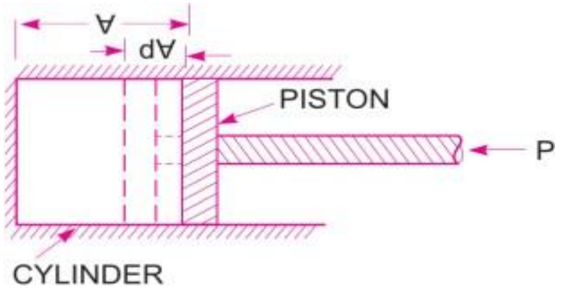
-Consider a liquid (say water) which is confined in a closed vessel. Let the temperature of liquid is 20^0C and pressure is atmospheric. This liquid is vaporizing at 100^0C.

-When vaporization takes place, the molecules escapes from the free surface of the liquid. These vapor molecules get accumulated in the space between the free liquid surface and top of the vessel. These accumulated vapors exert pressure on the liquid surface. This pressure is known as vapor pressure of the liquid or this is the pressure at which the liquid is converted into vapors.

2.10 Compressibility and bulk modulus

-Bulk modulus is defined as the ratio of compressive stress (increase in pressure) to volumetric strain.

-Consider a cylinder fitted with a piston as shown in fig. Let the pressure is increase to p + dp, the volume of gas decrease from V to V - dV.



Then increase in pressure = dp

Decrease in volume = dV

Volumetric strain = - $\frac{dV}{V}$

(-ve sign means the volume decreases with increase of pressure)

Bulk modulus K = $\frac{\text{Increase of pressure}}{\text{Volumetric starin}} = \frac{dp}{dV/V}$

And **Compressibility** is reciprocal of bulk modulus.

Compressibility = $\frac{1}{k}$

Properties of fluid

Sr. No.	Property	Water	Mercury
1	Density (ρ) Kg/m^3	1000	13600
2	Weight Density (w= ρ g) N/m^3	1000 X 9.81=9810	13600 X 9.81 = 133416
3	Specific gravity / Relative density	1	13.6
4	Dynamic Viscosity (μ) Ns/m^2 at 20^0 C	1.002 X 10^{-3}	1.560 X 10^{-3}
5	Kinematic Viscosity (μ) m^2/s at 20^0 C	1.002 X 10^{-6}	0.114 X 10^{-6}
6	Surface Tension (σ) N/m at 20^0 C	0.072	0.485

3. Fluid Pressure & Pressure Measurement

3.1 Fluid pressure

"It is defined as a normal force exerted by a fluid per unit area."

$$\text{Pressure} = \frac{Force}{Area}$$

Unit: 1 Pa = 1 N/m2

1 bar = 105 N/m2

Pressure head

"Pressure exerted by a liquid column can also be expressed as the height of equivalent liquid column called pressure head."

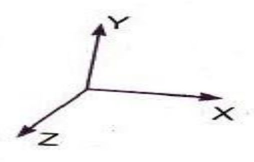
Pressure P = ρ g h

Where, P = Fluid Pressure, ρ = Density of fluid, h = Pressure head

Pressure head = $\frac{P}{\rho\, g}$ Unit, meter of fluid, cm of fluid.

Pascal's Law

"Pressure or Intensity of pressure at a point in a static fluid is equal in all directions."



Px = Py = Pz

3.2 Concept of absolute vacuum, gauge pressure, atmospheric pressure, absolute pressure

1. Atmospheric Pressure

-This pressure exerted by the atmosphere on any surface 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.

-Atmospheric pressure ate Mean Sea Level is 1.01325 bar or 1.01325 X 10^5 N/m^2.

- Atmospheric pressure = 1.01325 bar =1.01325 X 10^5 N/m^2

= 10.33 m of water = 0.76 m of Hg

2. Absolute Pressure

-It is defined as the pressure which is measured with reference to absolute zero pressure.

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

3. Gauge Pressure

-It is defined as the pressure which is measured above the atmospheric pressure.

-It can be measured by pressure measuring instrument in which atmospheric pressure is taken as datum and it marked as zero.

4. Vacuum Pressure (Negative Gauge Pressure)

-It is defined as the pressure below the atmospheric pressure.

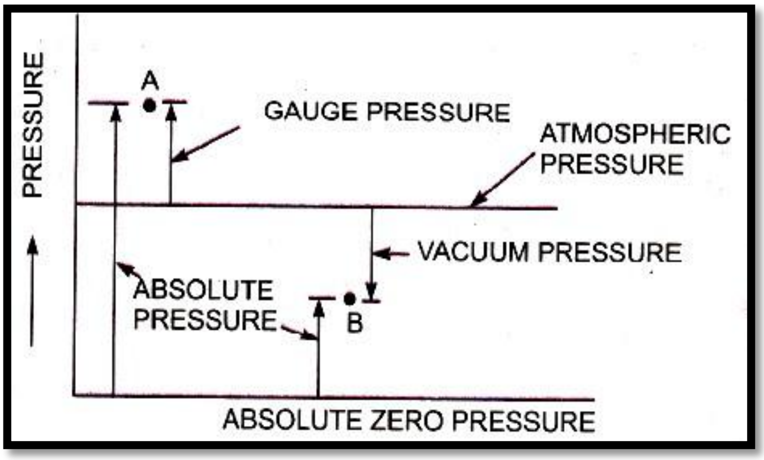


Fig. Relationship between pressures

-Absolute Gauge Pressure = Atmospheric Pressure + Gauge Pressure

-Absolute Vacuum Pressure = Atmospheric Pressure - Vacuum Pressure

3.3 Measurement of Pressure

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

1. Manometers 2. Mechanical gauges

1. Manometers- 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.

Manometers are broadly classified into:

A. Simple Manometers

B. Differential Manometers

2. Mechanical Gauges - 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.

The mechanical pressure gauges are:

A. Diaphragm pressure gauge

B. Bourdon tube pressure gauge

C. Dead weight pressure gauge

D. Below pressure gauge

3.4 Simple Manometers and Differential Manometer

1. Simple Manometers

-Simple monometers consists of glass tube having one of its end connected to a point where pressure is to be measured and other end is open to atmosphere.

-Types of Simple manometers are:

a. Piezometer

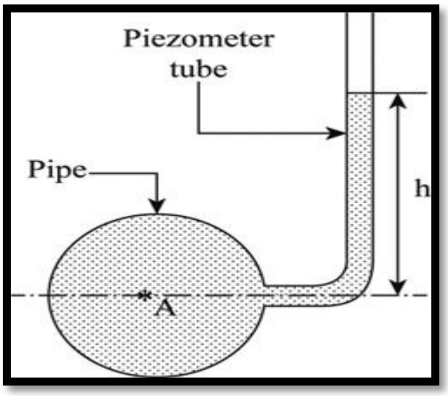
b. U-tube manometer

c. Single column manometer

d. Inclined column manometer

a. Piezometer

-It 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 as shown in Fig. 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.



-If at a point A, the height of liquid say water h in piezometer tube, then pressure at point A is given by ρ g h.

$P_A = \rho g h$

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

Merits

1. Simple in construction

2. Economical

Demerits

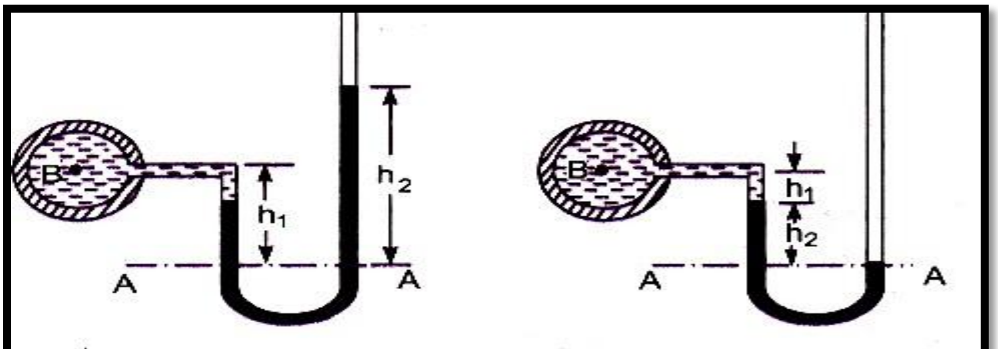
1. Not suitable for high pressure intensity.
2. Pressure of gases cannot be measured.

b. Simple U-tube Manometer

-A U-tube manometer consists of a glass tube bent in U-Shape, one end of which is connected to the point at which pressure is to be measured and the other end is exposed to atmosphere. U-tube consists of a liquid of specific of gravity is greater than the specific gravity of the liquid whose pressure intensity is to be measured.

(A) For Gauge Pressure

Let B is the point at which pressure is to be measured, whose value is p. The datum line is A-A as shown in Fig.



(a) For gauge pressure (b) For vacuum pressure

Let, h_1 = Height of the light liquid above the datum line

h_2 = Height of the heavy liquid above the datum line

ρ_1 is density of light liquid (pipe fluid) and ρ_2 is density of heavy liquid (Monomeric Fluid)

-As the pressure is the same for the horizontal surface. Hence pressure above the horizontal datum line A- A in the left column and in the right column of U-tube manometer should be same.

Hence, Pressure above datum line above A- A in the left column = Pressure above datum line above A-A in the right column

$$P_B + \rho_1 g h_1 = \rho_2 g h_2$$

$$P_B = \rho_2 g h_2 - \rho_1 g h_1$$

(B) For Vacuum Pressure

-For measuring vacuum pressure, the level of the heavy liquid in the manometer will be as shown in Fig.

Hence, Pressure above datum line above A- A in the left column = Pressure above datum line above A-A in the right column

$$P_B + \rho_1 g h_1 + \rho_2 g h_2 = 0$$

$$P_B = -(\rho_2 g h_2 + \rho_1 g h_1)$$

c. Single Column Manometer

-A single column manometer is a modified form of U-tube manometer in which reservoir having large cross sectional area (100 times) as compared to cross sectional area of U – tube connected to it as shown in Fig. 2.7.

-For any change in pressure, change in the level of manometeric liquid in the reservoir is small and change in level of manometric liquid in the U- tube is large. The other limb may be vertical or inclined. Thus there are two type of single column manometer as:

1. Vertical single column manometer
2. Inclined single column manometer

1. Vertical single column manometer-

Fig. shows the vertical single column manometer. Let X-X be the datum line the reservoir and in the right limb of the manometer, when it is not connected to the pipe. When the manometer is connected to the pipe, due to high pressure at A, the heavy liquid in the reservoir will be pushed downwards and will rise in the right limb.

Where, dh= Fall of the heavy liquid in reservoir

h_2 = Rise of heavy liquid in right limb

h_1 = Height of centre of pipe above X -X

P_A = Pressure at A

ρ_1 is density of liquid in pipe and ρ_2 liquid in reservoir.

As the area A is very large compared to a, hence dh is neglected.

$$P_A = \rho_2 g h_2 - \rho_1 g h_1$$

2. Inclined Single Column Manometer

Fig. shows the inclined single column manometer. This manometer is more sensitive. Due to inclination the distance moved by the heavy liquid in the right limb will be more.

Let L = length of heavy liquid moved in right limb form X – X

ϴ = Inclination of right limb with horizontal

h2 = Vertical rise of heavy liquid in right limb from = L Sin ϴ

The pressure at A is, $P_A = \rho_2 g h_2 - \rho_1 g h_1$

$$P_A = \rho_2 g L \sin\theta - \rho_1 g h_1$$

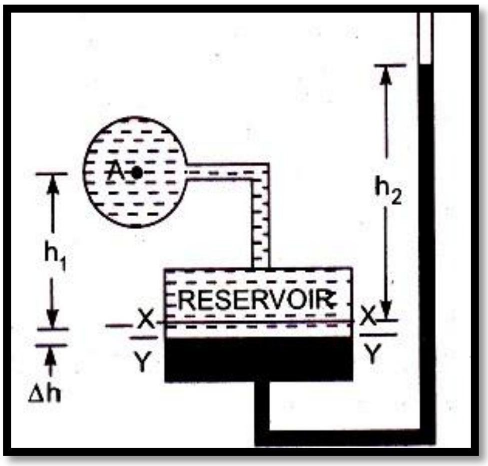


Fig. Vertical single column manometer

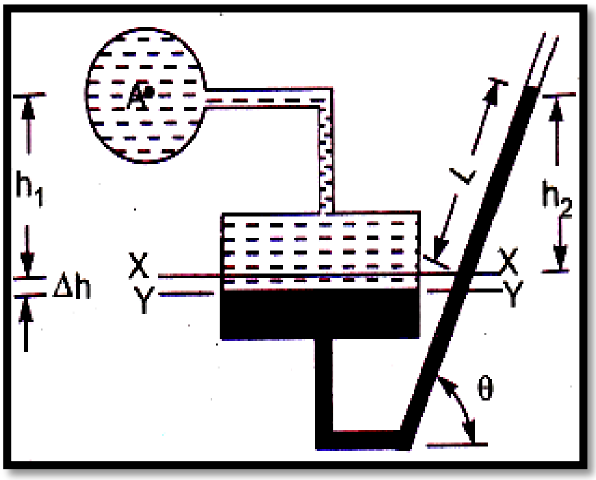


Fig. Inclined single column manometer

2. Differential Manometer

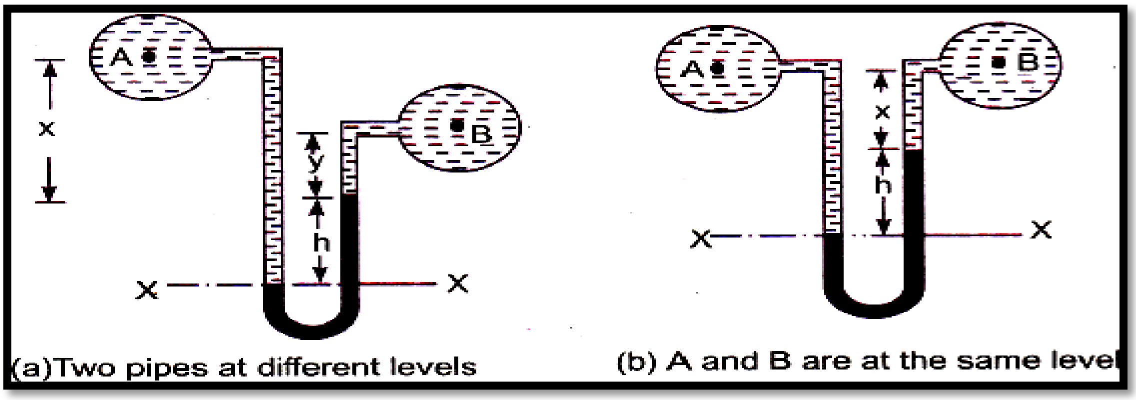
-Differential manometers are used to measure the pressure difference between two points. It is consists of a U-tube, containing heavy liquid, whose two ends are connected to the two points, whose difference of pressure is to be measured.

Types of differential manometers are:

a. U-tube Differential manometers

b. Inverted U-tube differential manometers

a. U-tube Differential manometers



In Fig. (a), the two points A and B are at different level and also contained liquids of different specific gravity. These points are connected to the U-tube manometer. Let the pressure at A and B are P_A and P_B .

Let, h = Difference of mercury level,

y = Distance of the centre of B, from the mercury level in the right limb

x = Distance of the centre of A, from the mercury level in the right limb

ρ_1 Density of liquid at A, ρ_2 Density of liquid at B and ρ_g Density of manometric liquid.

Taking at datum line at X-X,

Pressure above X-X in the left limb = Pressure above X-X in the right limb

$$P_A + \rho_1 g (x + h) = P_B + \rho_2 g y + \rho_g g h$$

$$P_A - P_B = \rho_2 g y + \rho_g g h - \rho_1 g (x + h)$$

In Fig. (b), the two points A and B are at same level and contained liquids of different density.

Taking at datum line at X-X,

Pressure above X-X in the left limb = Pressure above X-X in the right limb

$$P_A + \rho_1 g (x + h) = P_B + \rho_2 g x + \rho_g g h$$

$$P_A - P_B = \rho_2 g x + \rho_g g h - \rho_1 g (x + h)$$

b. Inverted U-Tube Differential Manometers

-It consists of an inverted U-tube having two ends are connected to the pipes at points A and B whose difference of pressure is to be measured as shown in Fig. It is used for measuring the difference of low pressures. Let the pressure at A is more than the pressure at B.

Let, h1= Height of liquid in left limb below the datum line X- X

h2 = Height of liquid in right limb

h = Difference of manometric fluid (Generally Light Liquid used)

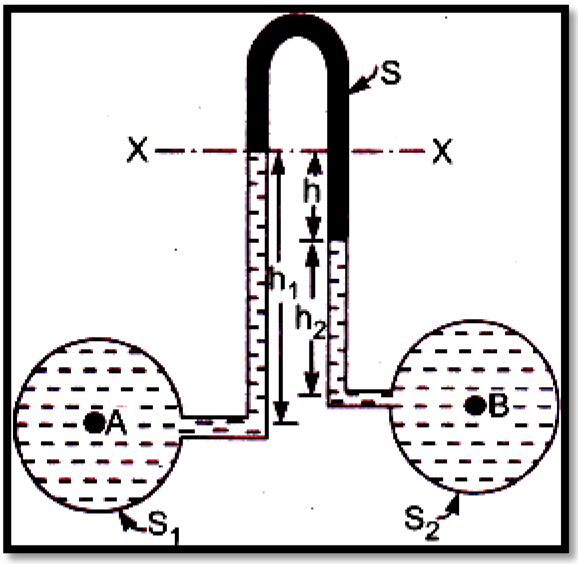
ρ_1 = Density of liquid at A

ρ_2 = Density of liquid at B

ρ_s = Density of light liquid

P_A = Pressure at A

P_B = Pressure at B



Pressure below datum line X-X in the left limb = Pressure below datum line X-X in the right limb

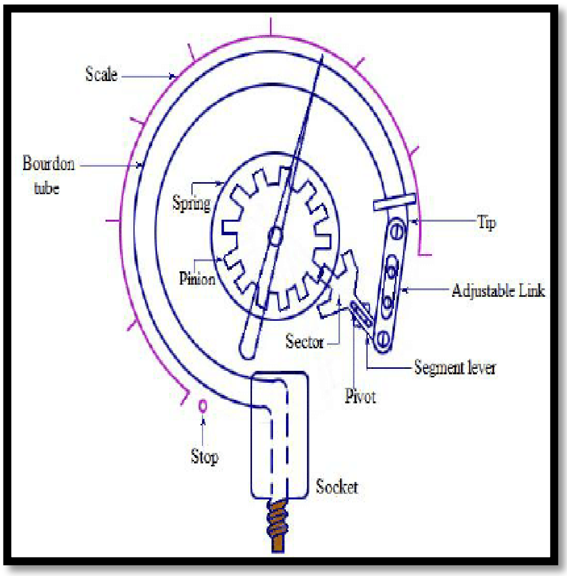
$$P_A - \rho_1 g h_1 = P_B - \rho_2 g h_2 - \rho_S g h$$

$$P_A - P_B = \rho_1 g h_1 - (\rho_2 g h_2 + \rho_S g h)$$

3.5 Bourdon tube pressure gauge

-This gauge is consist of elastic bent in circular arc, fixed at one end and free at other end as shown in Fig. The fixed end is attached at the side of application of pressure and free end attached with the sector through adjustable link. The sector is in mesh with the pinion which is fixed with the pointer on the calibrated scale.

-When the pressure inside the tube is increase, tube will uncoil. So that the pointer gives a reading on the scale due to movement of the pinion through sector and free end of tube.



Tube material: Brass, copper, stainless steel etc.

Advantages: Simple construction, Low cost, high pressure range (up to 700 kPa), Accuracy is good.

Disadvantage: Susceptibility to shock and vibration, spring constant effect is major consideration.

Why mercury is used as Manometric fluid / Desirable property of manometric fluid-

1. It has very high density so Hg column require les height.
2. It does not mix up with the liquids in the pipes.
3. It does not stick to the surface of tube.
4. At room temperature, the vapour pressure is negligible.
5. It does not chemically react with other liquids.

Advantages of Mechanical gauges over manometer

1. It provides correct measurement.
2. Small in size, occupies less space.
3. It can use for large variation in pressure.
4. Pressure can directly read on the scale and does not require any conversion.

Liquid use for manometer

1. Mercury 2. Water 3. Alcohol 4. Kerosene 5. Oil

4.1 Total Pressure and Centre of Pressure

Total pressure is defined as the force exerted by a static fluid on a surface either plane or curved when the fluid comes in contact with the surface and this force always normal to the surface.

Centre of pressure is defined as the point of application of the total pressure on the surface.

The submerged surfaces may be:

1. Plane surface submerged in static fluid
    a. Vertical plane surface

b. Horizontal plane surface

c. Inclined plane surface

2. Curved surface submerged in static fluid

Sr. No.	Type of Submerged Surface	Diagram	Total Pressure (F)	Centre of pressure (h)
1	Vertical plane surface		F= ρ g A x	$h = \frac{IG\ Sin^2\theta}{A\ x} + x$ Where $\theta = 90^0$ $Sin90^0 = 1$ Hence, $\mathbf{h = \frac{IG}{A\ x} + x}$
2	Horizontal plane surface		F= ρ g A x	$h = \frac{IG\ Sin^2\theta}{A\ x} + x$ Where $\theta = 0^0$ $Sin0^0 = 0$ Hence, **h = x**
3	Inclined plane surface		F= ρ g A x	Where θ = Between 0^0 to 90^0 $\mathbf{h = \frac{IG\ Sin^2\theta}{A\ x} + x}$

Where, F = Total Pressure, N

h = Centre of pressure, m

ρ = Density of fluid, kg/m^3

A = Area of given surface, m^2

I_G = MI about centroidal axis X-X, m^4

θ = Inclination angle of surface

x = Distance of CG of given surface from free surface, m

h = Distance of Centre of pressure from free surface, m