

Chemical Engineering (GATE & PSUs)

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GATE & Public Sectors

FLUID MECHANICS

GATE 2015 Top Results

Chemical Engineering



1st Rank
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GATE 2015 Result

Name	ARCHHIT TRICHAL	 <i>Archhit Trichal</i>		
Registration Number	CH8804151135			
Gender	Male			
Examination Paper	Chemical Engineering (CH)			
Marks out of 100 [†]	65.67	All India Rank in this paper	1	
Qualifying Marks ^{‡‡}	27.52 (General)	24.77 (OBC (NCL))	18.34 (SC/ST/PwD)	
			GATE Score	947

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GATE 2014 Topper
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GATE 2015 Cut-off Marks

BRANCH	GENERAL	SC/ST/PD	OBC(Non-Creamy)	Total Appeared
Chemical Engineering	27.52	18.34	24.77	15874

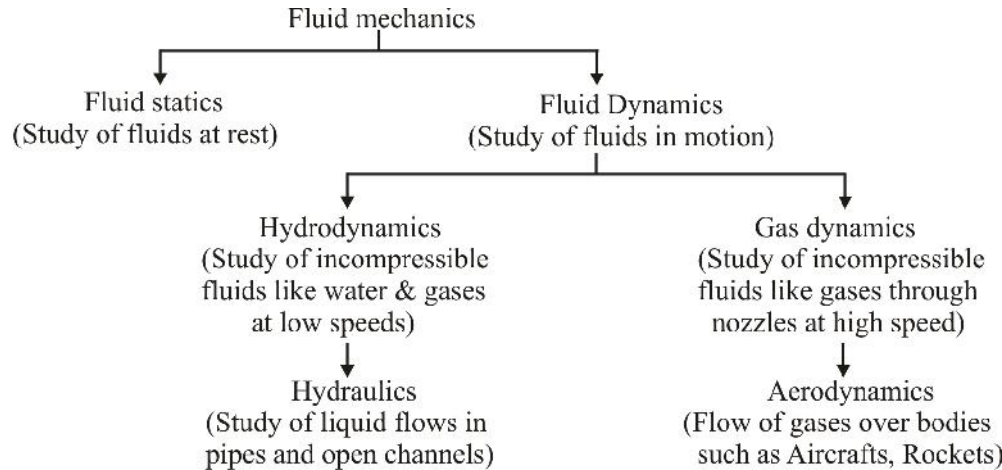
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CHAPTER-1 INTRODUCTION

Introduction

Fluid mechanics is the study of fluids at rest or in motion.



Definition of fluid: A substance in the liquid or gas phase is referred to as a fluid. A fluid is a substance that deforms continuously under the utilization of a shear (tangential) stress no matter how small the shear stress may be. As shown in figure when a shear stress is applied at any location in a fluid, the element oaa' which is initially at rest, will move to obb' , then to occ' , odd' and so on.

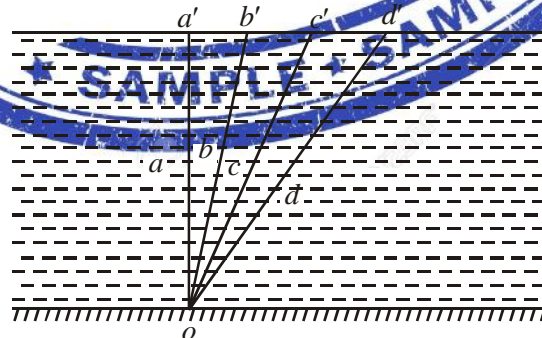


Fig.: Shear stress on a fluid only

→ The tangential stress in a fluid body rely on the velocity of deformation, and vanishes as the velocity approaches zero.

Distinction between A solid and a fluid

The molecules of a solid are more tightly packed as compared to that of the fluid.

A deformation of solid body undergoes either a definite angular deformation as shown in fig. The amount of deformation is proportional to the magnitude of utilized stress up to some limiting conditions.

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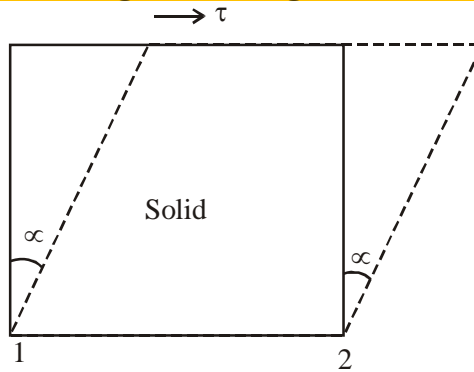


Figure: Deformation of a solid body

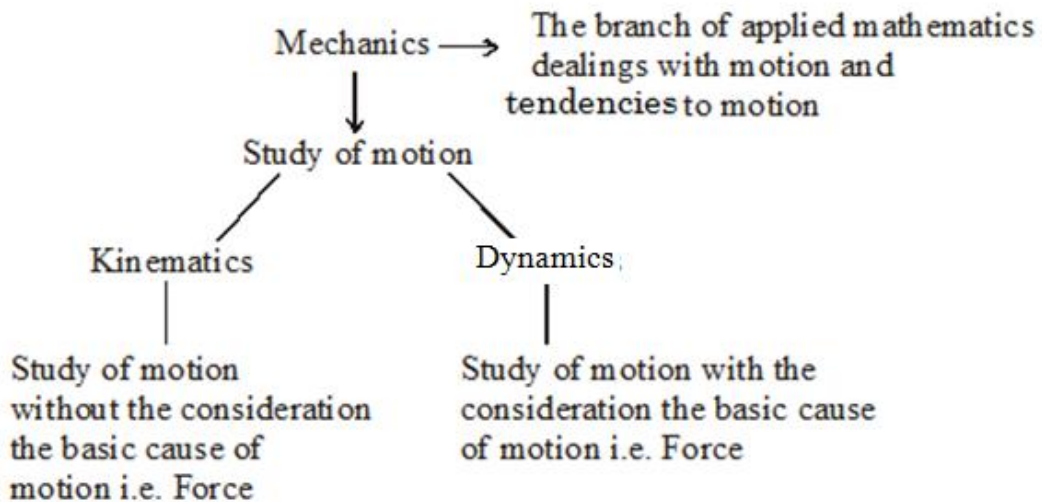
The angle of deformation α is called shear strain or angular displacement. Stress is defined as force per unit area. Normal component of a force acting on a surface per unit area is called Normal stress, and tangential component of force acting on a surface per unit area is called shear stress. Here τ is the shear stress. In solids, stress is proportional to strain, but in fluids, stress is proportional to strain rate.

- When this was an element of fluid, there would have been no fixed and even angular deformation an infinitesimally small shear stress was utilized.
- It can be simply said that white solids can resist tangential stress under static conditions, fluids can do it only under Dynamics situation.

Gas and Vapour

Gas and vapour are used as synonymous words.

The vapour phase of a substance is customarily called a gas when it is above critical temperature.



S – distance in m $\vec{V} = \frac{d\vec{s}}{dt} \text{ (m/s)}$

$\vec{a} = \frac{d\vec{v}}{dt} \text{ (m/s}^2\text{)}$

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Fluid is continuum: In macro system of fluid particles, the inter molecular distances can be treated as negligible as compare to the characteristics dimension of systems, so therefore we can assume adjacent to one molecule there is another molecule and there is no inter space between them so the entire fluid mass system can be treated as a continuous distribution of mass which continuum.

The conitnum idealization allows us to treat that the properties (like density) are varying continually in space with no jump discontinuities.

At low pressure i.e. high elevation, mean free path becomes large than characteristic length of system. Hence system cannot be modelled as a continuum.

Properties of Fluid:

SI and English units

SI System

Mass → kg

Length → m

Time → s

English system

mass → lbm (pound mass)

length – ft (foot)

Time → s (second)

Unit of force

SI system: Newton (N)

$$1\text{N} = 1\text{kg m/s}^2$$

cgs system: Dyne

$$1\text{dyne} = 1\text{g cm/s}^2$$

English system: pound force (lbf)

$$1\text{lbf} = (32.174)\text{lbm ft/s}^2$$

↓

1slug

Other common unit: kilogram force (kgf)

$$1\text{kgf} = 9.8\text{N}$$

Work or energy

SI unit: Joule or Nm

English system: Btu (British thermal unit)

$$1\text{Btu} = 1055.1\text{ J}$$

Note: Electrical energy is usually expressed in KWH

$$1\text{KWH} = 3.6 \times 10^6\text{J}$$

(Kilo watt hour)



PROPERTIES OF FLUID

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1. Mass density (...): It is defined as the ratio of the mass of a fluid to its volume. Hence mass per unit volume of fluid is said to density.

The density of liquids may be considered as constant while that of gases changes with the variation of pressure and temperature.

Density of water $\rightarrow 1000 \text{ kg/m}^3$

Atmospheric air $\rightarrow 1.21 \text{ kg/m}^3$

$$\rho = \frac{m}{V}$$

where, ρ – density kg/m^3

The density of most gases is directly proportional to pressure and inversely to temperature. For liquids (although the change in density is negligible with temperature & pressure), still density of liquid & solids depends more strongly on temperature than pressure.

2. Specific weight or weight density (γ): As it represents the force exerted by gravity on a unit volume of a fluid, SI unit of specific weight is N/m^3 .

\rightarrow It rely on the gravitational acceleration and mass density therefore gravitational acceleration (g) changes from place to place, thus, weight density will also vary.

\rightarrow It depends upon temperature and pressure because the mass density changes with temperature and pressure.

$$\text{Specific weight} = \frac{\text{Weight}}{\text{Volume}} = \frac{mg}{V}$$

$$\gamma = \rho \cdot g \text{ N/m}^3$$

γ for water is 9.81 kN/m^3

3. Specific volume (v): It is defined as volume per unit mass of a fluid. Hence it is reciprocal of mass density. SI unit: m^3/kg .

\rightarrow For liquids the density, weight density, specific volume changes only slightly with the variation of pressure and temperature.

\rightarrow For gases the values of density, weight density, specific volume vary greatly with variation of either pressure, or temperature or both.

4. Specific gravity (S): It is the ratio of weight density of a fluid to the weight density of a standard fluid.

\rightarrow For gas, air is taken as standard fluid, in the other hand, water is taken as standard fluid, for liquid.

\rightarrow Specific gravity is a dimensionless quantity. The substances with $S < 1$ are lighter than water and thus they would float on water (if immiscible)

Viscosity: It is property of a fluid by virtue of which it offers resistance to the movement of one layer of fluid over the adjacent layer. It is due to the cohesion and molecular momentum exchange between fluid layers.

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→ Let us suppose two plates sufficiently large placed a small distance y apart, the space between them being filled with fluid.

→ The lower plate is supposed to be at rest, whereas the upper one is moved parallel to it with a velocity V by the utilization of force F , corresponding to the area A , of the moving plate in contact with the fluid.

→ Particles of the fluid in contact with each plate will adhere to it when the distance Y and velocity V are not too great, the velocity v at a distance y from the lower plate will change uniformly from zero at the lower plate which is at rest, to v at the upper plate which is moving.

→ It may be seen from similar triangles in fig. that the ratio $\frac{V}{Y}$ can be replaced by the velocity gradient

$\left(\frac{dv}{dy}\right)$, which is the rate of angular deformation of fluid.

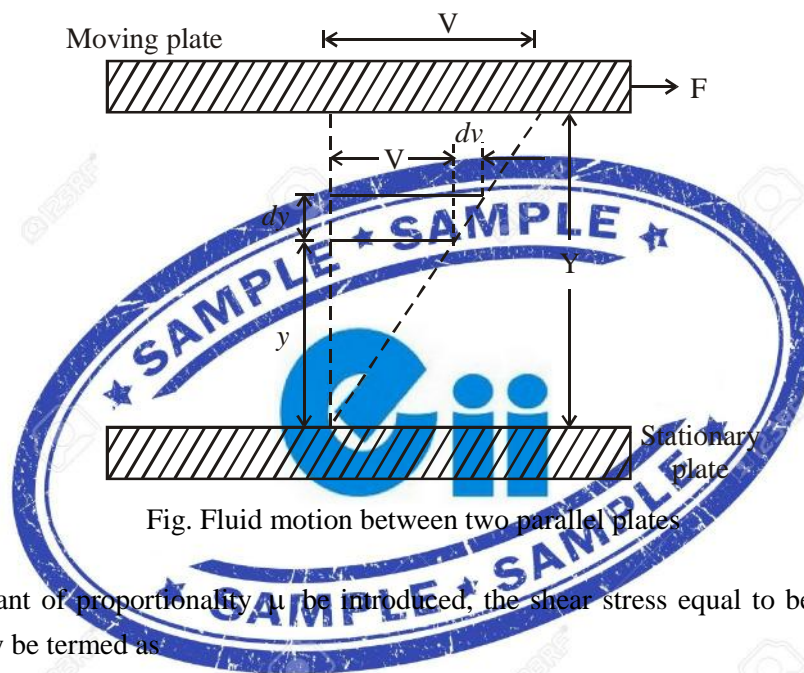


Fig. Fluid motion between two parallel plates

→ When a constant of proportionality μ be introduced, the shear stress equal to between any two thin sheets of fluid may be termed as

$$\tau = \frac{F}{A} = \mu \frac{V}{Y} = \mu \frac{dv}{dy} \quad \dots(i)$$

The above equation is said to be Newton's equation of viscosity,

$$\tau = \mu \frac{dv}{dy} \quad \boxed{\mu = \frac{\tau}{\frac{dv}{dy}}}$$

μ is called coefficient of viscosity, or dynamic viscosity, or viscosity of the fluid.

In other words, viscosity is the shear stress required to produce unit rate of angular deformation.

Where, τ – shear stress is N/m^2

$\frac{dv}{dy}$ – rate of shear strain $\left(\frac{1}{S}\right)$ or rate of shear deformation or velocity gradient.

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Unit of Viscosity: In SI unit $\text{N}\cdot\text{s}/\text{m}^2$ PaS [$1 \text{ N}/\text{m}^2 = 1 \text{ Pa}$]

In CGS unit $\text{dyne}\cdot\text{sec}/\text{cm}^2 = 1 \text{ poise}$

In MKS unit $\text{kgf}\cdot\text{sec}/\text{m}^2$

$$1 \text{ centi poise} = \frac{1}{100} \text{ poise}$$

The viscosity of water at 20°C is 1.002 centipoise (viscosity of the fluid is the slope of a plot of shear stress versus rate of deformation) (velocity gradient)

Newton's Law of Viscosity: The viscous shear stress between the adjacent layer at a distance y from surface will be directly proportional to the rate of shear strain.

$$\text{i.e.} \quad \tau \propto \frac{dv}{dy}$$

Viscosity is direct measurement of the internal resistance between the two layers in flow.

A plot of shear stress versus rate of deformation is a straight line for a Newtonian fluid.

Note: Viscosity is independent of rate of deformation for Newtonian fluids. Viscosity is actually a coefficient in stress – strain relationship.

Kinematic Viscosity (ν): Defined as the ratio of coefficient of dynamic viscosity (μ) to the density (ρ) of

$$\text{fluid } \nu = \frac{\mu}{\rho}$$

Unit of kinematic viscosity: SI unit m^2/s

CGS unit $\text{cm}^2/\text{sec} = \text{stoke}$

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

1 centistokes = $\frac{1}{100}$ stoke

Variation of Viscosity with temperature:

$$\text{Liquid} \quad \mu = \mu_o \left[\frac{1}{1 + \alpha t + \beta t^2} \right]$$

μ – viscosity of liquid at $t^\circ\text{C}$ (in poise)

μ_o – viscosity of liquid at 0°C (in poise)

α, β constants

with increase in temperature, viscosity decreases as cohesive forces are predominant, which get decreases with increase in temperature.

$$\text{Gas,} \quad \mu = \mu_o + \alpha t + \beta t^2$$

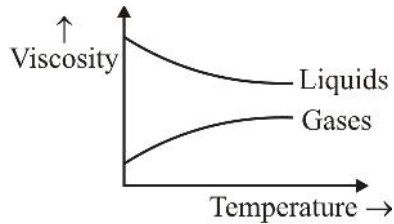
With increase in temperature, viscosity increases. Here, molecular momentum transfer predominates which increases with increase in temperature.

Kinetic theory of gases predicts that the viscosity of gases is directly proportional to the square root of

temperature

$$\eta_{gas} \propto \sqrt{T}$$

Device used to measure viscosity – ‘Viscometer’



Types of Fluid:

Newtonian fluid: In which linear relationship between the magnitude of shear stress and the resulting rate of deformation it means that constant of proportionality does not changes with the rate of deformation.

Non-Newtonian Fluid: In which there is a non-linear relation between the magnitude of the utilized shear stress and the rate of angular deformation.

Ideal fluid: Which is incompressible and is having no viscosity, is termed as an ideal fluid. It is only imaginary fluid as all the fluids, which exist, have some viscosity $\tau = 0$.

Real fluid: Which posses viscosity, is said to be real fluid, all the fluids, in actual practice, are real fluids. Viscous, compressible Surface tension exist offer resistance against fluid.

Thixotropic fluid: It is a non-Newtonian fluid, and has a non-linear relationship between the shear stress and the rate of angular deformation, beyond an initial yield stress, e.g. printers ink. The study of non-Newtonian fluid is termed as ‘rheology’.

Dilatants fluid: In this case apparent viscosity increases as the rate of shear deformation increases. So that this fluid called shear thickening fluid e.g. sugar in water, butter.

Pseudo-plastic fluid: Apparent viscosity decreases as the rate of shear deformation increases so this fluid is said to be shear thinning fluids, e.g. blood milk etc.

Bingham Plastic: Bingham plastic is one which has an initial yield stress after which it acts as a Newtonian fluid, called Bingham plastic e.g. sewage, mud, clay, tooth paste etc.

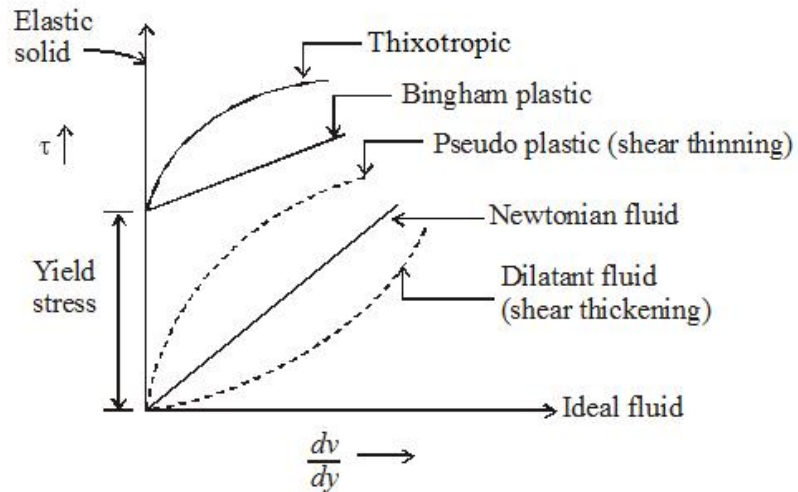


Fig.: Variation of shear stress with velocity gradient

$$\rightarrow \tau = A \left(\frac{dv}{dy} \right)^n + B$$

- (i) $B = 0$ and $n < 1 \Rightarrow$ Pseudo plastic e.g. blood and milk.
- (ii) $B = 0$ and $n > 1 \Rightarrow$ Dilatant fluid e.g. sugar in water.
- (iii) $B \neq 0$ and $n = 1 \Rightarrow$ Bingham plastic e.g. tooth paste.
- (iv) $B = 0$ and $n = 1 \Rightarrow$ Newtonian fluid e.g. water.

Bulk modulus, K: it is defined as the ratio of compressive stress to volumetric strain.

$$K = \frac{dP}{\left(-\frac{dV}{V} \right)}$$

where, dP – change in pressure = Compressive stress

$$\frac{dV}{V} - \text{volumetric strain} = \frac{\text{change in volume}}{\text{original volume}}$$

\rightarrow Bulk modulus for water at normal temperature and pressure is $2.06 \times 10^9 \text{ N/m}^2$.

\rightarrow Bulk modulus for air at normal temperature and pressure is $1.03 \times 10^5 \text{ N/m}^2$.

\rightarrow Thus, air is about 20000 times more compressible than water.

\rightarrow It is temperature dependent.

Compressibility and Elasticity:

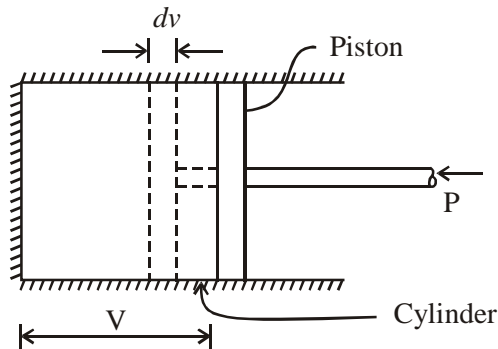
All fluids (liquid as well as gases) may be compressed by the application of external force, and if the external force is the compressed volumes of fluids expand to their original volumes. Hence fluids also possess elastic characteristics like elastic solids.

\rightarrow Compressibility is the inverse of the bulk modulus of elasticity K of the fluid.

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→ K is a measure of the incremental change in pressure dP which take place when a volume V of the fluid is changed by an incremental decrease in volume dV is negative.

→ Let us suppose that a cylinder fitted with a piston as shown in fig.



V = volume of a gas enclosed in the cylinder

P = pressure of gas when volume V .

Consider the pressure p is increased to $p + dP$, the volume of gas reduces from V to $V - dV$

Increase in pressure = dP decrease in volume = dV

Therefore, volumetric strain = $-\frac{dV}{V}$

Negative means the volume decreases with increase of pressure

Compressibility β or $\frac{1}{K}$ $\beta = -\left(\frac{dV}{V}\right) / dP$

$$K = -\frac{dP}{(dV/V)}$$

For an ideal gas $P = \dots RT$ and $\left(\frac{\partial P}{\partial \dots}\right)_T = RT = \dots$ and thus $K_{\text{ideal Gas}} = \dots$

Thus, the bulk modulus of compressibility or elasticity is equal to its absolute pressure (for an ideal gas).

Coefficient of volume expansion (S)

It is a quantity which represents the variation of volume of fluid with temperature at constant pressure.

$$S = \frac{\Delta V / V}{\Delta T} \text{ (at constant pressure)}$$

For an ideal gas

$$P = u RT$$

$$S_{\text{ideal gas}} = \frac{1}{T} (k^{-1})$$

Where T is the absolute temperature

Surface Tension and Capillarity:

Because of molecular attraction, liquid posses certain properties.

Cohesion means inter-molecular attraction between molecules of the same liquid.

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Adhesion means attraction between the molecules of a liquid and the molecules of solid boundary surface in contact with the liquid.

Surface tension is because of cohesion between liquid particles at the surface, on the other hand capillarity due to both cohesion and adhesion.

→ Major cause of surface tension is cohesion

→ Mathematically $\sigma = \frac{F}{L}$ unit N/m

where, σ – surface tension (N/m) F – tensile force l – length (m)

→ It is dependent on the fluid in contact with the liquid surface.

→ It is temperature dependent and decreases with rise in temperature and becomes zero at critical point.

Surface tension also represents the stretching work that needs to be done to increase the surface area of liquid by unit amount.

$$\text{Surface tension} = \frac{\text{Work done}}{\text{Increase in surface area of liquid}}$$

Note: The effect of pressure on surface tension is usually negligible.

Surface tension for water at 20°C = 0.073 N/m

For mercury = 0.440 N/m

The surface tension of mercury is large enough that mercury droplets form nearly spherical balls.

How to reduce surface tension: →

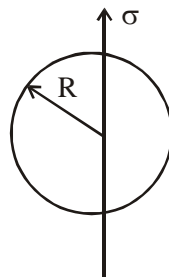
Certain chemicals, called surfactants, are added to liquid to decrease its surface tension. For e.g. soaps & detergents lower the surface tension of water.

Excess Pressure

A curved interface indicates a pressure difference across the interface with pressure being higher on the concave side.

Case I: Pressure Intensity inside a liquid droplet or air bubble.

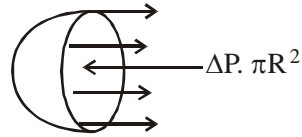
P_i = inner pressure P_o = outer pressure



$$\Delta P = P_i - P_o = \text{excess pressure}$$

A_c = circumferential area

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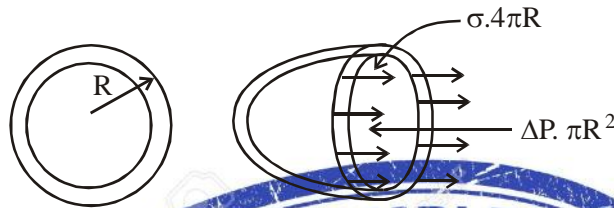


$$\Delta P \cdot \pi R^2 = \sigma \cdot 2\pi R \quad [\text{Surface tension} \times \text{Circumferential area}]$$

$$\Delta P = \frac{2\sigma}{R}$$

Case II: Pressure Intensity inside a soap bubble

$$\Delta P \cdot \pi R^2 = 4 \sigma \pi R$$



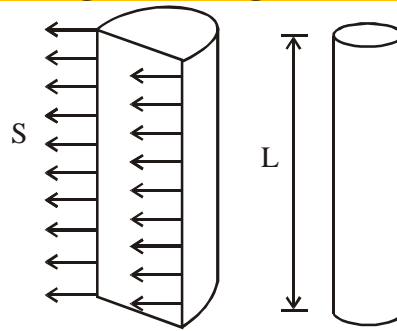
$$\Delta P = \frac{4\sigma}{R}$$

Note: When the droplet or bubble is in the atmosphere, P_o is simply atmospheric pressure

\Rightarrow The extra factor of 2 in the force balance for soap bubble is due to the fact that soap film has 2 surfaces (Inner & Outer) in contact with air.

Case III: Surface tension on a liquid jet consider a jet of length l , and diameter d .

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Force due to pressure = $P \times L \times d$

Force due to surface tension = $\sigma \times 2L$

For equilibrium $P \times L \times d = \sigma \times 2L$

$$P = \frac{\sigma \times 2L}{L \times d} \quad \boxed{P = \frac{2\sigma}{d}}$$

where, P – pressure intensity inside the jet (N/m^2)

σ – surface tension (N/m)

L – length of jet

d – diameter of jet

Wetting and Non-wetting liquid:

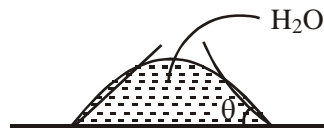
It depend on both cohesion and adhesion. It is mutual property of liquid-surface.

Angle of contact (θ)

It is the angle that the tangent to liquid surface makes with the solid surface at the point of contact.

If Adhesion \gg Cohesion:

Wetting (water – glass) $\left(\theta < \frac{\pi}{2} \right)$



θ for water glass

For pure H_2O glass $\theta = 0^\circ$

If cohesion \gg Adhesion (Non wetting) (Hg-glass) $\left(\theta > \frac{\pi}{2} \right)$

Capillarity: If a tube of very fine diameter is immersed in liquid then there may be the rise or fall of liquid level inside the tube depending upon the wetting and non-wetting behavior of the liquid with the tube surface,

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this rise or fall of liquid level is a phenomenon known as 'capillarity' and then the tube is very small diameter is said to be 'capillary tube'.

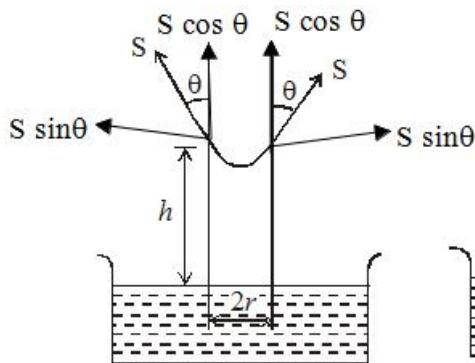


Figure. Capillary rise

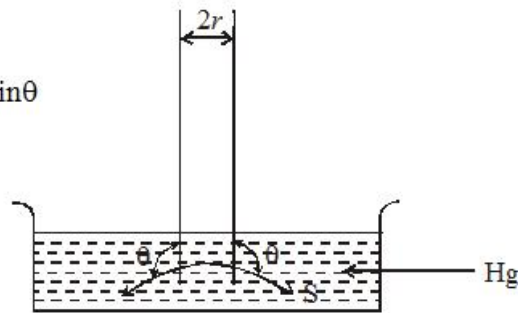


Figure. Capillary depression

Here, S is the force due to surface tension. The component $S \sin \theta$ will cancel out because of symmetry & $S \cos \theta$ will add up over the circumference of tube i.e. $2\pi r$

$$\therefore \uparrow = \frac{S}{2\pi r}$$

$$\text{or } S = \uparrow (2\pi r)$$

$$S \cos \theta = \uparrow (2\pi r) \cos \theta \quad \dots(i)$$

This vertical component of surface tension force will balance the weight of liquid column.

$$w = mg$$

$$w = \rho vg$$

$$w = \rho g (\pi r^2 h)$$

Equation (I) and (II)

$$\rho g (\pi r^2 h) = 2\pi r \sigma \cos \theta$$

$$h = \frac{2\sigma \cos \theta}{\rho r g}$$

$$\text{Capillary, rise, } h = \frac{2\sigma \cos \theta}{\rho r g}$$

Where, h = capillary rise or fall (m)

θ = angle of contact between liquid and glass tube

ρ = density of liquid (kg/m^3)

$g = 9.81 \text{ m/s}^2$ (Acceleration due to gravity)

σ = surface tension (N/m)

for water and clean glass tube $\theta = 0^\circ$.

– for mercury and glass tube $\theta = 128^\circ$.

– When the tube of radius r , is inserted in a mercury of specific gravity (S_1) and above which another liquid

of specific gravity (S_2) lies then capillary depression

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$$h = \frac{2\sigma \cos \theta}{r \gamma_w (S_1 - S_2)}$$

γ_w – Specific weight of water.

Note: for non-wetting liquid (e.g. mercury) $\theta > 90^\circ$, $\cos \theta = -ve$

Capillary rise (or fall) is inversely proportional to the radius of tube.

In practice, for tube diameter greater than 1cm, capillary effect for water is usually negligible.

Vapour pressure: If the liquid is confined in a closed vessel, the ejected vapour molecules get accumulated in the space between the free liquid surface and top of the vessel. This accumulated vapour of the liquid exerts a partial pressure on the liquid surface which is known as vapour pressure of the liquid.

Cavitation: It is the rupture of a liquid, or of a fluid-solid interface, caused by the reduction of the local static pressure produced by the dynamic action of the fluid in the interior and/or boundaries of liquid-system.

Cavitation occurs when the microscopic voids in liquid grow to a significant, visible size.

Difference between boiling and cavitation.

Though boiling is also the formation of voids in a liquid.

But boiling is caused by increase in temperature and cavitation is caused by reduction in pressure

\therefore Two phenomena are different.

Minimizing cavitation

Cavitation must be avoided in most flow system since it reduces performance, generates vibrations and noise and causes damage to equipment.

To minimize cavitation, the pressure should be maintained above vapour pressure of fluid everywhere in the flow.

Note: Since vapour pressure increases with increasing temperature, the risk of cavitation is greater at higher fluid temperature.

QUESTION SET

Q.1. A 2kg object weighs 1.9kgf on a spring balance. The value of g at this location (in m/s^2) is

- (a.) 0.95 (b.) 10.322 (c.) 9.316 (d.) 9.806

Solution: $F = ma(\text{kgf})$

$$F = 1.9 \times 9.8N$$

$$F = 18.62N$$

$$\text{Also } F = mg$$

$$\therefore mg = 18.62N$$

$$g = \frac{18.62N}{2kg} = 9.31m/s^2$$

Q.2. For $\mu = 0.249kg\ m^{-1}\ s^{-1}$ and $v = 3 \times 10^{-4}m^2/s$. Find specific gravity.

- (a.) 0.83 (b.) 0.93 (c.) 0.08.3 (d.) 0.093

Solution: $\dots(\text{density}) = \frac{\mu}{v} = \frac{0.249}{3 \times 10^{-4}} = 0.083 \times 10^4 = 0.83 \times 10^3\ kg/m^3$

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$$\text{Specific gravity} = \frac{\text{Density of liquid}}{\text{Density of water}}$$

$$S = \frac{0.83 \times 10^3 \text{ kg/m}^3}{10^3 \text{ kg/m}^3} = 0.83$$

Q.3. Viscosity has the dimensions

- (a.) $M^{-1}LT$ (b.) $ML^{-1}T^{-1}$ (c.) $ML^{-1}T^{-3}$ (d.) MLT^{-3}

Solution: $\ddagger = \sim \frac{du}{dy}$

$$\sim = \frac{\ddagger}{du/dy} = \frac{F/A}{du/dy} = \frac{[MLT^{-2}]/[L]^2}{[LT^{-1}]/[L]}$$

$$[\sim] = [ML^{-1}T^{-1}]$$

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