LECTURE NOTES

SUB: FLUID MECHANICS

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FLUID FLOW

Chemical engineers are concerned with transportation of fluids, both liquids and gases, from one location to another through pipes or ducts. This activity requires determination of the pressure drop through the system and consequently of the power required for pumping, selection of a suitable type of pumping device and measurement of the flow rates. In this chapter, we will deal with the types of flow patterns, determination of the pressure drop during fluid flow, methods of measuring flow, etc.
The branch of engineering science which deals with the behaviour of fluids at rest or in motion is called FLUID MECHANICS. The study of water is referred to as Hydraulics.

Fluid mechanics is classified as :

1. Fluid Statics and Fluid Dynamics.
2. Fluid statics deals with the study of fluids at rest which involves the study of pressure exerted by a fluid at rest and the variation of fluid pressure throughout the fluid.
   Fluid dynamics deals with the study of fluids in motion relative to stationary solid walls or boundaries.
   DEFINITIONS OF A FLUID

• A fluid is a substance which is capable of flowing if allowed to do so.
• A fluid is a substance that has no definite shape of its own, but conforms to the shape of the containing vessel.
• A fluid is a substance which undergoes continuous deformation when subjected to a shearing force/shear force.

Since liquids and gases / vapours possess the above cited characteristics, they are referred to as fluids.

Ideal Fluid :

• It is a fluid which does not offer resistance to flow / deformation / change in shape, i.e., it has no viscosity. It is frictionless and incompressible. However, an ideal fluid does not exist in nature and therefore, it is only an imaginary fluid.

• An ideal fluid is the one which offers no resistance to flow/change in shape.

Real Fluid :

It is a fluid which offers resistance when it is set in motion. All naturally occurring fluids
are real fluids.

CLASSIFICATION OF FLUIDS

1. Based upon the behaviour of fluids under the action of externally applied pressure
and temperature, the fluids are classified as :

(a) Compressible Fluids

(b) Incompressible Fluids.

2. Based upon the behaviour of fluids under the action of shear stress, the fluids are
classified as :

(a) Newtonian Fluids

(b) Non-Newtonian Fluids.

A fluid possesses a definite density at a given temperature and pressure. Although the
density of fluid depends on temperature and pressure, the variation of density with changes in
these variables may be large or small.

Compressible Fluid :

• If the density of a fluid is affected appreciably by changes in temperature and
pressure, the fluid is said to be compressible.

If the density of a fluid is sensitive to changes in temperature and pressure, the fluid
is said to be compressible.

Incompressible Fluid :

• If the density of a fluid is not appreciably affected by moderate changes in
temperature and pressure, the fluid is said to be incompressible.

If the density of a fluid is almost insensitive to moderate changes in temperature and
pressure the fluid is said to be incompressible.

Thus, liquids are considered to be incompressible fluids, whereas gases are considered to
be compressible fluids.

Definitions of Newtonian and Non-Newtonian fluids are covered later in this chapter
under the title viscosity.

PROPERTIES OF FLUIDS

The properties of fluids are

(i) Mass density (specific mass) or simply density (ρ).

(ii) Weight density (specific weight) (w).

(iii) Vapour pressure.

(iv) Specific gravity.

(v) Viscosity.

(vi) Surface tension and capillarity.

(vii) Compressibility and elasticity.

(viii) Thermal conductivity.

(ix) Specific volume.

Density :
Density (ρ) or mass density of a fluid is the mass of the fluid per unit volume. In the SI system, it is expressed in kg/m3
. The density of pure water at 277 K (4 oC) is taken as 1000 kg/m3
.
Weight Density :
Weight density of a fluid is the weight of the fluid per unit volume. In the SI system, it is expressed in N/m3
. Specific weight or weight density of pure water at 277 K (4 oC) is taken as 9810 N/m3
.
The relation between mass density and weight density is
$w = \rho g$
where g is the acceleration due to gravity (9.81 m/s2).

Specific Volume :

Specific volume of a fluid is the volume of the fluid per unit mass. In the SI system, it is expressed in m3/kg.

Specific Gravity :

The specific gravity of a fluid is the ratio of the density of the fluid to the density of a standard fluid. For liquids, water at 277 K (4 oC) is considered/chosen as a standard fluid and for gases, air at NTP (0°C and 760 torr) is considered as a standard fluid.

Vapour Pressure :

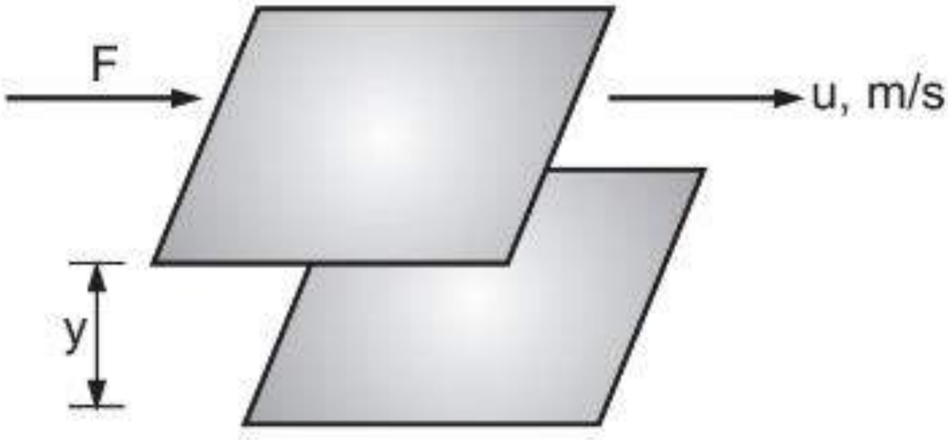
The vapour pressure of a pure liquid is defined as the absolute pressure at which the liquid and its vapour are in equilibrium at a given temperature or The pressure exerted by the vapour (on the surface of a liquid) at equilibrium conditions is called as the vapour
pressure of the liquid at a given temperature. Pure air free water exerts a vapour pressure of
101.325 kPa (760 torr) at 373.15 K (100 oC).

Surface Tension :

The property of liquid surface film to exert tension is called as the surface tension. It is the force required to maintain a unit length of film in equilibrium. It is denoted by the symbol σ (Greek sigma) and its SI unit is N/m.

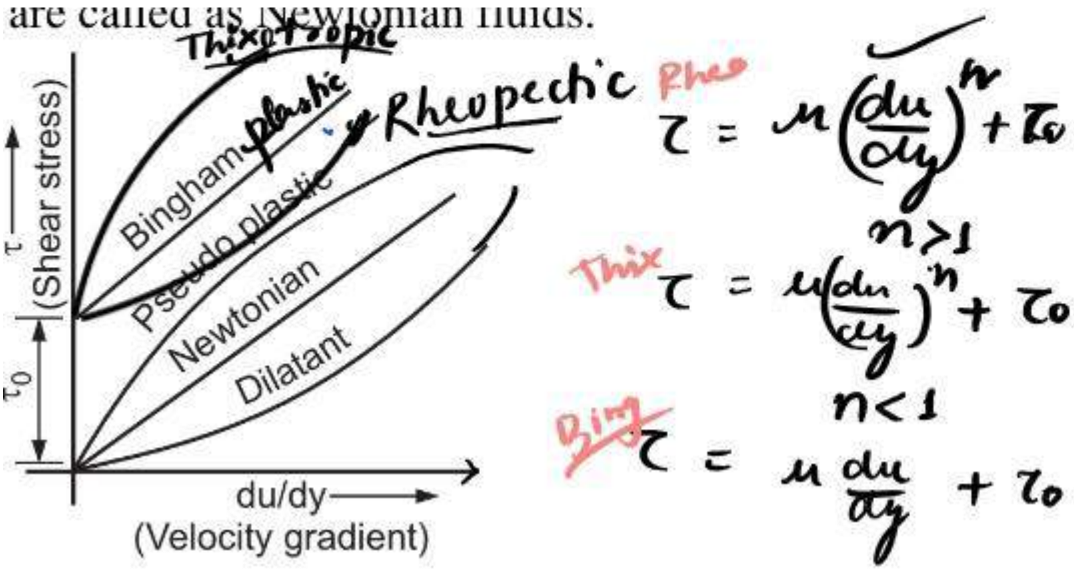
Viscosity :

• A fluid undergoes continuous deformation when subjected to a shear stress. The
resistance offered by a fluid to its continuous deformation (when subjected to a shear stress/force) is called viscosity
• The viscosity of a fluid at a given temperature is a measure of its resistance to flow.
• The viscosity of a fluid (gas or liquid) is practically independent of the pressure for the
range that is normally encountered in practice. However, it varies with temperature. For
gases, viscosity increases with an increase in temperature, while for liquids it decreases
with an increase in temperature.



NEWTONIAN AND NON-NEWTONIAN FLUIDS

For most commonly known fluids, a plot of τ v/s du/dy results in a straight line passing
through the origin and such fluids are called as Newtonian fluids.



Fluids that obey Newton's law of viscosity, i.e., the fluids for which the ratio of the shear stress to the rate of shear or shear rate is constant, are called as Newtonian fluids. This is true for all gases and for most pure liquids. Examples of Newtonian Fluids : All gases, air, liquids, such as kerosene, alcohol, glycerine, benzene, hexane ether etc., solutions of inorganic salts and of sugar in water.

Fluids for which the ratio of the shear stress to the shear rate is not constant but is considered as a function of rate of shear, i.e., fluids which do not follow Newton's law of viscosity are called as non-Newtonian fluids. Generally, liquids particularly those containing

a second phase in suspension (solutions of finely divided solids and liquid solutions of large molecular weight materials) are non-Newtonian in behaviour.

Examples of Non-Newtonian Fluids : Tooth pastes, paints,

gels, jellies, slurries and polymer solutions.
A Newtonian fluid is one that follows Newton's law of viscosity. If viscosity is independent of rate of shear or shear rate, the fluid is said to be Newtonian and if viscosity varies with shear rate, the fluid is said to be non-Newtonian.

There are three common types of non-Newtonian fluids.
(a) Bingham Fluids or Bingham Plastics : These fluids resist a small shear stress
indefinitely but flow linearly under the action of larger shear stress, i.e., these fluids do not
deform, i.e., flow unless a threshold shear stress value (τ_0) is not exceeded.
These fluids can be represented by
$\tau = \tau_0$, $du/dy = 0$, $\tau > \tau_0$, $\tau = \tau_0 + \eta . du/dy$
where τ_0 is the yield stress / threshold shear stress and η is commonly called as the
coefficient of rigidity.
Examples : Tooth paste, jellies, paints, sewage sludge and some slurries.
(b) Pseudoplastic Fluids : The viscosity of these fluids decreases with increase in
velocity gradient, i.e., shear rate.
Examples : Blood, solution of high molecular weight polymers, paper pulp, muds, most
slurries and rubber latex.

(c) Dilatent Fluids : The viscosity of these fluids increases with an increase in
velocity gradient.
Examples : Suspensions of starch in water, pulp in water, and sand filled emulsions.
The experimental curves for pseudoplastic as well as dilatent fluids can be represented
by a power law, which is also called the Ostwald-de-Waele equation.
$\tau = k (du/dy)^n$
where k and n are arbitrary constants.
Newtonian fluids : $n = 1, k = \mu$
Pseudoplastic fluids : $n < 1$
Dilatent fluids : $n > 1$
Pseudoplastics are said to be shear-rate-thinning and dilatent fluids are said to be shearrate-thickening.

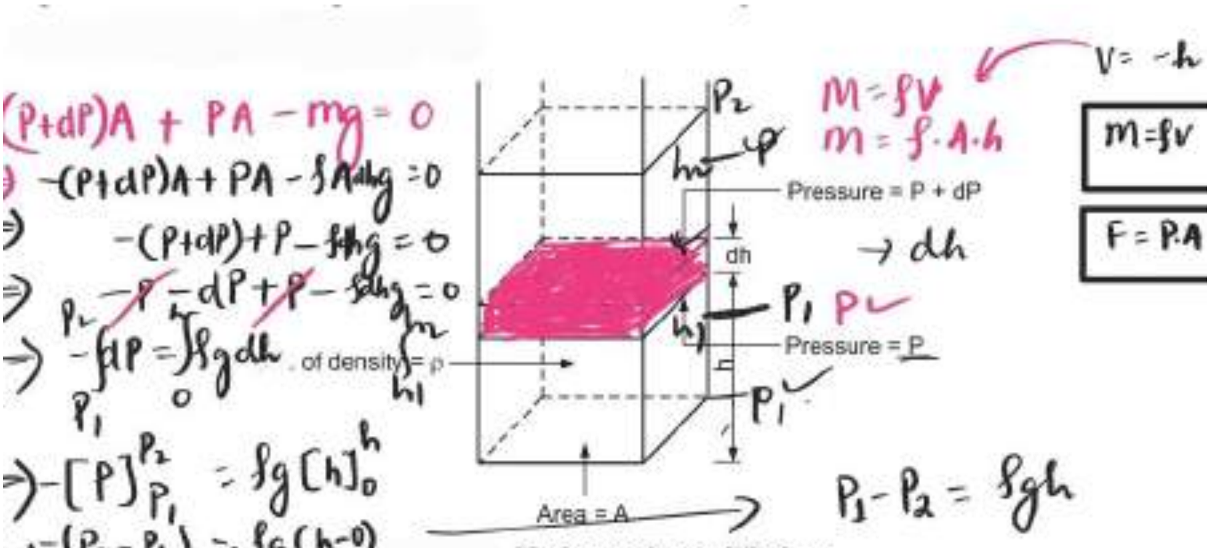
PRESSURE

The basic property of a static fluid is pressure. When a certain mass of fluid is contained in a vessel, it exerts forces at all points on the surfaces of the vessel in contact. The forces so exerted always act in the direction normal to the surface in contact. The normal force exerted by a fluid per unit area of the surface is called as the fluid pressure. If F is the force acting on the area A, then the pressure or intensity of pressure is given by
$P = F/A$
In a static fluid, the pressure at any given point is the same in all the directions. If the pressure at a given point was not the

same in all directions, there would be non-equilibrium and the resultant force should exist. As the fluid is in static equilibrium, there is no net unbalanced force at any point. Hence, the pressure in all directions is the same and thus independent of direction.

Pressure Head :
The vertical height or the free surface above any point in a liquid at rest is called as the
pressure head. The pressure head may be expressed as
$h = P/\rho g$,
$(N/m^2)/(kg/m^3 \times m/s^2)$
where P is in N/m^2, ρ in kg/m^3 and g in m/s^2
The units of h are m of liquid.
As the pressure at any point in a static liquid depends upon the height of the free surface
above the point, it is convenient to express a fluid pressure in terms of pressure head. The
pressure head is then expressed in terms of meters of a liquid column.

HYDROSTATIC EQUILIBRIUM



Hydrostatic equilibrium

Consider the vertical column of a single static fluid shown in Fig. 7.3. In this column of
the static fluid, the pressure at any point is the same in all directions. The pressure is also
constant at any horizontal plane parallel to the earth's surface, but it varies with the height of
the column (it changes along the height of the column). Let the cross-sectional area of the
column be A m2
and the density of the fluid be ρ kg/m3. Let 'P', N/m2
be the pressure at a
height 'h' (meter) from the base of the column. At a height h + dh from the base of the
common (another horizontal plane), let the pressure be P + dP, N/m2
. The forces acting on a

small element of the fluid of a thickness dh between these two planes are :

(i) Force (P + dP)A is acting downwards. … taken as +ve.

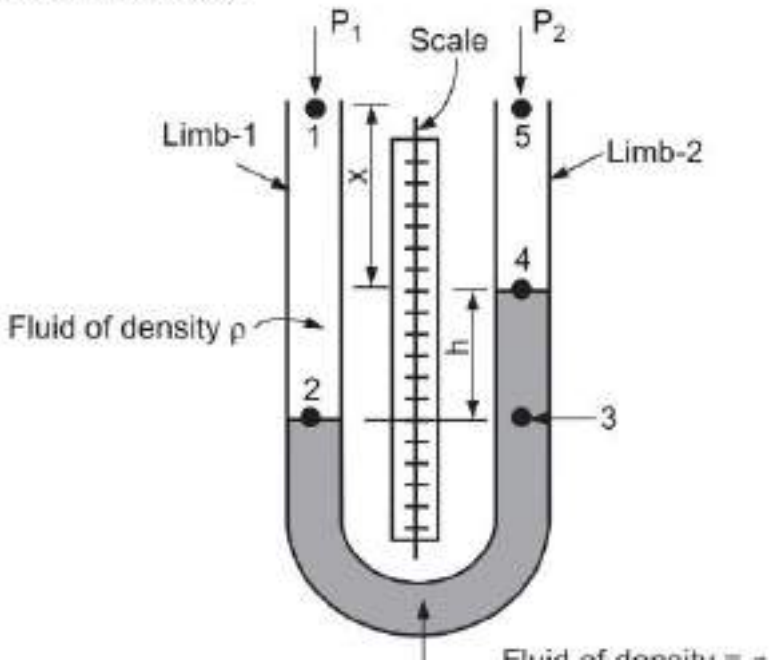
(ii) Force due to gravity is acting downwards and is equal to mass times acceleration
due to gravity : mg = V ρ g = A.dh.ρ.g … taken as –ve.
where m is the mass of the fluid contained within the two planes.

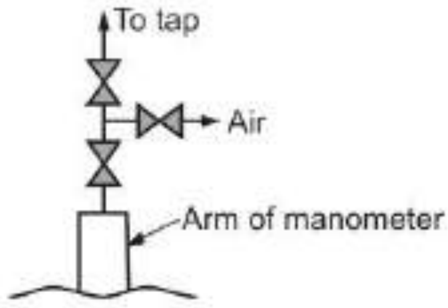
(iii) Force PA is acting upwards … taken as –ve.

MANOMETERS

Manometers are the simplest pressure measuring devices and are used for measuring
low pressure or pressure differences.

U-tube Manometer





U-tube manometer is the simplest form of manometer. It consists of a small
diameter U-shaped tube of glass. The tube is clamped on a wooden board. Between
the two arms or legs of the manometer, a scale is fixed on the same board. The Utube
is partially filled with a manometric fluid which is heavier than the process
fluid. The two limbs of the manometer are connected by a tubing to the taps
between which the pressure drop is to be measured. Air vent valves are provided at
the end of each arm for the removal of trapped air in the arm. The manometric fluid
is immiscible with the process fluid. The common manometric fluid is mercury.

U-tube manometer is filled with a given manometric fluid (fluid M) upto a certain height. The remaining portion of the U-tube is filled with the process fluid/flowing fluid of density ρ including the tubings. One limb of the manometer is connected to
the upstream tap in a pipeline and the other limb is connected to the downstream tap

in the pipeline between which the pressure difference $P_1 - P_2$ is required to be measured. Air, if any, is there in the line connecting taps and manometer is removed. At steady state, for a given flow rate, the reading of the manometer, i.e., the difference in the level of the manometric fluid in the two arms is measured and it gives the value of pressure difference in terms of manometric fluid across the taps (stations). It may then be converted in terms of m of flowing fluid.

Consider a U-tube manometer as shown in Fig. 7.4 connected in a pipeline. Let pressure P_1be exerted in one limb of the manometer and pressure P_2be exerted in
the another limb of the manometer. If P_1 is greater than P_2
, the interface between the
two liquids in the limb 1 will be depressed by a distance 'h' (say) below that in the limb 2. To arrive at a relationship between the pressure difference ($P_1 - P_2$) and the difference in the level in the two limbs of the manometer in terms of manometric
fluid (h), pressures at points 1, 2, 3, 4 and 5 are considered.
Pressure at point 1 = P_1
Pressure at point 2 = $P_1 + (x + h)\,\rho.g$
Pressure at point 3 = Pressure at point 2 = $P_1 + (x + h)\,\rho.g$
(as the points 2 and 3 are at the same horizontal plane).
Pressure at point 4 = $P_1 + (x + h)\,\rho.g - h\,.\,\rho_M.g$
Pressure at point 5 = $P_1 + (x + h)\,\rho.g - h\,.\,\rho_M.g - x.\rho.g$
Pressure at point 5 = P_2
Then, we can write,
$P_2 = P_1 + (x + h)\,.\,\rho.g - h\,\rho_M.g - x\,.\,\rho.g$

$P_1 – P_2 = \Delta P = h(\rho_M – \rho)g$

where ΔP is the pressure difference and 'h' is the difference in levels in the two arms of the manometer in terms of manometric fluid. If the flowing fluid is a gas, density ρ of the gas will normally be small compared with the density of the manometric fluid, ρ_M and thus Equation (7.27) reduces to

$\Delta P = P_1 – P_2 = h . \rho_M.g$

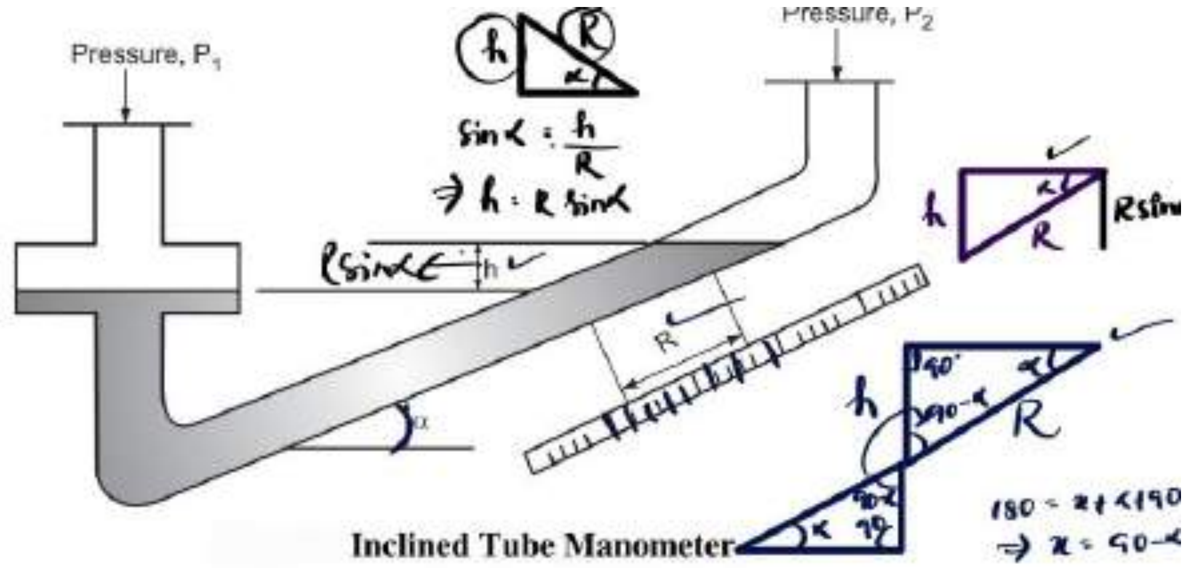
Inclined Manometer

• Inclined manometers are used for measuring small pressure differences.

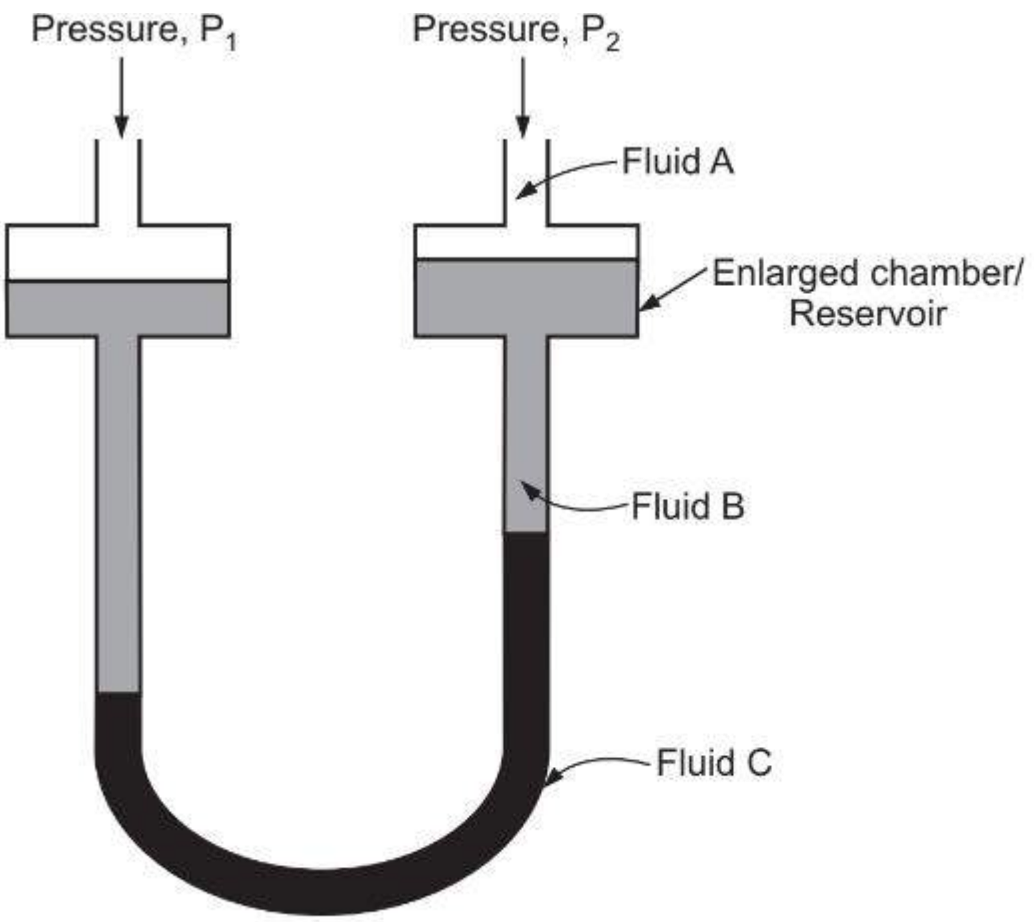
• This type of manometer is shown below. One arm of the manometer is inclined

at an angle of 5 to 10o with the horizontal so as to obtain a larger reading. (e.g., movement of 7 to 10 mm is obtained for a pressure change corresponding to 1 mm head of liquid.)

In the vertical leg of this manometer an enlargement is provided so that the movement of the meniscus in this enlargement is negligible within the operating range of the manometer. If the reading R(in m) is taken as shown, i.e., distance travelled by the meniscus of the manometric fluid along the tube, then



Differential Manometer / Two Liquid Manometer / Multiplying Gauge



Differential Manometer

Differential manometer is used for the measurement of very small pressure differences or for the measurement of pressure differences with a very high
precision. It may often be used for gases.
It consists of a U-tube made of glass. The ends of the tube are connected to two enlarged transparent chambers / reservoirs. The reservoirs at the ends of each arm are of a

large cross-section than that of the tube. The manometer contains two manometric liquids of different densities and these are immiscible with each other and with the fluid for which the pressure difference is to be measured. This type of manometer is shown ii the above figure. The densities of the manometric fluids are nearly equal to have a high sensitivity of the manometer. Liquids which give sharp interfaces are commonly used, e.g.,

paraffin oil and industrial alcohol, etc