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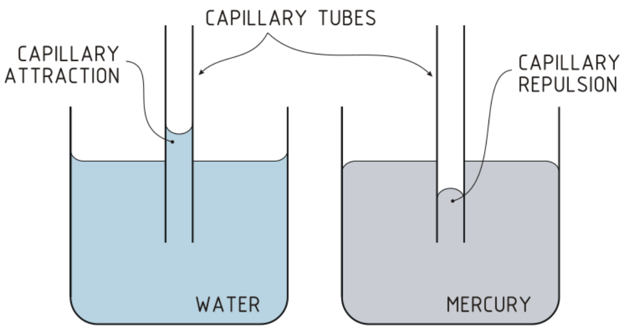
PROPERTIES OF FLUIDS



Course Contents

1.1 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. Thus this branch of science deals with the static, kinematics and dynamics aspects of fluids. The study of fluids at rest is called fluid statics. The study of fluids in motion, where pressure force are not considered, is called fluid kinematics and if the pressure forces are also considered for the fluid in motion, that branch of science is called fluid dynamics.

1.2 Properties of Fluids

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’.
- The unit of mass density is kg/m3.
- Mathematically,

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

- The value of density of water is 1000 kg/m^3.

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,

$$w = \frac{\text{Weight of fluid}}{\text{Volume of fluid}}$$

$$= \frac{(\text{Mass of fluid}) \times (\text{Acceleration due to gravity})}{\text{Volume of fluid}}$$

$$= \frac{(\text{Mass of fluid}) \times g}{\text{Volume of fluid}}$$

$$= \rho \times g$$

$$\boxed{w = \rho g}$$

- The value of specific weight of water is 9.81 X 1000 N/m^3 in SI unit.

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 m^3/kg.

- Mathematically,

$$\text{Specific volume} = \frac{\text{Volume of fluid}}{\text{Mass of fluid}}$$

$$= \frac{1}{\frac{\text{Mass of fluid}}{\text{Volume of fluid}}}$$

$$= \frac{1}{\rho}$$

- Thus specific volume is the reciprocal of mass density.

4) Specific gravity

- 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,

$$S(\text{for liquid}) = \frac{\text{Weight density(Density) of liquid}}{\text{Weight density(Density) of water}}$$

$$S(\text{for gases}) = \frac{\text{Weight density(Density) of gas}}{\text{Weight density(Density) of air}}$$

- Specific gravity of mercury is 13.6.

1.3 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.

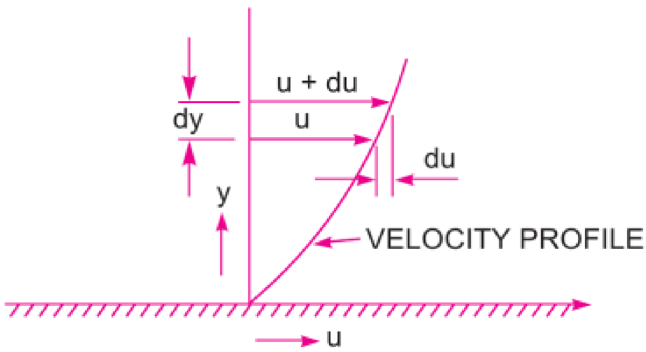


Figure 1 Velocity variation near a solid boundary

- 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).

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

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

- Where μ is the constant of proportionality and is known as the co-efficient of dynamic viscosity or only viscosity.
- Where $\frac{du}{dy}$ represents the velocity gradient.
- SI unit of viscosity is Ns/m^2.

1.3.1 Kinematic viscosity

- It is define as the ratio between the dynamic viscosity and density of fluid.
- It is denoted by the Greek symbol ν(called 'nu').
- Thus mathematically,

$$\upsilon = \frac{\text{Viscosity}}{\text{Density}}$$

$$\boxed{\therefore \upsilon = \frac{\mu}{\rho}}$$

- SI unit of kinematic viscosity is m^2/sec.

1.3.2 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,

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

1.3.3 Variation of Viscosity with Temperature

- The viscosity of fluid is due to two contributing factors,
    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. However in the case of liquids the molecules are very close to each other and accordingly a large cohesion exists. Hence in liquids, the viscosity is mainly due to molecular momentum transfer.

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

$$\mu = \mu_0 \left(\frac{1}{1 + \alpha t + \beta t^2} \right)$$

Where μ = viscosity of the liquid at t°C in poise

μ_0 = viscosity of the liquid at 0°C in poise

α and β are constant characteristics of the liquid

- For water, μ_0 = 1.79×10^{-3} poise α = 0.03368 β = 0.000221
- *For gas*
- In this case of gases, viscosity depends mainly on transfer of molecular momentum in a direction at right angles to the direction of motion. As the temperature increases, the molecular agitation increases i.e. there will be large momentum transfer and hence the viscosity increases.

$$\mu = \mu_0 + \alpha t - \beta t^2$$

- For air, μ_0 = 0.000017, α = 0.000000056, $\beta = 0.1189 \times 10^{-9}$

1.3.4 Types of fluids

- The fluid may be classified into the following five types:
  a) Ideal fluid
  b) Real fluid
  c) Newtonian fluid
  d) Non-Newtonian fluid
  e) Ideal plastic fluid

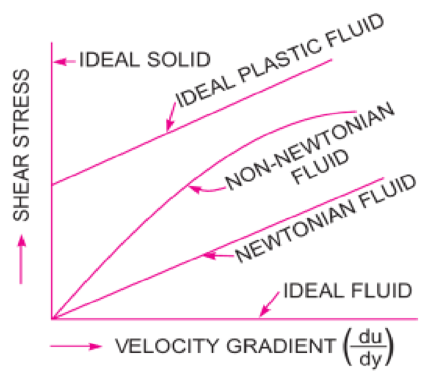


Figure 2 Types of fluid

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.

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.

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.

1.4 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.

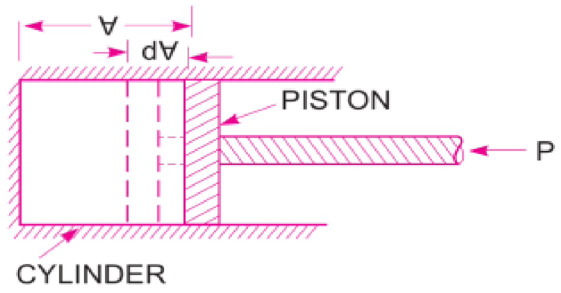


Figure 3 Piston cylinder assembly

$$\text{Then increase in pressure} = dp \ \text{kgf}/\text{m}^2$$

$$\text{Decrease in volume} = dV \ \text{m}^3$$

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

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

$$= \frac{dp}{-\frac{dV}{V}}$$

$$= \frac{-dp}{dV}V$$

$$\text{Compressibility} = \frac{1}{K}$$

1.5 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.

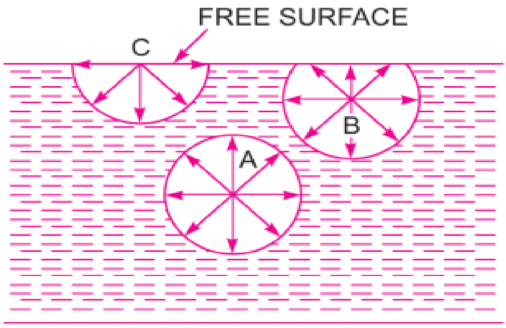


Figure 4 Surface tension

- 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

- Consider a small spherical droplet of a liquid of radius 'r'. On the entire surface of the droplet, the tensile force due to surface tension will be acting.
- Let σ = Surface tension of the liquid
  p = Pressure intensity inside the droplet (in excess of the outside pressure)
  d = Dia. of droplet

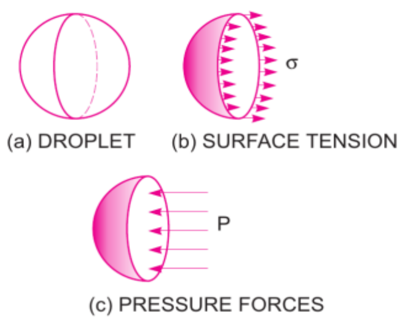


Figure 5 Force on droplet

- Let droplet is cut into two halves.
- The forces acing on one half (say left half) will be....
  a) Tensile force due to surface tension acting around the circumference of the cut portion as shown in fig and is equal to

$$= \sigma \times \text{Circumference}$$
$$= \sigma \times \pi d$$

  b) Pressure force on the area

$$= p \times \frac{\pi}{4} d^2$$

- These two forces will be equal and opposite under equilibrium condition i.e.,

$$p \times \frac{\pi}{4} d^2 = \sigma \times \pi d$$
$$\therefore p = \frac{\sigma \times \pi d}{\frac{\pi}{4} d^2}$$
$$\boxed{\therefore p = \frac{4\sigma}{d}}$$

- Equation shows that with increase of diameter of the droplet, pressure intensity inside the droplet decreases.

2) *Surface Tension on a Hollow Bubble*

- A hollow bubble like a soap bubble in air has two surfaces in contact with air, one inside and other outside.
- Thus two surfaces are subjected to surface tension.

$$p \times \frac{\pi}{4} d^2 = 2(\sigma \times \pi d)$$
$$\therefore p = \frac{2\sigma \times \pi d}{\frac{\pi}{4} d^2}$$
$$\boxed{\therefore p = \frac{8\sigma}{d}}$$

3) *Surface Tension on a Liquid Jet*

- Consider a liquid jet of diameter 'd' and length 'L' as shown in fig.
- Let σ = Surface tension of the liquid
  p = Pressure intensity inside the liquid jet above the outside pressure
- The equilibrium of the semi jet, we have

$$\text{Force due to pressure} = p \times \text{area of semi jet}$$
$$= p \times L \times d$$
$$\text{Force due to surface tension} = \sigma \times 2L$$

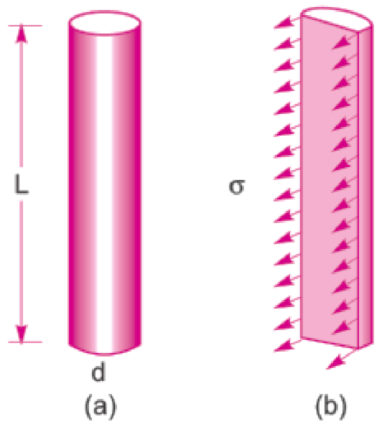


Figure 6 Forces on liquid jet

- Equating the forces we have

$$\therefore p \times L \times d = \sigma \times 2L$$

$$\boxed{\therefore p = \frac{2\sigma}{d}}$$

1.6 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.

Expression for Capillarity Rise

- Consider a glass tube of small diameter 'd' opened at the both ends and is inserted in a liquid, say water. The liquid will rise in the tube above the level of liquid.
- Let h=height of liquid in the tube.

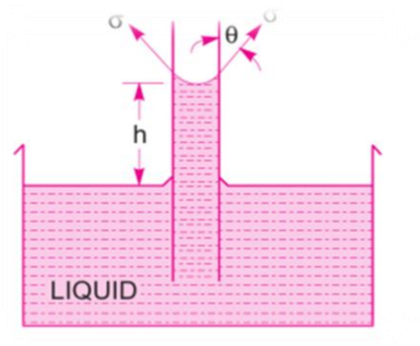


Figure 7 Capillarity rise

– Under a state of equilibrium, weight of liquid of height h is balanced by the force at the surface of the liquid in the tube. But the force at the surface of the liquid in the tube is due to the surface tension.

– Let σ = Surface tension of liquid

θ = Angle of contact between liquid and glass tube.

$$\text{Weight of liquid of height h in the tube} = (\text{Area of tube} \times h) \times \rho \times g$$

$$= \frac{\pi}{4} d^2 \times h \times \rho \times g \qquad \cdots\cdots\cdots(1)$$

where ρ = density of liquid

$$\text{Vertical component of the surface tensile force} = (\sigma \times \text{Circumference}) \times \cos\theta$$

$$= \sigma \times \pi d \times \cos\theta \qquad \cdots\cdots\cdots(2)$$

For equilibrium, equating (1) and (2)

$$\frac{\pi}{4} d^2 \times h \times \rho \times g = \sigma \times \pi d \times \cos\theta$$

$$\therefore h = \frac{\sigma \times \pi d \times \cos\theta}{\frac{\pi}{4} d^2 \times \rho \times g}$$

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

– The value of θ between water and clean glass tube is approximately equal to zero and hence $\cos\theta$ is equal to unity.

– Then rise of water is given by

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

Expression for Capillarity Fall

– If the glass tube is dipped in mercury, the level of mercury in the tube will be lower than general level of the outside liquid as shown in fig.

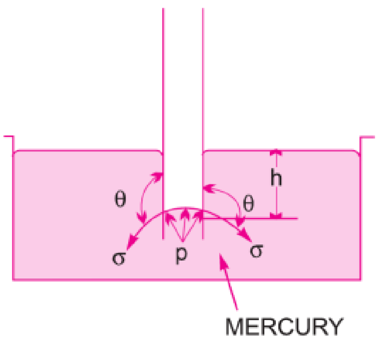


Figure 8 capillarity fall

- Let h = height of depression in tube
- Then in equilibrium, two forces are acting on the mercury inside the tube. First one is due to surface tension acting in the downward direction and is equal to

$$=\sigma\times\pi d\times\cos\theta \qquad \cdots\cdots\cdots(1)$$

- Second force is due to hydrostatic force acting upward and is equal to intensity of the pressure at the depth 'h' X Area

$$=p\times\frac{\pi}{4}d^2$$

$$=\rho gh\times\frac{\pi}{4}d^2 \qquad \cdots\cdots\cdots(2)$$

- Equating the two forces

$$\sigma\times\pi d\times\cos\theta=\rho gh\times\frac{\pi}{4}d^2$$

$$\boxed{\therefore h=\frac{4\sigma\cos\theta}{\rho gd}}$$

- Value of θ for mercury and glass tube is 128°.

1.7 Vapor Pressure and Cavitation

- A change from a liquid state to gaseous state is known as vaporization. Vaporization (which is depend 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°C and pressure is atmospheric. This liquid is vaporize at 100°C. 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.
- Again consider the same liquid at 20°C at the atmospheric pressure in the closed vessel. If the pressure above the liquid surface is reduced by some means, the boiling temperature will also reduce. If the pressure is reduced to such an extent that it become equal to or less than vapor pressure, the boiling of liquid will start, though the temperature of liquid is 20°C.
- Thus a liquid may boil even at ordinary temperature, if the pressure above the liquid surface is reduced so as to be equal or less than the vapor pressure of the liquid at that temperature.
- Now consider a flowing liquid in a system. If the pressure at any point in this flowing liquid becomes equal to or less than the vapor pressure, the vaporization of the liquid starts. The bubbles of these vapors are carried by the flowing fluid into the

region of the high pressure where they collapse, giving rise to high impact pressure. The pressure developed by the collapsing bubbles is so high that the material from adjoining boundaries gets eroded and cavities are formed on them. This phenomenon is known as cavitation.

- Hence the cavitation is the phenomenon of formation of vapor bubbles of a flowing liquid in a region where the pressure of the liquid falls below the vapor pressure and sudden collapsing of these vapor bubbles in a region of higher pressure.
- When vapor bubbles collapse, a very high pressure is created. The metallic surface, above which the liquid is flowing, is subjected to these high pressures, which cause pitting action on the surface. Thus, cavities are formed on the metallic surface and hence the name is cavitation.

1.8 References

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"Work is the only thing that gives substance to life."

– Albert Einstein