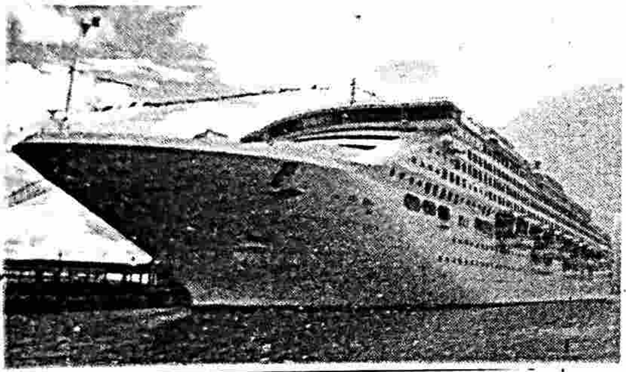
Chapter 10

Mechanical Properties of Fluids



INSIDE

10.1 Introduction

What is fluid mechanics? From the name itself it is clear that it is the branch of applied mechanics concerned with the statics and dynamics of fluids. The analysis of the behaviour of fluids is based on the fundamental laws of mechanics along with the mass and energy conservation principle. Both liquids and gases together are called fluids. Fluids, in contrast to solids, lack the ability to resist deformation and they have the ability to move (in fact fluid means flow). Fluids have no definite shape of their own. An ideal liquid is incompressible. It takes, the shape of the vessel in which it is taken and it has a free surface area. A gas, though a fluid, is compressible and occupies all the space made available to it. We need not say much on the importance of fluids but to remember "without air and water (both are fluids) life on earth is not possible".

10.2 Fluid

*A **fluid** is a substance which deforms continuously or flows, because it cannot withstand*

Curriculum Objectives

- To develop the concept of fluid pressure through group discussion and simple experiments.
- To arrive at the expression for fluid pressure through discussion and explanations and use the expression for solving problems.
- To develop the ideas related to Pascal's law, Buoyancy, Archimedes' principle, Floatation and their applications in daily life through demonstration, seminar, discussion and problem solving.
- To develop the concept of atmospheric pressure, through experiments and demonstrations.
- To develop the concept of surface energy, surface tension, relation between them, angle of contact, drops and bubbles through group activity, demonstration and discussion.
- To develop the concept of capillary rise and surface tension through group discussion, experiments, demonstration solving of problems and projects.
- To deveop the concept of viscosity, Stoke's law, stream line flow and turbulent flow through group discussion and sloving of numerical problems.
- To develop the concept of Reynold's number, Bernoulli's theorem and their application in daily life through discussions, demonstration and project.
- To use appropriate and relevant theories, rules, formulae etc. to carry out the project on cleaning effect of detergent and construction of a dancing ball in a jet.

a shearing stress. If a fluid is at rest all forces must be perpendicular to its surface.

10.2.1 Differences Between Solids and Fluids

i. For a solid, the strain is a function of the applied stress, within the elastic limit. But for a fluid, the rate of strain is proportional to the applied stress.

ii. In a solid the strain is independent of time over which the force is applied and it disappears when the applied force is removed, if the elastic limit is not exceeded. But in the case of a fluid, it continues to flow as long as there is an applied force and will not regain its original form when the force is removed.

10.2.2 Differences Between Liquids and Gases

Both liquids and gases are fluids. But they have distinctive characteristics of their own.

A liquid is incompressible. A given mass of liquid occupies a definite volume. It forms a free surface (if the volume of the container is greater than the volume of the liquid).

A gas can be compressed. Changes of volume with pressure are large and are related to temperature changes. A given mass of a gas has no fixed volume and will expand continuously unless restrained by a containing vessel. A gas fills completely any vessel in which it is taken and hence it has no free space.

10.2.3 Density

***Density** of a substance of uniform composition is defined as its mass per unit volume*

$$\text{Density } \rho = \frac{\text{Mass(m)}}{\text{Volume(V)}}$$

Density is a scalar quantity.

Unit : In S.I. – kg m^{-3}

Dimensional formula – $[M^1L^{-3}T^0]$

Density of a gas varies considerably with pressure, but density of a liquid does not. This shows that a gas can be compressed easily, but a liquid cannot.

Densities of some common fluids at STP

TABLE -1

(STP means standard temperature (0°C) and 1 atm pressure)

Fluid	ρ **(kg m^{-3})**
Water	1.00×10^3
Sea water	1.03×10^3
Mercury	13.6×10^3
Ethyl alcohol	0.806×10^3
Whole blood	1.06×10^3
Air	1.29
Oxygen	1.43
Hydrogen	9.0×10^{-2}
Interstellar space	$\approx 10^{-20}$

10.2.4 Specific Gravity and Relative Density

*The **specific gravity** of a substance is the ratio of density of the substance to that of water at 4°C.*

Specific gravity is a dimensionless quantity. It is a mere number. It has nothing to do with gravity. Hence a new term is used called ***relative density*** instead of specific gravity. The term relative density could describe the concept more precisely.

$$\text{Relative Density (RD) of a substance} = \frac{\text{Density of the substance}}{\text{Density of water at 4°C}}$$

10.3 PRESSURE

***Pressure** at a point is defined as the normal force exerted on unit area.*

$$\text{ie., Pressure} = \frac{\text{Force}}{\text{Area}}$$

Unit

In S.I. $\rightarrow Nm^{-2}$ or kg m^{-1} s^{-2}

Other practical units → pascal (Pa), bar, torr, atmosphere

1 Pa = 1 Nm^{-2}

1 atmosphere (atm) = 1.013×10^5 Pa

1 bar = 10^5 Nm^{-2} ≈ 1 atm

1 torr = 133 Pa (or pressure exerted by 1 mm of mercury)

Dimensional formula of pressure → $[M^1L^{-1}T^{-2}]$

10.3.1 Fluid Statics - Thrust and Pressure

Fluid statics deals with the study of fluids at rest. The general rules are;

i. a static fluid has no shearing force acting on it.

ii. any force between the fluid and the boundary must be at right angles to the boundary.

Whether the surface is plane or curved, the force is normal to the surface. This total normal force is called thrust.

Hence ***thrust** is defined as the normal force acting on the fluid surface.*

Thus in the case of fluids, pressure at a point is defined as the thrust acting per unit area

ie., Pressure (P) = $\dfrac{\text{Thrust(F)}}{\text{Area(A)}}$

A simple device used for measuring pressure in a fluid is shown in Fig. 1.

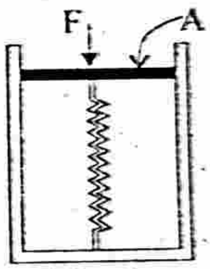


Fig. 1

The device consists of an evacuated cylinder enclosed with a light piston of base area A connected to a spring as shown. When this device is immersed in a fluid, the fluid exerts a force on the top of the piston and compresses it until the inward force of the fluid is balanced by the outward force of spring. If the spring is already calibrated, the fluid pressure can be directly measured. If F is the force on the piston of area A, then average pressure, $P = \dfrac{F}{A}$

10.3.2 Expression for Fluid Pressure

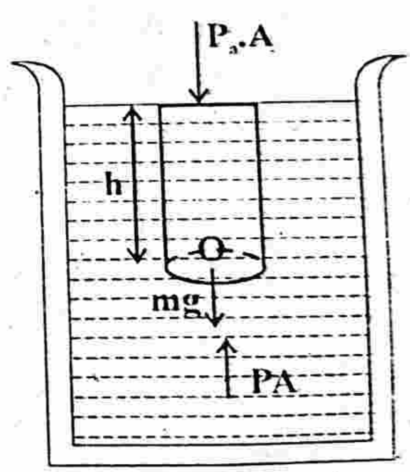


Fig. 2

Consider a cylindrical column of a fluid (liquid) of density ρ taken in a vessel. Let 'h' be the height of the cylindrical column of fluid and A the cross sectional area. The three forces acting on this cylindrical column of fluid are

i. Weight of the fluid mg acting downwards.

ii. Force PA exerted by the fluid below the cylindrical column acting upwards and

iii. Down force P_a.A exerted by the atmosphere (P_a is the atmospheric pressure).

Since we are interested only in the liquid pressure, the force (iii) is not considered.

At equilibrium, $mg = PA$

$$P = \frac{mg}{A}$$

m = mass of fluid = $Ah\rho$

$$\text{Hence } P = \frac{Ah\rho g}{A}$$

$\therefore P = h\rho g$ ...... (1)

ie., Pressure exerted by the fluid at O is $h\rho g$. If we consider the force due to atmosphere also, then total pressure at O, called ***absolute pressure***, is

$P_t = P_a + h\rho g$ ..... (2)

Equation (2) shows that the pressure P_t at depth below the surface of a liquid opened to the atmosphere is greater than atmospheric pressure by an amount ρgh. The excess of pressure $P_t - P_a$, at depth h is called a ***gauge pressure*** at that point.

Solved Examples

1. A tank 5 m high is half filled with water and other half filled with a liquid immiscible of relative density 0.85. Calculate the pressure at the bottom of the tank.

Sol.

Given, $h = 5$ m, $h_1 = 2.5$ m, $h_2 = 2.5$ m $\rho_w = 10^3$ kgm^{-3}, $\rho_o = 0.85 \times 10^3$ kgm^{-3}

$g = 9.8$ ms^{-2}.

Pressure, $P = h_1\rho_1 g + h_2\rho_2 g$

$= 2.5 \times 10^3 \times 9.8 + 2.5 \times 0.85 \times 10^3 \times 9.8$

$= 4.533 \times 10^4$ Nm^{-2}.

2. To what height should a cylindrical vessel be filled with a homogeneous liquid to make the force with which the liquid presses on the sides of the vessel to the force exerted by the liquid on the bottom of the vessel?

Sol.

Let 'h' be the height of the liquid and ρ be its density. Let r be the radius of the vessel. Then

Force at the bottom, $F_1 = \pi r^2 h\rho g$

Average pressure of liquid on the wall $= \frac{h\rho g}{2}$

Area of the wall in contact with the liquid $= 2\pi rh$

Force on the sides of the wall,

$$F_2 = \frac{h\rho g}{2} \times 2\pi rh = \pi r\rho gh^2$$

By the data given in the question, $F_1 = F_2$

ie., $\pi r^2 h\rho g = \pi r\rho gh^2$

$\therefore h = r$

ie., height to which the liquid column to be filled is equal to the radius of the vessel.

3. What is the pressure on a swimmer 10 m below the surface of a lake?

Sol.

Given $h = 10$ m, $\rho = 1000$ kgm^{-3}, $g = 10$ ms^{-2}

$P_t = P_a + \rho gh$

$= 1.01 \times 10^5 + 1000 \times 10 \times 10$

$= 2.01 \times 10^5$ Pa

≈ 2 atm

This shows that there is a 100% increase in pressure from surface level. At a depth of 1 km, the increase in pressure is 100 atm. Submarines are designed such that it can withstand enormous pressure.