# MECHANICAL ENGINEERING

## Fluid Mechanics and Hydraulic Machines

Comprehensive Theory
*with* Solved Examples *and* Practice Questions

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# Fluid Mechanics and Hydraulic Machines





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# Fluid Mechanics and Hydraulic Machines

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CHAPTER

1

# Fluid Properties

## 1.1 INTRODUCTION

- A substance in the liquid or gas phase is referred as a fluid.
- Fluid is capable of flowing and conforms to the shape of the containing vessel.
- Fluid undergoes continuous deformation under the influence of shearing forces no matter how small the forces may be.
- This property of continuous deformation in technical terms is known as 'flow property', whereas this property is absent in solids.
- The distinction between a solid and a fluid is made on the basis of their ability to resist an applied shear stress. A solid can resist an applied shear stress by deforming itself by a fixed amount. On the other hand, a fluid shows its flow property under the application of shear stresses due to which it deforms continuously and does not come back to its previous position.
- In case of solids, total deformation is significant, whereas, in case of fluids, rate of deformation is significant in defining the properties.
- If a fluid is at rest, there can be no shearing forces acting and therefore, all forces in the fluid must be perpendicular to the planes upon which they act.
- Fluids may be classified as Ideal fluids or real fluids.

**(i) Ideal Fluids:** Ideal fluids are those fluids which have neither viscosity nor surface tension and they are incompressible. In nature, the ideal fluids do not exist and therefore, they are only imaginary fluids.

**(ii) Real Fluids:** Practical or real fluids are those fluids which possess viscosity, surface tension and compressibility.

## 1.2 FLUID MECHANICS

- Fluid mechanics is the study of fluids at rest (fluid statics) or in motion (fluid dynamics).
- The basic laws which are applicable to any fluid for analysis of any problem in fluid mechanics, are
  (i) The law of conservation of mass
  (ii) Newton's second law of motion
  (iii) The principle of angular momentum
  (iv) The first law of thermodynamics
  (v) The second law of thermodynamics

## 1.3 FLUID AS A CONTINUUM

- In a fluid system on macro scale, the intermolecular spacing between the fluid particles is treated as negligible and the entire fluid mass system is assumed as continuous distribution of mass, and such continuous mass of fluid is known as continuum.
- This assumption is valid only if the fluid system is very large as compared to the spacing between the particles. (Continuum is invalid at low pressure i.e. at high elevation)
- As a consequence of the continuum, each fluid property is assumed to have a definite value at every point in space. Thus, the fluid properties such as density, temperature and velocity etc., are considered as continuous functions of position and time.

  **For Example:**

  Velocity field, $V = \vec{V}(x, y, z, t)$ or $V = u\hat{i} + v\hat{j} + w\hat{k}$

  where, each velocity component, $u$, $v$ and $w$ will be a function of $x$, $y$, $z$ and $t$.

  $\vec{V}(x, y, z, t)$ indicates the velocity of a fluid particle that is passing through the point $x$, $y$, $z$ at time instant $t$.

  Thus, the velocity is measured at the same location at different points of time.

  In case of steady flow,

  $$\frac{\partial \vec{V}}{\partial t} = 0$$

  Therefore, $V = \vec{V}(x,y,z)$

### 1.3.1 The No Slip Condition

- Consider the flow of a fluid over a stationary solid surface that is non-porous. As per the experimental observation, it has been found out that a fluid in motion comes to a complete stop at the surface of solid body and assumes zero relative velocity with solids surface. It represents that the fluid in direct contact with a solid, stick to the surface and there is no slip. This is known as "no slip condition".
- The fluid property responsible for the no slip condition and development of the boundary layer is viscosity.
- The no slip condition is responsible for the development of velocity profile.
- Another consequence of no slip condition is the surface drag or skin friction drag.

## 1.4 FLUID PROPERTIES

- Any characteristic of a fluid system is called a fluid property.
- Fluid properties are of two types:
  - (i) **Intensive Properties:** Intensive properties are those that are independent of the size of the system or the amount of material in it. **Example:** Temperature, pressure, density etc.
  - (ii) **Extensive Properties:** Extensive properties are those whose values depend on the size or extent of the system. **Example:** Total mass, total volume, total momentum etc.
- Following are some of the intensive and extensive properties of a fluid system.

  (i) Viscosity (ii) Surface tension (iii) Vapour pressure (iv) Compressibility and elasticity

## OBJECTIVE BRAIN TEASERS

**Q.1** If the dynamic viscosity of a liquid is 0.012 poise and its R.D. is 0.79, then its kinematic viscosity in stoke is

(a) 0.0152 (b) 0.152
(c) 1.52 (d) 15.20

**Q.2** The velocity distribution, in m/s near the solid wall at a section in a laminar flow is given by $u = 5\sin(5\pi y)$. If $\mu = 5$ poise, the shear stress at $y = 0.05$m, in N/m$^2$ is

(a) 39.27 (b) 27.77
(c) 38.9 (d) 26.66

**Q.3** Kinematic viscosity of fluid depends upon

(a) Temperature (b) Pressure
(c) Density (d) Surface tension
(a) 1 and 2 (b) 1 and 3
(c) 1, 2 and 3 (d) 1, 2, 3 and 4

**[MSQ]**

**Q.4** A fluid indicated the following shear stress and deformation rates :

| $\frac{du}{dy}$ (units) | 0 | 1 | 2 | 4 |
|---|---|---|---|---|
| $\tau$ (units) | 10 | 15 | 20 | 30 |

This fluid is classified as

(a) Newtonian (b) Bingham Plastic
(c) Dilatant (d) Pseudoplastic

**Q.5** Kerosene is known to have a bulk modulus of elasticity $K = 1.43 \times 10^9$ N/m$^2$ and a relative density of 0.806. The speed of sound in kerosene, (in m/s) is

(a) 1332 (b) 1075
(c) 1197 (d) 184

**Q.6** If 5.66 m$^3$ of oil weighs 4765 kg, then its mass density, specific weight and specific gravity respectively are

(a) 841.87 kg/m$^3$, 8.26 kN/m$^3$ and 0.842
(b) 8.26 kg/m$^3$, 841 kN/m$^3$ and 8.42
(c) 841.87 kg/m$^3$, 841 kN/m$^3$ and 8.42
(d) None of these

**Q.7** A reservoir of capacity 0.01 m$^3$ is completely filled with a fluid of coefficient of compressibility $0.75 \times 10^{-9}$ m$^2$/N. The amount of fluid that spill over (in m$^3$), if pressure in the reservoir is reduced by $2 \times 10^7$ N/m$^2$ is

(a) $0.15 \times 10^{-4}$ (b) $1 \times 10^{-4}$
(c) $1.5 \times 10^{-4}$ (d) None of these

**Q.8** Assuming that sap in trees has the same characteristic as water and that it rises purely due to capillary phenomenon, what will be the average diameter of capillary tubes in a tree if the sap is carried to a height of 10 m? (Take surface tension of water = 0.0735 N/m & $\theta = 0°$)

(a) 0.003 mm (b) 0.03 mm
(c) 0.3 mm (d) 0.006 mm

**Q.9** A small circular jet of mercury 0.1 mm in diameter issue from an opening. What is the pressure difference between the inside and outside of the jet when at 20°C? (Surface tension of mercury at 20°C is 0.514 N/m)

(a) 41 kPa (b) 21.5 kPa
(c) 10.28 kPa (d) 5.14 kPa

**Q.10** An apparatus produces water droplets of diameter 70 μm. If the coefficient of surface tension of water in air is 0.07 N/m, the excess pressure in these droplets, in kPa, is

(a) 5.6 (b) 4.0
(c) 8.0 (d) 13.2

**Q.11** If the surface tension of water air interface is 0.073 N/m, the gauge pressure inside a rain drop of 1 mm diameter is

(a) 146.0 N/m$^2$ (b) 0.146 N/m$^2$
(c) 73.0 N/m$^2$ (d) 292.0 N/m$^2$

**Q.12** The capillary rise in a 3 mm tube immersed in a liquid is 15 mm. If another tube of diameter 4 mm is immersed in the same liquid, the capillary rise would be

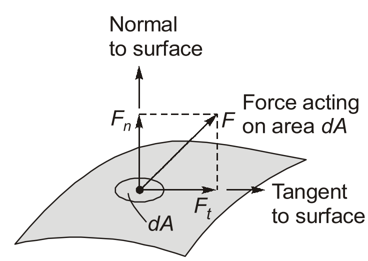
(a) 11.25 mm (b) 20.00 mm
(c) 8.44 mm (d) 26.67 mm

# CHAPTER 2

# Fluid Pressure & its Measurement

## 2.1 INTRODUCTION

- Stress at a point is defined as force per unit area and is determined by dividing the force by the area upon which it acts.
- The normal component of a force acting on a surface per unit area is called the normal stress, and the tangential component of the force acting on a surface coplanar with cross-section or material per unit area is called shear stress.
- When fluid is confined within solid boundaries, it exerts forces against boundary surfaces. The exerted force always act in direction normal to the surface in contact. Because fluid at rest cannot sustain shear stress and hence no tangential component of force.
- In a fluid at rest, the normal stress is called pressure.
- In this chapter, we will discuss the fluid pressure and the various instruments available for its measurement.




Normal stress : $\sigma = \dfrac{F_n}{dA}$

Shear stress : $\tau = \dfrac{F_t}{dA}$

**Fig.** Components of a force

## 2.2 PRESSURE AT A POINT IN A FLUID

- Pressure or intensity of pressure may be defined as the compressive force exerted on a unit area in the normal direction. Thus, $p = \dfrac{dF}{dA}$, where $dF$ = force acting on an infinitesimal area $dA$.

### 2.2.1 Pascal's Law for Pressure at a Point

- According to Pascal's law, pressure at a point in a static fluid system is same in all directions.
- It means that the pressure at a point in a fluid at rest, or in motion, is independent of direction as there are no shearing stresses present.

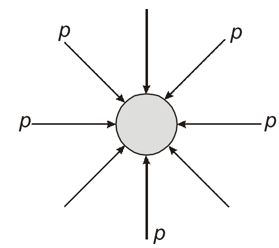



**Fig.** A point in a fluid system

- In a fluid system, pressure is a scalar quantity as it has a magnitude but no specific direction.
- It applies to a fluid at rest. In case of flowing fluid, shear stresses will be set up as a result of relative motion between particles of the fluid.

  The pressure at a point is then considered to be the mean of the normal forces per unit area (stresses) on three mutually perpendicular planes. Since, these normal stresses are usually large compared to shear stresses, it is generally assumed that Pascal's law still applies in flowing fluids also.

**Validation of the Law:** Consider a small wedge-shaped fluid element of unit length in equilibrium. The mean pressure at the three surfaces are $p_1$, $p_2$ and $p_3$ and the force acting on a surface is the product of mean pressure and the surface area. From Newton's second law, a force balance in the $x$-direction and $z$-direction gives

$$\Sigma F_x = ma_x = 0; \quad p_1 \Delta y \Delta z - p_3 \Delta y\, l \sin\theta = 0 \qquad \text{...(i)}$$

$$\Sigma F_z = ma_z = 0; \quad p_2 \Delta y \Delta x - p_3 \Delta y\, l \cos\theta - \frac{1}{2}\rho g \Delta x\, \Delta y\, \Delta z = 0 \qquad \text{...(ii)}$$

where $\rho$ = density and $W = mg = \frac{1}{2}\rho g \Delta x \Delta y \Delta z$ is the weight of fluid element.

Geometric relations are : $\Delta x = l \cos\theta$, $\Delta z = l \sin\theta$

Applying geometric relations in Equation (i) and (ii), we get,

$$p_1 - p_3 = 0$$

$$\Rightarrow \quad p_1 = p_3$$

$$p_2 - p_3 - \frac{1}{2}\rho g\, \Delta z = 0$$

For infinitesimal element (fluid element shrinks to a point ), $\Delta z \to 0$

then, $p_2 = p_3$

$\therefore \quad p_1 = p_2 = p_3 = p$

Thus, we conclude that the pressure at a point in a fluid has the same magnitude in all directions. This result is applicable to fluids in motion as well as in rest since pressure is scalar in a fluid system.

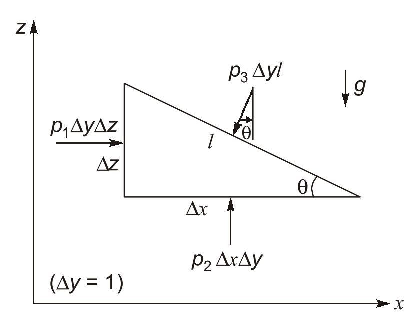



**Fig.** Fluid Element

### 2.2.2 Units of Pressure

- 1 Pa = 1 N/m$^2$
- 1 bar = $10^5$ Pa = 0.1 MPa
- 1 psi = 6888.1 Pa, 1 atm = 14.7 psi
- 1 MPa = 1 N/mm$^2$
- 1 kgf/cm$^2$ = $9.81 \times 10^4$ N/m$^2$
- 1 atm = 101325 Pa = 0.10325 Bar
- 1 torr = 1 mm of Hg
- Pressure can also be represented in terms of height of liquid columns.

**Ex.:** 1 atm = 760 mm of Hg = 10.3 m of water. Here, Pa stands for Pascal.

- Generally, these gauges are used for measuring high pressures and where high precision is also not required.
- Following are the types of the mechanical gauges :
  (a) Bourdon Tube Pressure Gauge (b) Diaphragm Pressure Gauge
  (c) Bellows Pressure Gauge (d) Dead - weight Pressure Gauge

**NOTE:** Strain gauge transducers and piezoelectric transducers are also used to measure pressure. Quartz or Rochelle salt are example of materials that are used in piezoelectric transducers.

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## OBJECTIVE BRAIN TEASERS

**Q.1** If a Mohr circle is drawn for a fluid element inside a fluid body at rest, it would be :
(a) a circle not touching the origin
(b) a circle touching the origin
(c) a point on the normal stress axis
(d) a point on the shear stress axis

**Q.2** The pressure in meters of oil of specific gravity 0.8 equivalent to 80 m of water is :
(a) 64 m (b) 88 m
(c) 80 m (d) 100 m

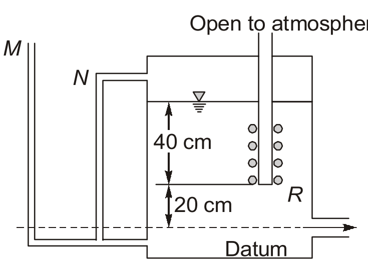
**Q.3** The mass density of a liquid with variable density is given by $\rho = 1000 + 0.008\ y^{3/2}$, where $\rho$ is in kg/m$^3$ ; $y$ is measured in meters. The depth at which the pressure intensity will be 900 kPa, is
(a) 91.5 m (b) 101.5 m
(c) 112.5 m (d) 114.5 m

**Q.4** If barometric reading at surface of liquid is 750 torr., then the absolute pressure at a depth of 3 m below the surface of liquid of relative density 0.9 will be ________ kPa

**Q.5** In a mercury column-type barometer, the correct local atmospheric pressure is obtained by considering correction due to vapour pressure of mercury as follows ; $H_a$ =
(a) $H - h_v$ (b) $H_0 + h_v$
(c) $H_0 / h_v$ (d) $h_v - H_0$
[where, $H_a$ = correct local pressure in mm of mercury, $H_0$ = observed barometer reading in mm of mercury and $h_v$ = vapour pressure of mercury in mm.]

**Q.6** The standard atmospheric pressure is 101.32 kPa. The local atmospheric pressure at a location was 91.52 kPa. If a pressure is recorded as 22.48 kPa (gauge), it is equivalent to
(a) 123.80 kPa (abs) (b) 88.84 kPa(*abs*)
(c) 114.00 kPa(*abs*) (d) 69.04 kPa(*abs*)

**Q.7** The tank shown in figure discharge water at constant rate for all water levels above the air inlet *R*. The height above datum to which water would rise in manometer tubes *M* and *N* respectively, are



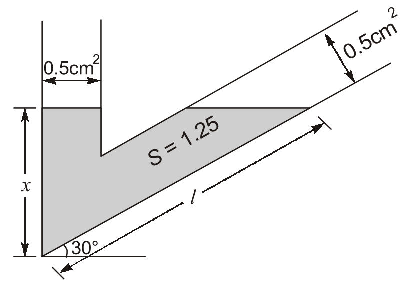

(a) (60 cm, 20 cm) (b) (40 cm, 40 cm)
(c) (20 cm, 20 cm) (d) (20 cm, 60 cm)

**Q.8** Normal stresses are of the same magnitude in all directions at a point in a fluid
(a) only when the fluid is frictionless
(b) only when the fluid is at rest
(c) only when there is no shear stress
(d) in all cases of fluid motion

**Q.9** Identify the CORRECT statement:
(a) Local atmospheric pressure is always less than the standard atmospheric pressure
(b) Local atmospheric pressure depends only on the elevation of the place
(c) A barometer reads the difference between the local and standard atmospheric pressure
(d) Standard atmospheric pressure is 760 mm of mercury

## CONVENTIONAL BRAIN TEASERS

**Q.1** An equilibrium liquid level condition is shown in the given figure. If additional 10 cm$^3$ of water is added through the inclined limb, then, what will be the rise in the meniscus in vertical tube?




**Solution :**

Let $x$ = Original liquid level in the vertical limb

$l$ = Original liquid level in the inclined limb

From the original pressure balance

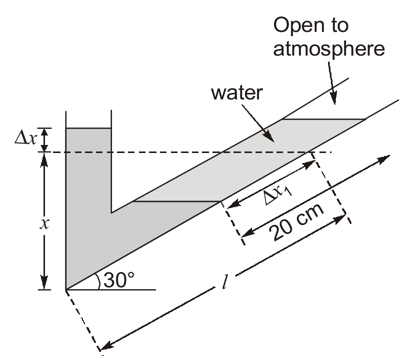
$$l \sin 30° = x$$

$$\Rightarrow \quad x = (l/2) \quad \text{...(i)}$$

From Volume Balance $\Delta x_1 = \Delta x$ ...(ii)

Length of water added $= \dfrac{10}{0.5} = 20$ cm

From final pressure balance




$$(x + \Delta x) \times 1.25 = (l - \Delta x)\sin 30° \times 1.25 + 20 \sin 30° \times 1$$

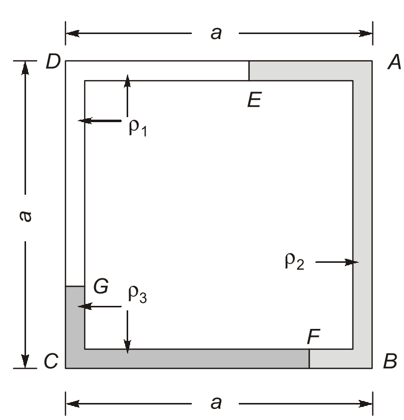
$$\Rightarrow \quad (x + \Delta x) \times 1.25 = \frac{l}{2} \times 1.25 - \frac{\Delta x}{2} \times 1.25 + \frac{20}{2}$$

$$\Rightarrow \quad \left(\frac{l}{2} + \Delta x\right) \times 1.25 = \frac{l}{2} \times 1.25 - \frac{\Delta x}{2} \times 1.25 + 10 \quad \{\because x = l/2\}$$

$$\Rightarrow \quad \Delta x\left[1.25 + \frac{1.25}{2}\right] = 10$$

$$\Delta x = \frac{10 \times 2}{(2.5 + 1.25)} = \frac{20}{3.75} = 5.33 \text{ cm}$$

**Q.2** A glass tube of uniform bore is bent into the form of a square of sides $a$ and filled with equal amounts of three immiscible liquids of densities $\rho_1$, $\rho_2$ and $\rho_3$. It is known that $\rho_1 < \rho_2 < \rho_3$. If the tube arrangement is placed in a vertical plane (i.e. two sides vertical) and if one of the vertical sides is completely filled with the liquid of density $\rho_2$.




(a) Show that $\dfrac{1}{3}(2\rho_3 + \rho_1) > \rho_2 > \dfrac{1}{3}(\rho_3 + 2\rho_1)$