Fluid Mechanics

Unit – I

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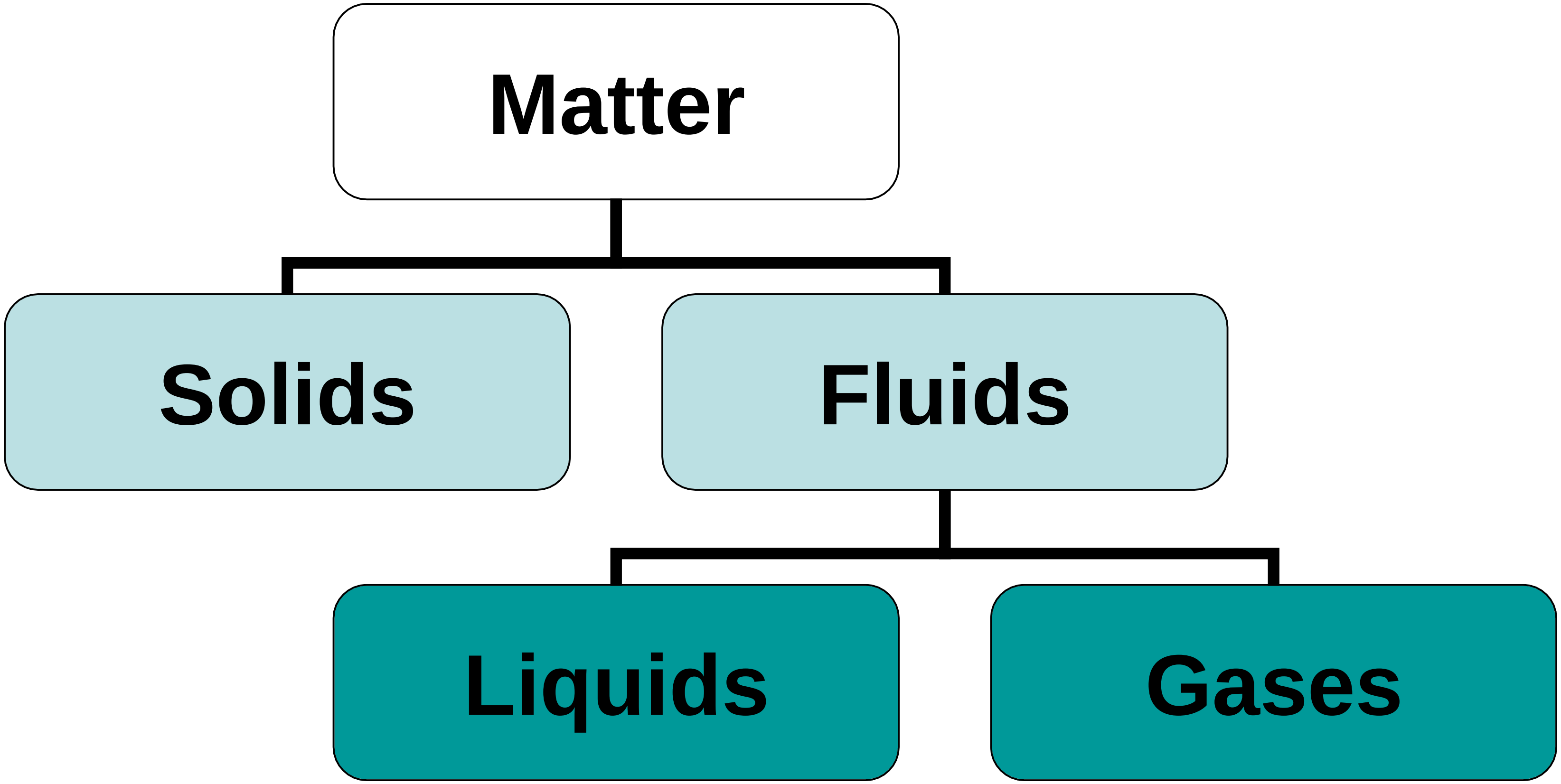
Fluid Mechanics - Introduction



Fluid Mechanics - Introduction

Solid	Fluids: Liquid	Fluids: Gases
• Molecules are closely packed • Can resists tensile, compressive and shear forces up to certain limit	• Molecular spacing more than solid but sufficient to keep in definite volume	• Forces of attraction are much less & hence great freedom
	Fluids have no tensile strength of very little of it and it can resists compressive forces only when it is kept is a container. When subjected to shear force fluid deforms continuously as long the force is applied	

- The inability of fluid to resists the shearing stresses gives them a characteristics property to change the shape of flow

Important aspect about fluid

- Though fluid is unable resists the shearing stresses it offers resistance to shearing force
- There exists a shearing stress between adjacent layers when the fluid flow
- If the fluid is at rest there exists no shear force

Gases Vs Liquids

❑**Gases are compressible whereas liquids are incompressible**

❑**Gases expand indefinitely and liquids does not**

Definition of Fluid

Fluid may be defined as the substance which is capable of flowing. It has no definite shape of its own but confirms to the shape of the containing vessel; further even a small amount of shear force exerted on a fluid will cause it to undergo a deformation which continues as long as the force continues to be applied

- The important and comprehensive definition to be remembered

What is Fluid Mechanics

- **Branch of science which deals with the behavior of fluid at rest as well as in motion and Includes study of both liquids and gases**
- Gases are mostly studied as a part of Thermodynamics and Fluid Mechanics mostly caters to liquids
- Scope involves – water supply, irrigation, navigation, power plants, piping engineering, bio-engineering, hydro machinery………
- With advent of Computational Techniques for solving flow problems (CFD) significance of fundamental understanding of fluid mechanics has increased.

Fluid Mechanics

Fluid Mechanics

- **Fluid Statics**
  Study of fluid at rest
- **Fluid Kinematics**
  Study of fluid in motion without consideration of forces
- **Fluid Dynamics**
  Study of fluid in motion with the consideration of forces

Course contents

- **Please refer SPPU curriculum**

- **Text Books**

1. Dr. P.N. Modi and Dr. S.M. Seth - Hydraulics and Fluid Mechanics including Hydraulic Machines, Standard Book House

2. Dr. R.K. Bansal - Fluid Mechanics and Hydraulic Machines - I, Laxmi Publication Pvt. Ltd., New Delhi.

3. Streeter, Wylie, Bedford - Fluid Mechanics, McGraw Hill Publication.

4. Raja Subramanian – Fluid Mechanics (Introduction and Applications) Jaico Publication House 2010

- **Reference Books**

1. White - Fluid Mechanics, McGraw Hill Publication

2. Irving Shames - Mechanics of Fluid, McGraw Hill Publication

3. Murlidhar and Biswas - Advanced Fluid Engineering, Narosa Publication.

4. G. S. Sawhney - Fundamentals of fluid mechanics, I.K. International Publishing House Pvt. Limited, New-Delhi, 2008

- The above list is suggested by the faculty, you may refer SPPU as well

Properties of Fluid

Mass density :–

mass per unit volume – kg/m^3 (read as kg per cubic meter) – 1000 kg/m^3 for water – denoted by ρ (Find the value for air in books)

Specific weight :–

Weight per unit volume N/m^3 – 9810 N/m^3 for water - denoted by w or γ (gamma) (Find the value for air)

Specific volume:-

1/ρ - m^3/kg (Read as cubic meter per Kg)

Specific Gravity:-

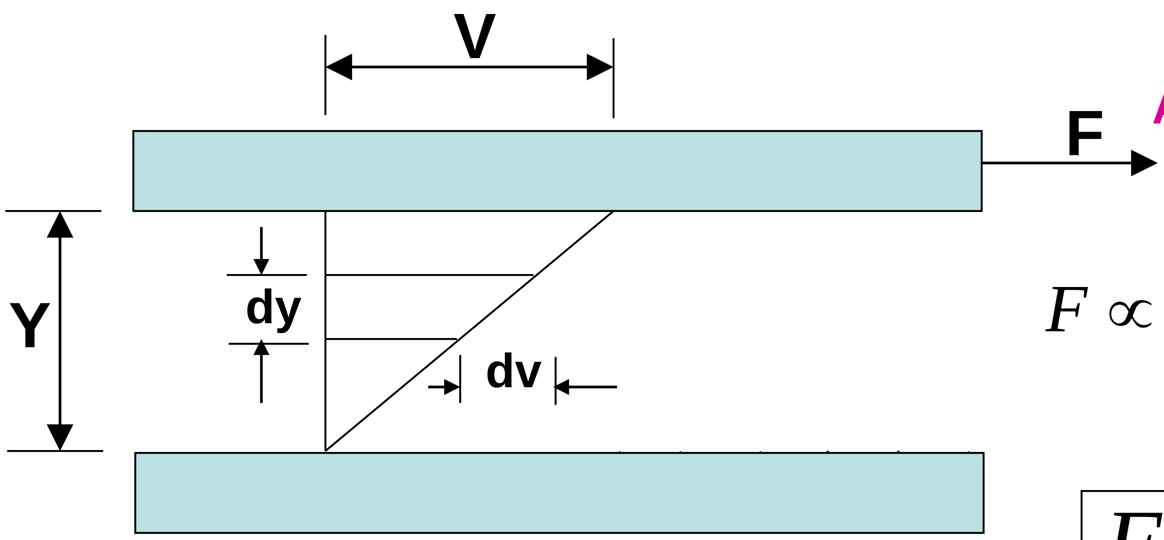
$$\frac{\text{mass density of fluid}}{\text{mass density of standard fluid}}$$

- ✓ **Standard fluid is usually water and its specific gravity is 1**
- ✓ **Specific gravity has no unit or it's a dimensionless quantity**
- ✓ **Also known as relative density**

Viscosity – The most important property

- Viscosity is the property of fluid by virtue of which it offers **resistance to the flow** of one layer of fluid over an adjacent layer.

- It is primarily due to **cohesion** and **molecular momentum exchange** between fluid layers and as the flow occurs these effects appear as shearing stresses between the moving layers of fluid



Appreciate the physics

$$F \propto A \; ; F \propto V \; ; F \propto \frac{1}{Y}$$

$$\frac{F}{A} \propto \frac{V}{Y} \propto \frac{dv}{dy}$$

Viscosity – The most important property

$$\frac{F}{A} = \tau$$ ⟹ $$\tau = \mu \frac{dv}{dy}$$ – **Newton's Equation of Viscosity**

τ = shear stress

μ = Coefficient of viscosity or viscosity or absolute viscosity or dynamic viscosity

Thus

$$\mu = \frac{\tau}{dv / dy}$$

Mathematically, viscosity is defined as the shear stress required to produce unit rate of angular deformation

SI unit is $N.s/m^2$

1 $N.s/m^2$ = 10 poise

1 Poise = dyne-sec/cm^2

Kinematic Viscosity

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

ν = the Kinematic viscosity
ρ = mass density

SI unit is m^2/s **1 $m^2/s = 10^4$ Stokes**

1 Stoke = cm^2/s

- **Its independent of pressure in the range normally encountered in practice**
- **Changes substantially with temperature – for liquid it decreases with temperature and for gases it increases with it.**

Measurement of viscosity of liquids using Redwood viscometer

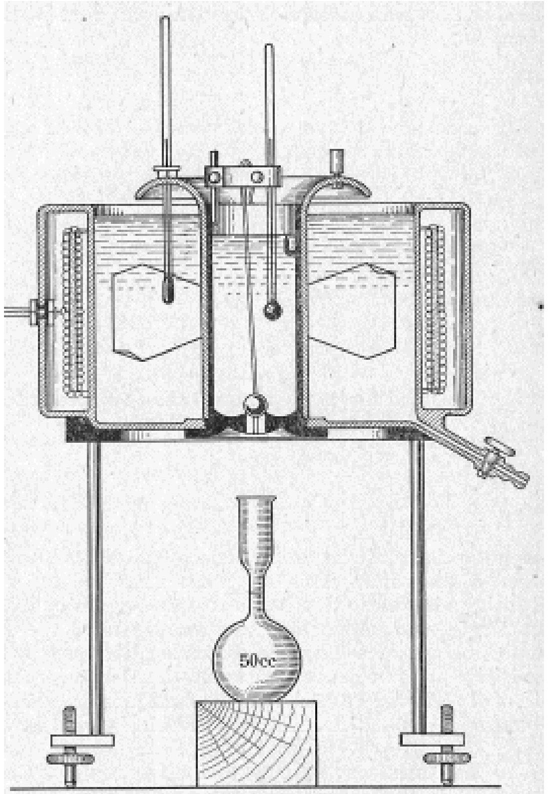
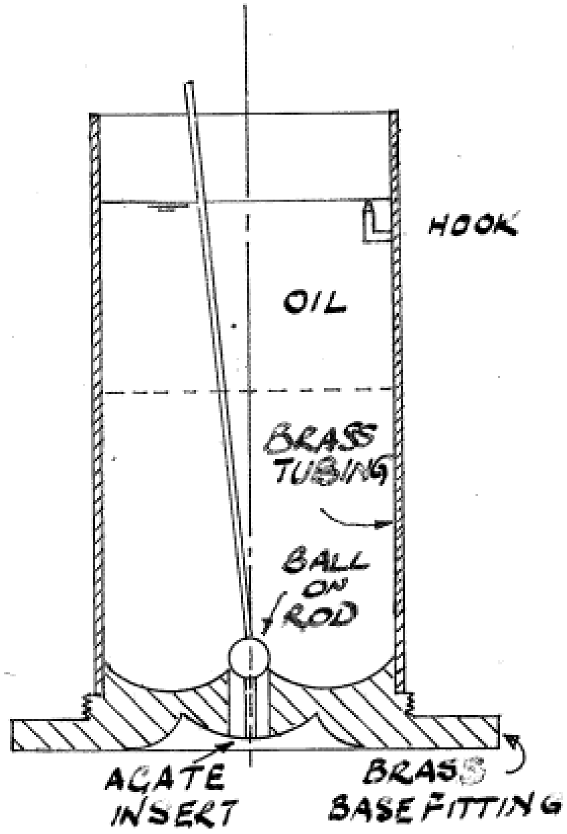
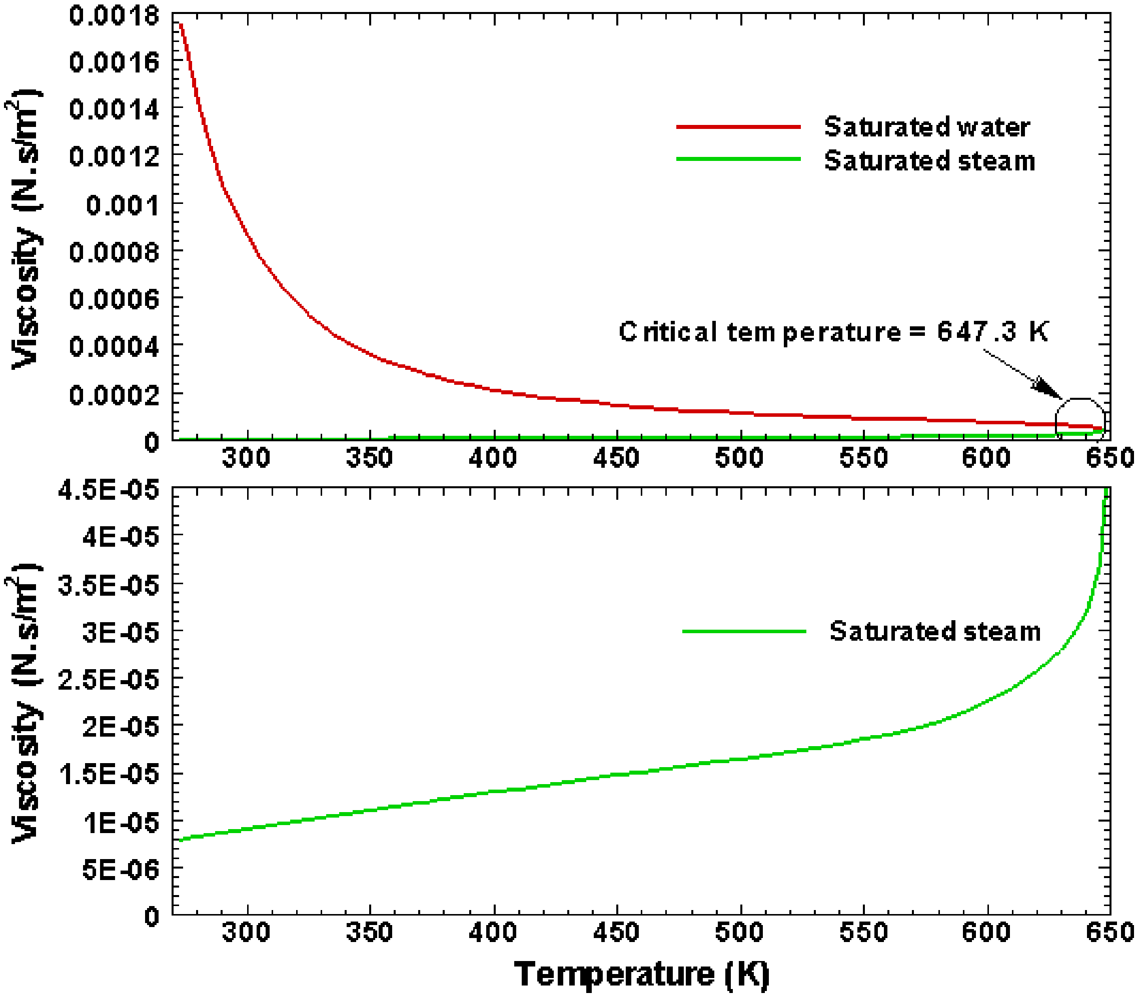


Fig. 206



$$\upsilon(\textbf{Stokes}) = 0.0026t(\textbf{sec}) - \frac{1.175}{t(\textbf{sec})} \qquad \mu = \rho \times \upsilon$$

Effect of pressure and temperature on Viscosity

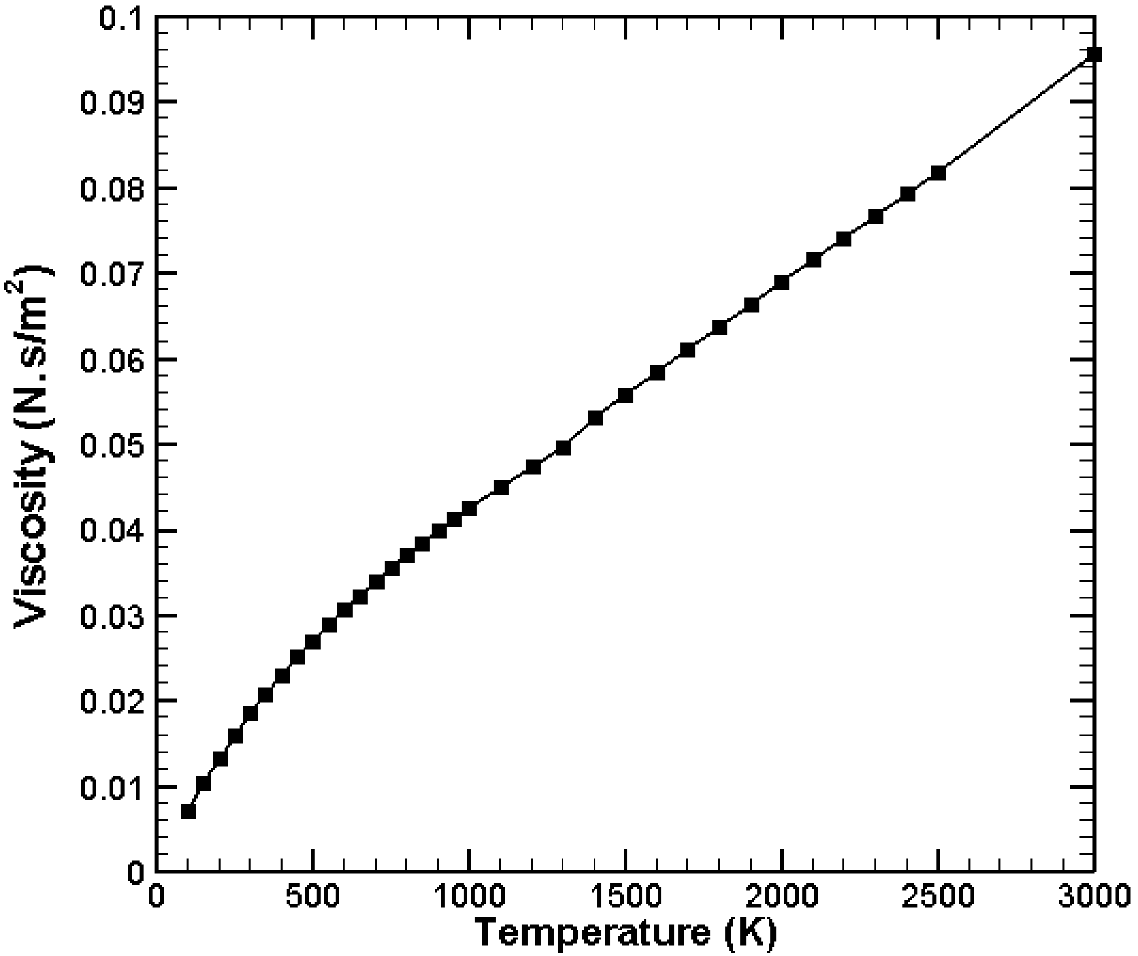


- For liquids - decreases with temperature

- For gases - increases with increase in the temperature.

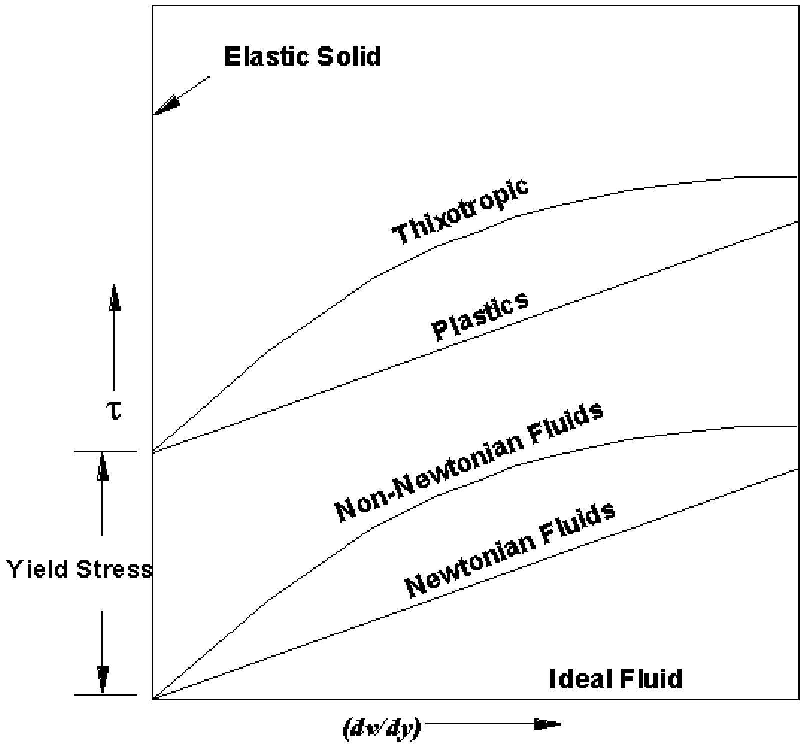
Viscosity is independent of pressure in the range normally encountered in practice

Effect of temperature on the viscosity of air



Types of Fluids

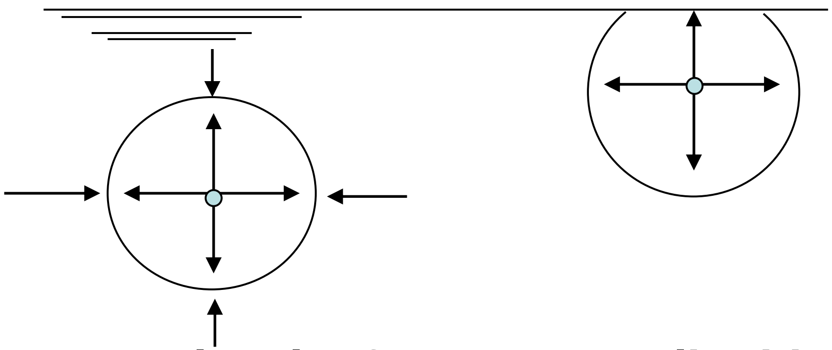
- **Newtonian Fluids – follow Newton's Law of Viscosity e. g. water, air, glycerin, kerosene etc.**
- **The relation between magnitude of shear stress and resulting rate of deformation is linear.**
- **Non-Newtonian Fluids – Non-linear relation between magnitude of shear stress and resulting rate of deformation**
- **Ideal Fluid – zero viscosity – horizontal axis**



- **Plastics** – non-Newtonian substance which needs an initial yield stress to cause a continuous deformation
- **Thixotropic substance - non-Newtonian which has non-linear relation between shear stress and rate of deformation beyond initial yield stress (printers ink).**
- **Elastic body – represented by vertical axis**

Study of non-Newtonian fluids is called Rheology

Surface Tension



Inter molecular forces near a liquid surface

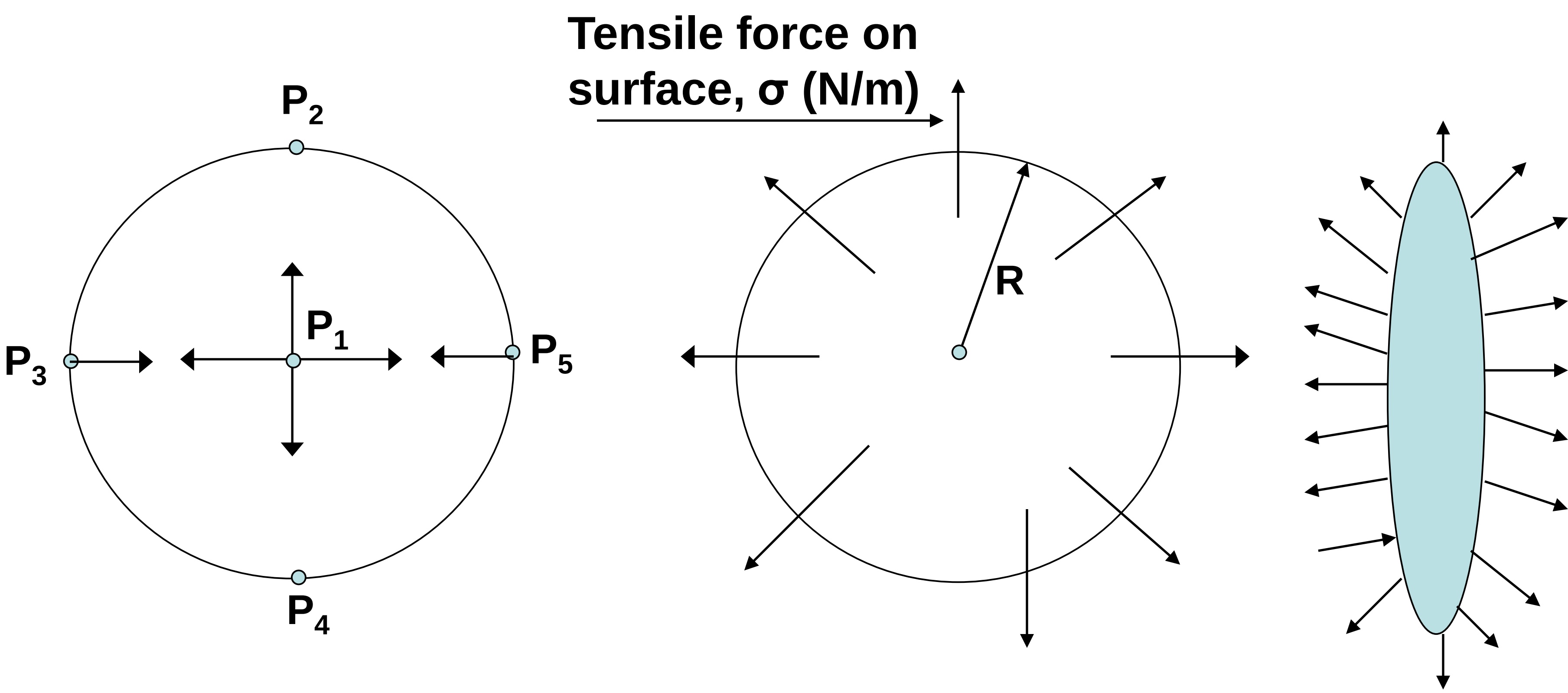
❑Consider the liquid at rest

❑The inner molecule is equally attracted on all sides and hence is in equilibrium

❑The molecules near the surface experience a tensile force.

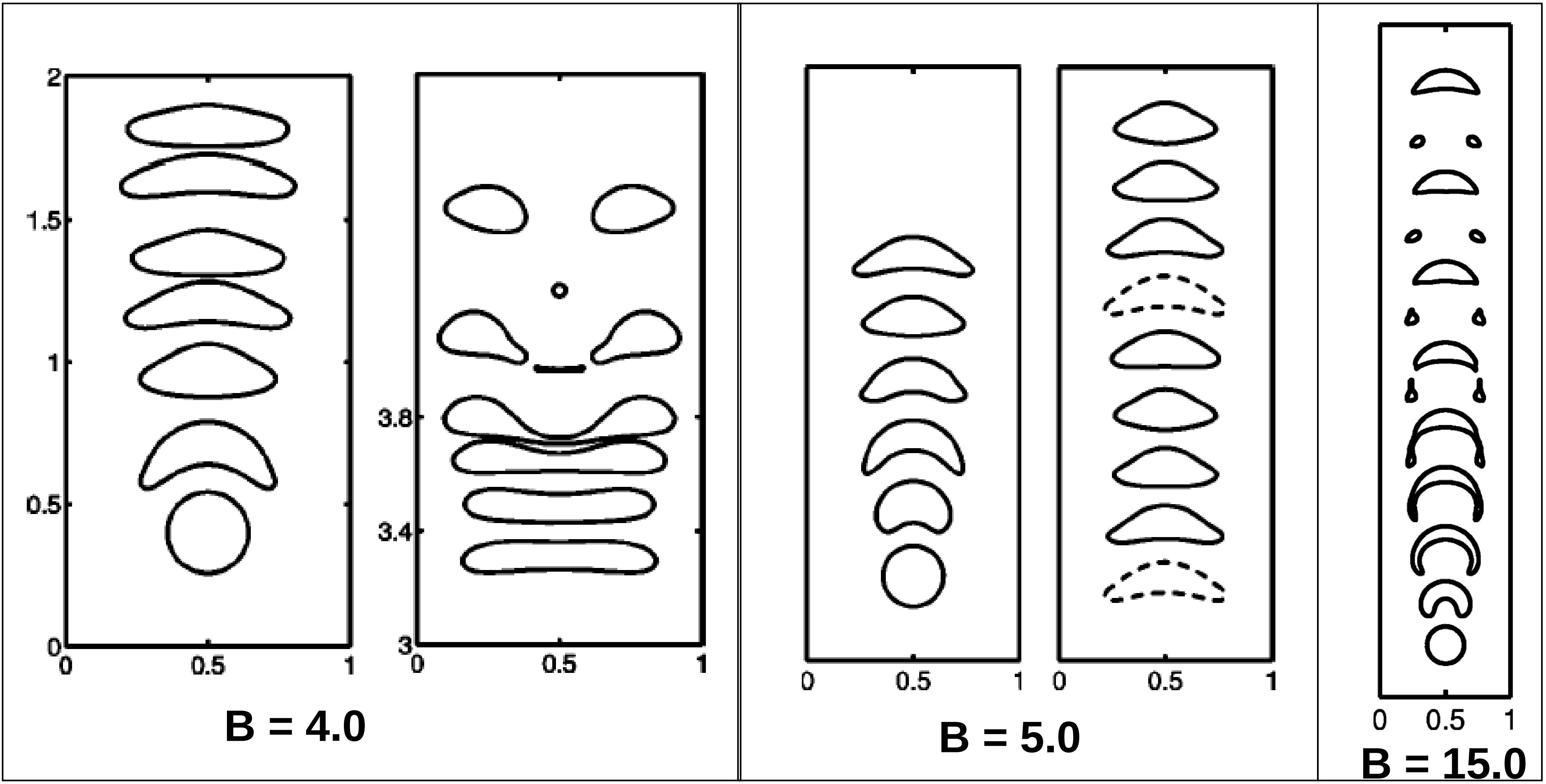
- The property of the liquid surface to exert a tension is called surface tension
- It is the force required to maintain the unit length of film under equilibrium
- SI unit is N/m and its magnitude depends on the fluid in contact with liquid; also depends on temperature; decreases with rise in temperature
- Water and air – 0.075 N/m at 19°C and 0.06 N/m at 100°C
- Mercury and air – 0.504 N/m at room temp

Surface Tension in a droplet



- Consider a vertical plane at the centre of the fluid droplet through P_1, P_2 and P_4
- Magnitude of Tensile force on vertical plane = $\sigma \times 2\pi R$
- Force on the vertical plane due to pressure = $p \times \pi R^2$
- The force equilibrium gives $\sigma = \dfrac{pR}{2}$

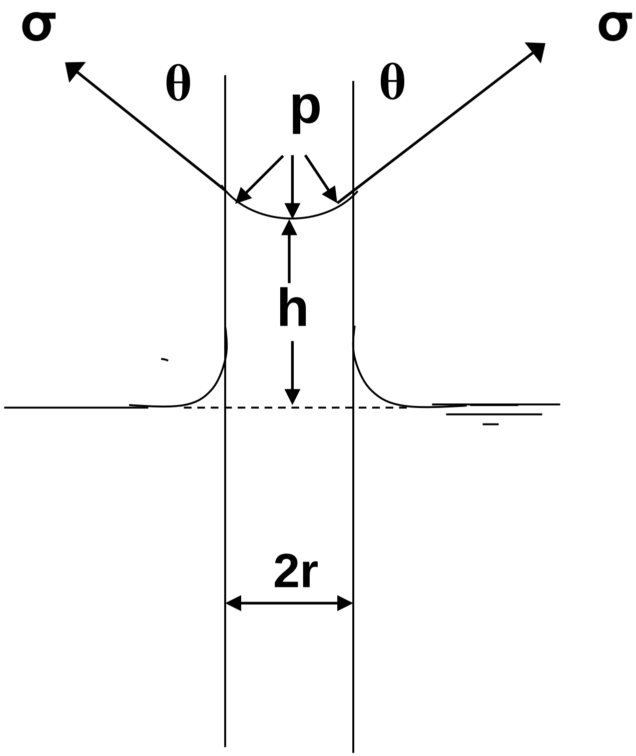
Surface Tension in a bubble – a significance



Variation in the shape of the bubble with change in a Bond number which is a function of surface tension (Norman and Michael, Physics of Fluids, 2005)

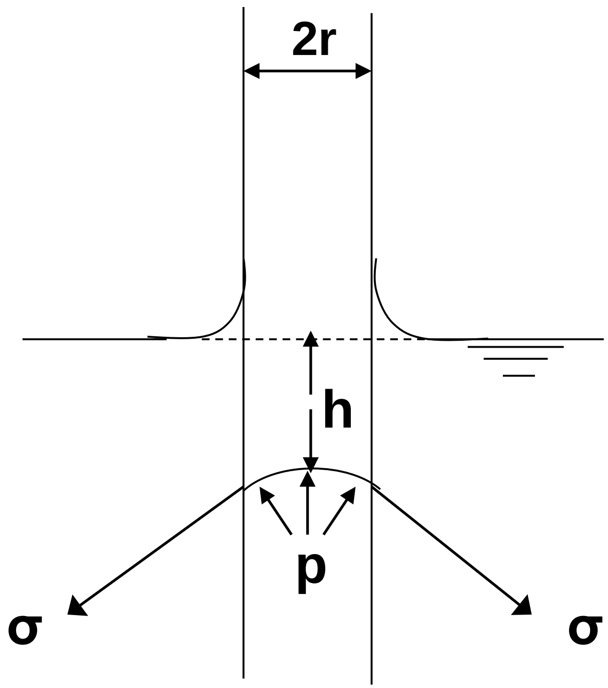
Capillarity

Dominant adhesion



Capillary Rise

Dominant cohesion



Capillary Depression

- The phenomenon of rise or fall of liquid surface relative to the adjacent general level of liquid is known as capillarity
- Rise of depression can be determined by considering the equilibrium of the liquid column in a small tube

Capillarity

The forces acting on the liquid column are:

1. **Self weight of fluid – (Specific weight × volume of fluid) acting in the downward direction**

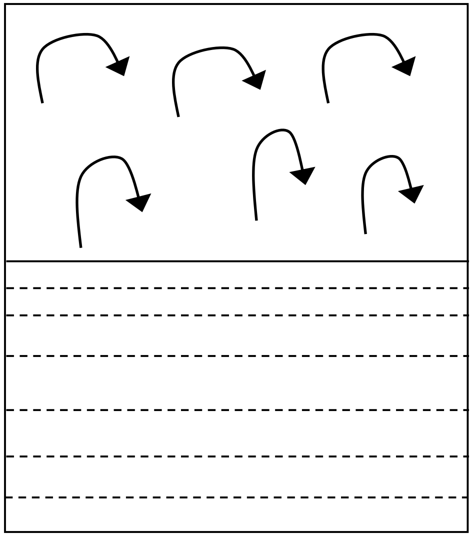
2. **Total force due to ST – (σ × circumference) × cosθ – acts in the upward direction for rise and downward direction for depression**

Thus $sw\pi r^2 h = 2\pi r \sigma \cos\theta$ ⇒ $h = \dfrac{2\sigma\cos\theta}{swr}$

For water θ = 0 ⇒ $h = \dfrac{2\sigma}{swr}$

Assumption : the curved surface of the meniscus is a section of sphere which is true for r < 2.5 mm

Vapour Pressure



- Temperature and pressure are dependent properties for pure substance
- Saturation temperature – at given pressure pure substance changes the phase (Water – at 1 atm - 100°C
- Saturation pressure - at given temperature pure substance changes the phase (Water – at 100°C -1 atm)

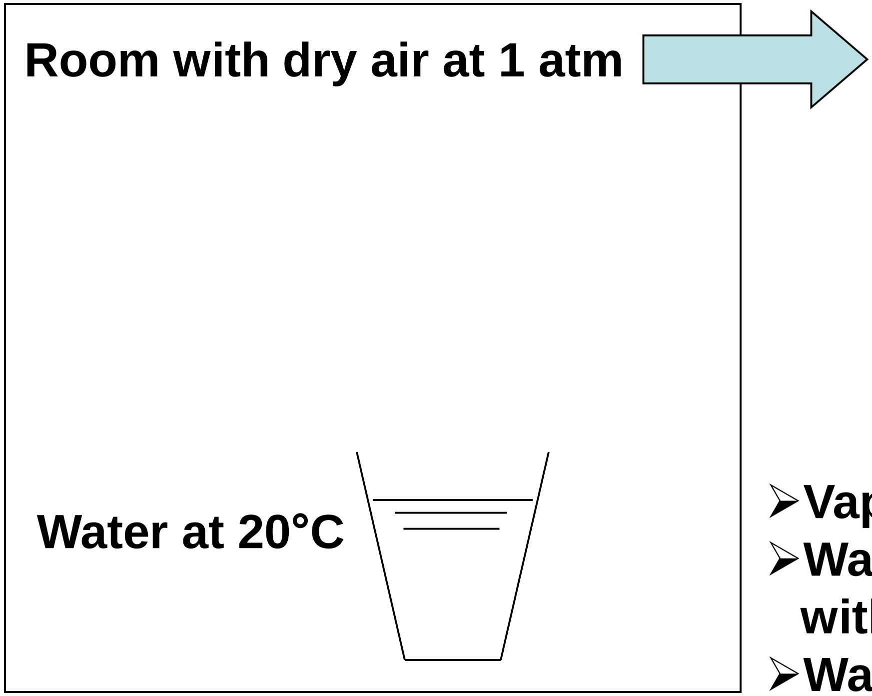
- The vapor pressure of a pure substance is defined as the pressure exerted by its vapor in *phase equilibrium* with its liquid at a given temperature.

- P_v is the property of pure substance and it turns out to be equal to saturation pressure, P_{sat} i. e. ($P_v = P_{sat}$)

- **Do not confuse vapor pressure with partial pressure**

- **Partial pressure is always less than or equal to vapor pressure**

Vapour Pressure



Two possibilities

- **Water evaporates away or**
- **Evaporation stops when partial pressure of vapor in the room rises to 2.34 kPa at which phase equilibrium is established**

- **Vapor pressure increases with temperature**
- **Water boils at 134°C in a pressure cooker with 3 atm pressure.**
- **Water boils at 93°C at 2000m elevation where pressure is 0.8 atm**

Cavitation

In the system at any point if pressure reduces below the vapour pressure liquid starts boiling and vapour bubbles are formed. When bubbles move to high pressure region these collapse giving rise to high impact pressure which may erode the adjoining walls and cause the cavity formation. Such a phenomenon is called cavitation.

Vapour Pressure

Saturation pressure for different liquids

Liquid	Saturation pressure in bar
Carbon Tetrachloride	0.12753
Benzene	0.100062
Ethyl Alcohol	0.057879
Water	0.023446
Mercury	1.73×10^{-6}
Glycerin	1.37×10^{-7}

Saturation pressure of water at different temperatures

Temperature in °C	**Saturation pressure in bar**
-10	**0.0026**
-5	**0.00403**
0	**0.00611**
10	**0.0123**
20	**0.0234**
100	**1.013 (1 atm)**
200	**15.54**
300	**85.81**

Compressibility and Elasticity

All the fluids may be compressed by application of external force and when this force is removed the compressed volume expands to its original volume. This property of fluid is known as compressibility. It is be quantitatively expressed as inverse of bulk modulus of elasticity.

$$k = \frac{\textbf{stress}}{\textbf{strain}} = -\frac{dp}{dV/V}$$

Matter	Bulk Modulus in N/m2	Remark
Water	2.06×10^{9}	**Water is considered as practically incompressible**
Mild Steel	2.06×10^{11}	**Water is 100 times compressible than M.S.**
Air	1.03×10^{5}	**Air is 20000 times compressible than water**

Mach number and velocity of sound

Inertia force, F_i = mass × acceleration → $F_i = \rho \times L^3 \times \frac{L}{T^2}$

$$F_i = \rho \times L^2 \times \frac{L^2}{T^2} \Rightarrow F_i = \rho \times L^2 \times V^2$$

Elasticity force, F_e = Bulk modulus × area → $F_e = k \times A$

$$\Rightarrow F_i = k \times L^2$$

Thus $\frac{F_i}{F_e} = \frac{\rho \times L^2 \times V^2}{k \times L^2} = \frac{V^2}{k/\rho} = \frac{V^2}{c^2}$ → **Cauchy Number**

- **Where '*c*' is the velocity of sound and is given by** $c = \sqrt{k/\rho}$ **which represents the velocity of sound**
- **The square root of Cauchy number is called Mach number**

Mach number and velocity of sound

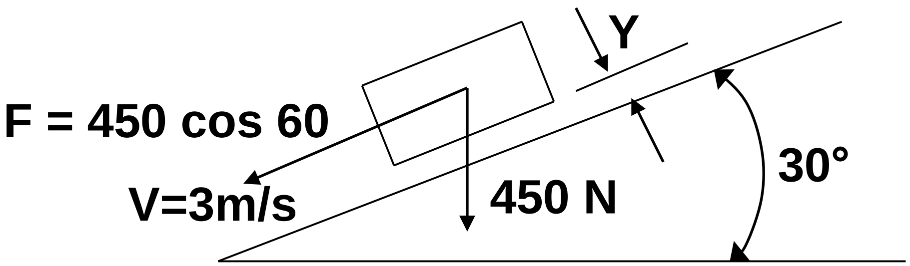
$$M_a = \frac{V}{c} = \frac{V}{\sqrt{k/\rho}}$$

- **V = *c* indicates critical value of fluid velocity – Sonic Flow**
- **V > *c* – Supersonic Flow**
- **V < *c* – Subsonic Flow**
- **V >> *c* – Hypersonic Flow**

- **Higher Mach number signifies the predominance of effect of compressibility**.
- **If Ma < 0.4 the effect of compressibility can be neglected**

Problem – A body weighing 450 N with a flat surface area of 930 cm^2 slides down lubricated inclined plane making an angle of 30° with horizontal. For viscosity of 1 poise and body speed of 3m/s, determine the lubricant film thickness.

Solution



Given – Weight of the body = 450 N

Area of plate = 930cm^2 = 0.093m^2

Angle of inclination = 30 °

viscosity = μ = 1 poise = 0.1 N.s/m2

Velocity of body = V = 3 m/s

Assumptions – Fluid is Newtonian and follows linear variation between shear stress and rate of angular deformation

Force along the direction of plane = 450 cos 60 = 225 N

Shear stress, $\tau = Force / area = 225(\mathbf{N}) / 0.093(\mathbf{m^2}) = 2419.35(\mathbf{N/m^2})$

$$\tau = \mu \frac{dv}{dy} = \frac{V}{Y} \Rightarrow 2419.35(\mathbf{N/m^2}) = 0.1(\mathbf{N.s/m^2}) \times \frac{3(\mathbf{m/s})}{Y(\mathbf{m})}$$

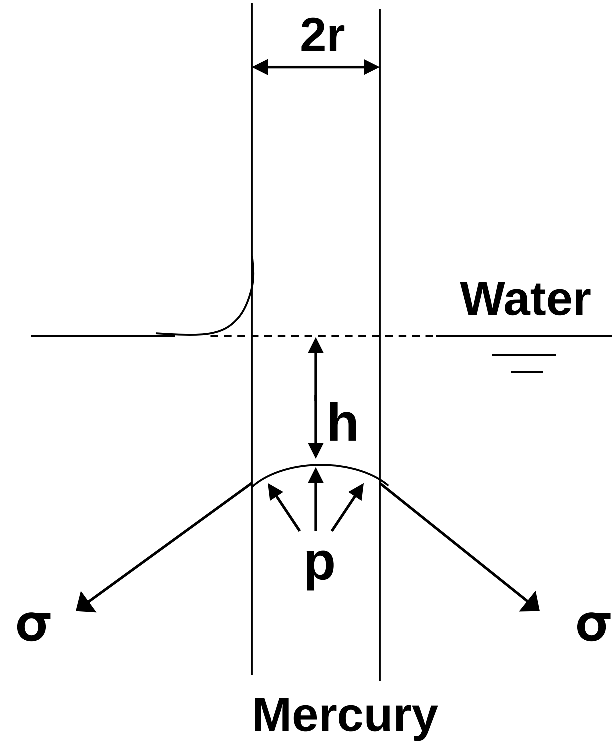
Y = 0.000124m = 0.124mm

Problem – A glass tube 0.25 mm in diameter contains a mercury column with water above the mercury. The temperature is 20 °C at which the surface tension of mercury in contact with air is 0.37 N/m. What will be the capillary depression of the mercury? Take angle of contact as θ = 130 °

Solution :

Given

- **Radius of tube, r = 0.125 mm**
- **Surface tension σ = 0.37 N/m**
- **Angle of contact θ = 130 °**



$$h = \frac{2\sigma\cos\theta}{rw(s_1 - s_2)}$$

$$h = \frac{2\times 0.37\times\cos 130}{0.125\times 10^{-3}\times 9810(13.6-1)} = -0.0307\,\mathbf{m} = -3.07\,\mathbf{cm}$$

Problem - A 400mm diameter shaft is rotating at 200 rpm in a bearing of length 120mm. If thickness of the oil film is 1.5mm and dynamic viscosity of oil is 0.7N.s/ m2 , determine torque required to overcome the friction in the bearing and power utilized in overcoming viscous resistance. Assume linear velocity profile.

Solution

- **Radius of shaft, r = 0.2m**
- **Viscosity μ = 0.7 N.s/m^2**
- **Y = 1.5 mm, N = 200 rpm**
- **Length of shaft, L = 0.12 m**

$$V = \frac{\pi DN}{60} = \frac{\pi \times 0.4 \times 200}{60} = 4.186 \ \mathbf{m/s}$$

$$A = 2\pi \times R \times L = 2\pi \times 0.2 \times 0.12 = 0.15072\mathbf{m^2}$$

$$\tau = \mu \frac{dv}{dy} = 0.7(\mathbf{N.s/m^2}) \frac{4.186(\mathbf{m/s}) - 0}{1.5 \times 10^{-3}(\mathbf{m^2})} = 2790.66\mathbf{N/m^2}$$

$$F = \tau \times A = 2790.66(\mathbf{N/m^2}) \times 0.15072(\mathbf{m^2}) = 420.60\mathbf{N}$$

$$T = F \times R = 420.60 \times 0.2 = 84.12\mathbf{N/m}$$

$$Power = \frac{2\pi NT}{60} = \frac{2\pi \times 200 \times 84.12}{60} = 1760.91\mathbf{Watt}$$

A Newtonian fluid is in the clearance between a shaft and a concentric sleeve. When a force of 600 N is applied to the sleeve parallel to the shaft, the sleeve attains a speed of 1 m/s. If a 1500 N force is applied, what speed will sleeve attain? The temperature of the sleeve remains constant.

In a 5 cm long journal bearing arrangement, the clearance between journal and bearing is 0.1 mm. The shaft is 2 cm diameter and rotates at 3000 rpm. The dynamic viscosity of the lubricant is 0.1 poise. Considering the liquid to be Newtonian, calculate frictional torque- the journal has to overcome and the corresponding power loss?