UES011: THERMO-FLUIDS

(FLUIDS/FLUID MECHANICS**)**

- This course teaches the application of the principles of mechanics to the analysis of fluids at rest or in motion.
- Analysis of fluid systems in engineering includes techniques for flow measurement, determination of forces exerted by fluids, analysis of fluid propulsion systems etc.

What is mechanics and fluid mechanics?

- Mechanics - oldest physical science that deals with stationary and moving bodies under the influence of forces.
- Fluid mechanics - subcategory of mechanics that deals with the study of fluids at rest (fluid statics) or in motion (fluid kinematics and fluid dynamics).
- Also deals with the interaction of fluids with solids at the boundaries and other fluids.

Fluid dynamics can be divided into several categories - Hydrodynamics, Hydraulics, Gas dynamics, Aerodynamics.

- Hydrodynamics is the study of fluids in motion that are practically incompressible (e.g. liquids, especially water and gases at low speeds)
- Hydraulics - subcategory of hydrodynamics that deals with liquid flows in pipes and channels
- Gas dynamics deals with the flow of fluids that undergo significant density changes (e.g. gas flow through a nozzle at high speed)
- Aerodynamics deals with the flow of gases (especially air) at high speed over bodies such as aircraft, rockets and automobiles

Applications of Fluid Mechanics

- inter disciplinary subject
- has applications in different branches of engineering

Civil Engineering

- Hydraulics, Hydraulic structures, bridges, drainage, buildings etc.

Mechanical

- Pumps, turbines, engines, power generation, streamlining of bodies etc.

Electronics, Electrical and EIC

- Heat transfer and cooling, electronic systems, power generation, instrumentation etc.

Aerospace

- Aircraft, rockets, helicopters, jet engines etc.

Marine Engineering

- Oceanography, wave & wind power, ships, yachts etc.

Bioengineering

- Internal fluid flows, cardiovascular and respiratory systems etc.

What is a 'fluid'?

- We commonly think of a substance/matter existing in one or more of the three phases: solid/liquid/gas.
- At extremely high temperatures it can also exist as plasma.

❖ A substance in the liquid or gas phase is a fluid.

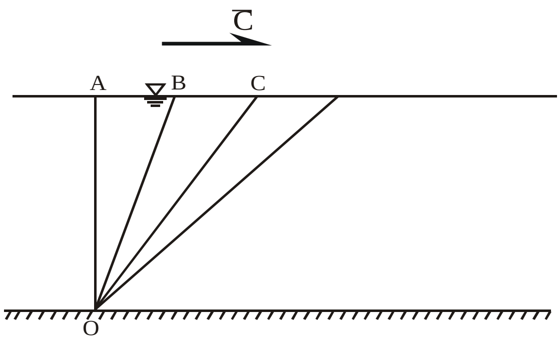
- Solids, liquids and gases exhibit different characteristic.

Description	Solids	Liquids	Gases
Molecular spacing	Closely spaced	Relatively large	Largest
Intermolecular bonds	Strong	Weaker than solids	Weak
Arrangement of molecules	Repeatable pattern	Groups of molecules move about each other	Molecules move about at random

To distinguish between solids and fluids, we need a property/characteristic which distinctly separates them. This property is the response to applied shear stress.

- A solid can resist applied shear stress whereas a fluid deforms continuously under the applied shear stress (no matter how small is it).

ILLUSTRATION: **Deformation of a fluid element at rest**



- Fluid element is represented by line **OA (**initial position over a solid surface).
- When shear stress **τ** is applied, continues to move or deform to new positions **OB**, **OC**,----
- Inability of fluids to resist shear stress give fluids, a property to flow.

Observations:

(i) Fluid at rest experiences zero shear stress (no shear stresses are present).

(ii) No slip condition occurs at the surface *i.e.* velocity of fluid relative to the surface is zero (no relative velocity, fluid particles will stick to the surface)

(iii) As fluid flows, there exist shear stresses between the adjacent fluid layers which oppose the movement of one layer of fluid over the adjacent layer - this phenomenon gives rise to viscosity of fluid

(iv) Stress is the force divided by area over which it acts.

- Tangential component of force acting on the surface per unit area is called the shear stress (shear force is the force parallel to the surface).
- Normal component of force acting on the surface per unit area is called the normal stress.

❖ For fluids at rest, normal stress is called fluid pressure.

Definition of a Fluid and Fluid Mechanics

- Fluid may be defined as a material substance which cannot sustain/resist a shear stress (deforms continuously under the action of shear stress) when it is at rest.
- As a result, a fluid is capable of flowing.It has no definite shape of its own, but conforms to the shape of a containing vessel.

Fluid mechanics - subcategory of mechanics that deals with the study of fluids at rest or in motion.

- Study of **FM** may be divided into three categories:
- Fluid Statics**- s**tudy of fluids at rest.
- Fluid Kinematics**-** study of fluids in motion without considering the forces responsible for the fluid motion.
- Fluid Dynamics**- s**tudy of fluids in motion with forces causing flow are taken into consideration.

PHYSICAL PROPERTIES OF FLUIDS

Mass density

- is the mass of fluid contained within a unit volume at standard temperature and pressure (**STP**)
- denoted by symbol ρ (rho)
- Also known as specific mass.

$\therefore$ Mass density, $\rho = \frac{m}{\forall}$, **m** is the mass of fluid having volume, $\forall$

Units

- SI system- **kg/m³**
- ρ of water at 4^oC (maximum density) and ρ of air at 20^oC and standard atmospheric pressure are 1000 kg/m^3 and 1.24 kg/m^3, respectively.

❖ Values of standard atmospheric pressure (**Absolute values**)

- 1 bar = 10^5 N/m^2 or 1 atmosphere (atm) = 101325 Pa or N/m^2 = 101.325 kN/m^2 or kPa

Specific weight

- is the weight of fluid per unit volume at **STP.**
- may be denoted by γ(gamma).
- Also known as weight density or unit weight.

∴ Specific weight, $\gamma = \frac{W}{\forall}$, **W** is the weight of fluid having volume∀

Units

- SI system- **N/m³**
- γ of water at 4°C and standard atmospheric pressure is 9810 N/m³ or 9.810 kN/m³

Relationship between mass density and specific weight

$$\frac{W}{\forall} = \frac{mg}{\forall} = \rho g \qquad \therefore \gamma = \rho g$$

Specific gravity

- is the ratio of specific weight (or mass density) of fluid, γ_s to the specific weight (or mass density) of a standard fluid.
- For liquids - standard fluid is taken as water at 4°C.
- For gases - air or hydrogen at some specified temperature and pressure.
    - ❖ Also known as relative density.
- may be denoted by **G** or **S** $\qquad \therefore G_L = \frac{\gamma_L}{\gamma_w}$

Observation:

- By knowing the specific gravity of any fluid, its specific weight can be calculated
- For example, specific gravity of mercury is 13.6, find its specific weight
- What is the specific gravity of water?

Specific volume

- is the volume per unit mass of fluid.
- Thus, reciprocal of mass density.
- Generally used in the study of compressible fluids.

Compressibility

- All matter are compressible to some extent.
- Consider some arbitrary substance undergoing compression.

- Degree of compressibility of a substance is characterised by its bulk modulus of elasticity

- Given as

$$\text{Bulk modulus, } K = \frac{\text{Stress}}{\text{Strain}} = \frac{\text{Pressure increment}}{(\text{Compressive volumetric strain})} = \frac{\delta p}{\left(-\frac{\delta\forall}{\forall}\right)}$$

- (- ve sign - increase in pressure will cause a decrease in volume)

❖ Bulk modulus of liquids is high (**K** for water = **2.2GPa)**

∴ For large pressure changes, change in density is very small

- Density of liquids can normally be regarded as constant i.e. liquids are incompressible.

❖ Bulk modulus of gases is small (**K** for air = 0.000101 **GPa)** i.e. gases are readily compressed.

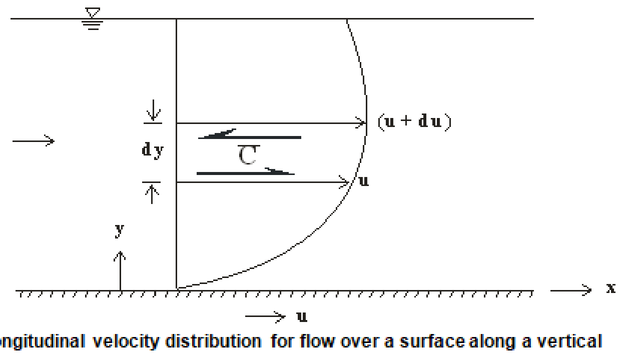
- Gases can also be considered incompressible when flow velocities are very small.
- At high velocities, compressibility of gas must be considered.

Observation: In some cases where large or sudden pressure changes are encountered, it is necessary to consider the effects of compressibility of liquids.

Example: '**water hammer'** phenomenon (rapid closure of a valve provided in pipeline)

Viscosity

- All real fluids resist shearing motion *i.e.* any force tending to cause one layer to move over another.
- Shear stresses are therefore developed within real fluids when these move.
- Resistance to the movement of one fluid layer over another is known as fluid viscosity.
- The phenomenon of viscosity can be illustrated with the help of experimental study of velocity distribution for flow over a surface.



Longitudinal velocity distribution for flow over a surface along a vertical

- Velocity
  - ➢ is zero at the surface (no slip condition).
  - ➢ increases as distance from the surface increases.
- Shows - there is some resistance to flow between the fluid layer & the surface and between the adjacent layers of fluid.

√ Consider two adjacent layers of fluid having velocities **u** and (**u+du**), distance **dy** apart.

- Upper layer is moving fast relative to lower layer.
- Due to relative velocity, a shear stress acts between these fluid layers.
- Fast moving upper layer exerts a shear stress on the lower slow moving layer in the positive direction of ***u***(x-direction)
- Similarly, lower layer exerts a shear stress in the opposite direction of **u** on the upper moving fast layer
- Newton assumed/postulated that for straight and parallel motion of a given fluid, shear stress τ acting between the fluid layers is proportional to spatial change of velocity *i.e.*

$$\text{Shear stress, } \tau \propto du/dy, \quad \text{or} \quad \tau = \mu \frac{du}{dy}$$

- μ (mu) is a constant of proportionality and is called coefficient of viscosity /dynamic viscosity/viscosity; of fluid

❖ Dynamic viscosity of fluid expresses its resistance to shearing flows, where adjacent layers move parallel to each other with different velocities

- (**du/dy**) is also called velocity gradient
- Equation is known as Newton's law of viscosity

Observations:

(i) Viscous or shear resistance to flow at the surface, $\mathbf{R = \tau A}$

- **A** is the surface area on which shear stress is acting

(ii) As shear stress is proportional to velocity gradient.

$\therefore$ Shear stress is maximum where velocity gradient is maximum and is zero where velocity gradient is zero. Maximum shear stress occurs at the surface and decreases progressively with distance away from the surface.

(iii) Viscosity of fluids is greatly influenced by variation in **T** and **P.**

Viscosity of liquids decreases with increasing temperature whereas for gases, it increases with a rise in temperature. High pressures also effect the viscosity of a liquid. Viscosity increases with increasing pressure.

(iv) For flow in pipes,

- $\mathbf{y = (R - r)}$, **R** = radius of pipe and **r** = any radius $< \mathbf{R} \therefore \mathbf{dy = - dr}$,

(v) Units and dimensions of viscosity

$$\tau = \mu \frac{du}{dy} \quad \Rightarrow \frac{\text{Force}}{\text{Area}} = \mu \frac{\text{Velocity}}{\text{distance}} \quad \Rightarrow \frac{F}{L^2} = \mu \frac{(L/T)}{L}$$

$\therefore \mu = \frac{FT}{L^2}$ L is the characteristic dimension.

Units

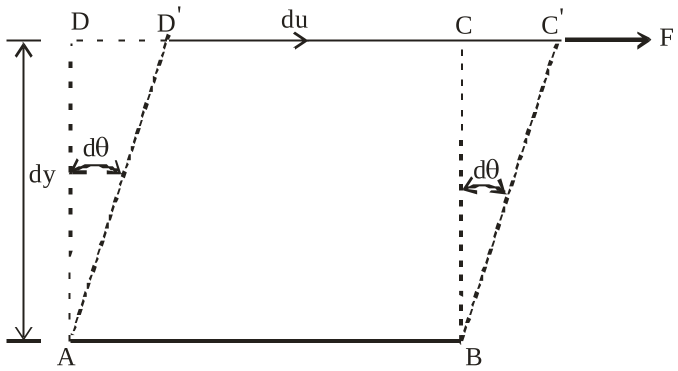
System	Units of μ
SI	Ns/m^2 = Pa s
MKS	$kg(f).s/m^2$
CGS	$dyn.s/cm^2$

- **$dyn.s/cm^2$** is also called poise (**P**)
- Poise is a relatively large unit - centipoise (**cP**) is generally used.
- 1 cP = 10^{-2} P
- Viscosity of water and air at 20^{o}C and SAP are 1 cP and 0.0181 cP, respectively.

Dimensions: $\mu = \frac{FT}{L^2} = \frac{(MLT^{-2})(T)}{L^2} = ML^{-1}T^{-1}$

- SI units of μ can also be expressed as **kg/m s.**

(vi) Viscosity of a fluid can also be defined as a measure of its resistance to shear deformation



Deformation of fluid between two plates

- Consider two plates **AB** and **CD** placed at a distance ***dy*** apart.
- Space (***ABCD***)between them is filled with a fluid
- Let a shear force **F** is applied to the upper plate **CD** in time **dt.**
- The plate moves to **C′D ′** relative to the lower plate with velocity **du.**
- Due to velocity gradient, shear stress sets up which distort the fluid element to **ABC′D′.**

$$DD' = CC' = (du \times dt)$$

- Also, for small angular displacement, **dθ**

$$DD' = dy \times d\theta$$

- Equating,

$$du \times dt = dy \times d\theta \quad \Rightarrow \frac{du}{dy} = \frac{d\theta}{dt}$$

$$\therefore \tau = \mu \frac{d\theta}{dt}$$

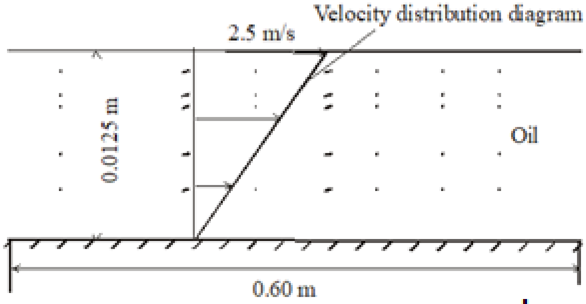
$\therefore$ In fluids, shear stress is proportional to shear strain rate [rate of fluid deformation (**$d\theta/dt$**)]

- ❖ (In solids, shear stress is proportional to shear strain)
- ❖

Problems:

Q1: The space between two horizontal square flat parallel plates of size 600 x 600 mm each, is filled with oil of specific gravity 0.95. The thickness of oil film is 12.5 mm. The upper plate which moves at 2.5 m/s requires a force of 98 N to maintain this speed. Determine (i) dynamic viscosity of oil (ii) kinematic viscosity. Assume linear velocity distribution in the gap.

Solution:



- According to Newton's law of viscosity, $\tau = \mu \frac{du}{dy}$

$\therefore$ Viscous resistance acting at the upper plate due to viscosity of oil, $\mathbf{R} = \tau \mathbf{A} = \mu \frac{du}{dy} \times \mathbf{A}$

- Here,
- **R** = **F** = 98 N (Under equilibrium condition, R = Force acting)
- **A** = 0.6 × 0.6 m²
- **du** = (2.5 – 0) = 2.5 m/s (Linear velocity distribution)
- **dy** = 12.5 mm = 0.0125 m
- Substituting the values in the equation and solve for **μ**, to get
- Dynamic viscosity, $\mu = 1.36\ Ns/m^2$ **(Ans)**
- Kinematic viscosity, $\nu = \frac{\mu}{\rho}$
- Here, $\rho = 0.95 \times 1000 = 950\ kg/m^3$

$\therefore$ Kinematic viscosity, $\nu = 14.3$ stoke **(Ans)**

Q2: A 400 mm diameter shaft is rotating at 200 rpm in a bearing of length 120 mm. If thickness of oil film is 1.5 mm and viscosity of oil is 7 P, determine (i) torque required to overcome friction in bearing (ii) power utilised in overcoming viscous resistance.

Solution: **D** = 400 mm, **n** = 200 rpm, **L** = 120 mm, **t** = 1.5 mm, **μ** = 7 P = 0.7 Pa.s

- Since the gap between shaft and the bearing is small, therefore linear velocity distribution may be assumed in the gap.
- Angular velocity of shaft, $\omega = \frac{2\pi n}{60} = \frac{2\pi \times 200}{60} = 20.94 \text{ rad/s}$

∴ Tangential velocity of the shaft, $u = \omega \times r = 20.94 \times 0.2 = 4.2 \text{ m/s}$

- **du** = (**u** – **0**) = 4.2 m/s
- **dy** = **t** = 0.0015 m
- Surface area, **A = πD × L**
- Viscous resistance offered to the shaft, $R = \tau A = \mu \frac{du}{dy} \times A$
- Substituting the values in the equation and solve for **R,** to get
- **R = 295.6 N**
- Torque required to overcome friction in bearing, **T**

= Viscous resistance × lever arm

∴ **T = R** × D/2 = 295.60 × (0.4/0.2) = **59.12 N-m (Ans)**

- Power utilised in overcoming viscous resistance,
- **P = T × ω** = 59.12 × 20.94 = 1237.97 W

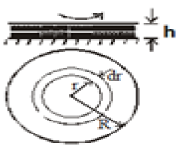
❖ Power can also be calculated by using, **P = R × u**

= 295.60 × 4.2 = **1241.5 W (Ans)**

Q3: A disc of diameter **D** is rotated in a fluid of viscosity **μ** at a small distance **h** from a fixed surface. Find an expression for torque necessary to maintain angular velocity **ω**.

Solution: In this case, velocity varies in the radial direction.

∴ Considering a small elementary ring of disc of thickness **dr** at a radius **r**, from the centre of disc as shown in **Figure**.



Viscous resistance acting on the elementary area **dA**, **dR = τdA**

$$= \mu \frac{du}{dy} \times 2\pi r dr \qquad = \mu \frac{u}{h} \times 2\pi r dr \qquad = \mu \frac{\omega r}{h} \times 2\pi r dr$$

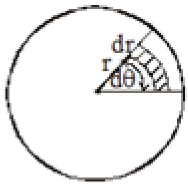
∴ Viscous torque acting on the elementary ring, $dT = dR \times r = \mu \frac{\omega}{h} \times 2\pi r^3 dr$

$\therefore$ Total torque acting on the disc, $T = \int_0^R \mu \frac{\omega}{h} \times 2\pi r^3 dr \quad = \frac{2\pi\mu\omega}{h} \times \left(\frac{R^4}{4}\right)$

$$\therefore T = \frac{\pi\mu\omega D^4}{32h}$$

- Required expression.

<u>2nd method:</u>



- Consider a sector of disc as shown in **Figure**:

$\therefore$ Area of elementary ring, $\mathbf{dA = (rd\theta)dr}$

$$\therefore dR = \tau \times dA = \mu \frac{\omega r}{h}(rd\theta)dr \qquad \therefore dT = dR \times r = \mu \frac{\omega}{h} r^3 d\theta dr$$

$$\therefore T = \mu \frac{\omega}{h} \int_0^R \int_0^{2\pi} d\theta (r^3 dr) \qquad = \frac{2\pi\mu\omega}{h} \int_0^R r^3 dr \qquad = \frac{2\pi\mu\omega}{h}\left(\frac{R^4}{4}\right)$$

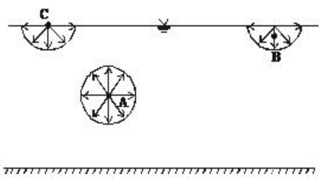
$$\therefore T = \frac{\pi\mu\omega D^4}{32h}$$

SURFACE TENSION AND CAPILLARITY

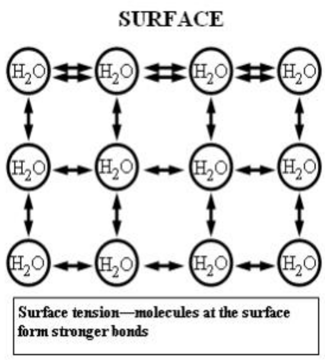
- Liquids have the characteristic properties of cohesion and adhesion.
- Water is a wetting liquid whereas mercury is a non-wetting liquid.
- Water spreads over any surface (adhesion > cohesion).
- Mercury tends to gather into droplets (cohesion > adhesion).

Surface tension

- Arises from the forces of attraction between the adjacent molecules of a liquid and between the liquid molecules & those of any adjacent substance



Concept of surface tension



- Surface tension is the force required to maintain unit length of free surface in equilibrium.

- may be denoted by symbol σ (sigma)

❖ σ isneither a force nor a stress but force per unit length

SI units: **N/m**

❖ σvalues are generally quoted for liquids when these are in contact with air.

- For air-water interface (at 20°C),σ = 0.0736 N/m.
- For air-mercury interface, σ=0.4944 N/m.

Effects of Surface Tension

i) Dust particles collecting on liquid surface.

ii) Different liquids behave differently.

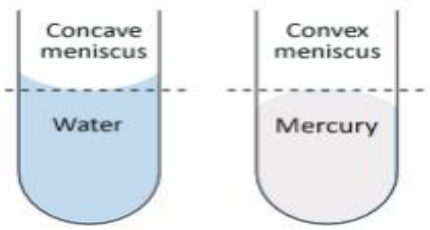
– water has a concave meniscus

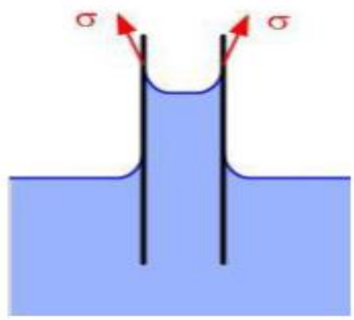
– mercury has a convex meniscus

iii) Capillary attraction/capillarity/meniscus effect

Ability of a liquid to flow in narrow spaces without any assistance and in opposite to gravity force.

iv) Formation of: rain drops, soap bubbles, dew drops on grass etc.



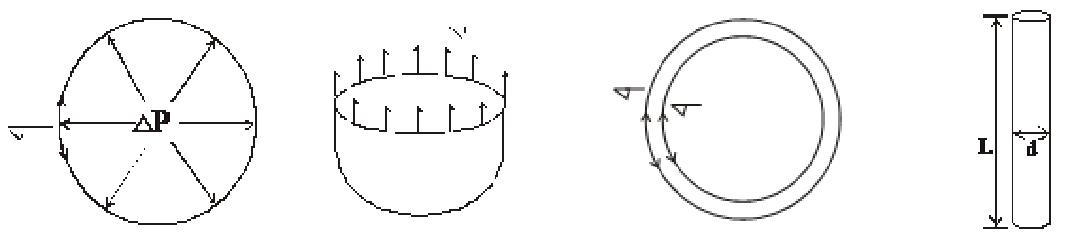


- Let us discuss the effect of surface tension for the following cases:

  (a) Liquid droplet (**Example:** rain drop)

  (b) Hollow bubble (**Example**:soap bubble)

  (c) Liquid jet



(a) Liquid droplet (b) Hollow bubble (c) Liquid jet

❖ In each case, two forces are acting viz. a tensile force and a pressure force

- Tensile force is due to the surface tension.

- Pressure force is due to pressure intensity (**Δp**).

Liquid droplet

- Consider a small spherical droplet of liquid of dia. ***d***
- In this case, surface tension force acts on the outer surface of droplet i.e. circumference **πd**

$$\therefore \text{ Surface tension force} = \sigma\ (\pi d)$$

- **PF** acts in a direction normal to the surface *i.e.* on the projected area **(π/4)D²**

$$\therefore \text{ Pressure force} = \Delta p\ (\pi/4)D^2$$

- Under equilibrium, these two forces will be equal and opposite $\therefore \Delta p = \dfrac{4\sigma}{d}$

Hollow bubble

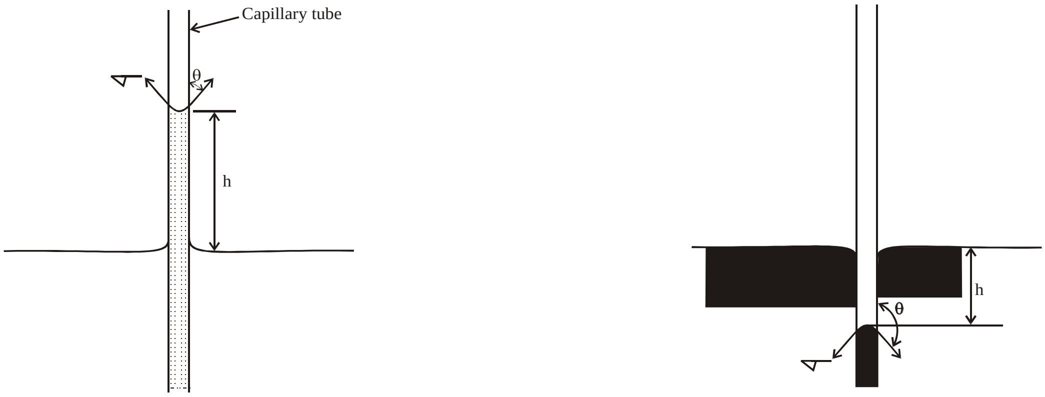
- Has two surfaces in contact with air, one inside and the other outside.
- On each of these two surfaces, surface tension force acts.
- Pressure force remains the same
- Under equilibrium; $2(\sigma\pi d) = \Delta p\ (\pi/4)D^2$

Liquid jet

- Consider a liquid jet of diameter ***d*** and length ***L***
- **STF** is acting along the sides (**2L+2d**) whereas **PF** is acting on the projected area (**d × L**)
- Since **L >> d,** $\therefore (2L + 2d) \cong 2L$
- Under equilibrium; $\sigma\ (2L) = \Delta p\ (d \times L)$
- ❖ In all cases, $\Delta p = (p_i - p_o)$, p_i is the internal pressure intensity and p_o outside pressure intensity *i.e.* atmospheric pressure.

Capillary attraction/capillarity/meniscus effect

- is the ability of a liquid to flow in narrow spaces without any assistance and in opposite to gravity force
- Phenomenon of capillary can be demonstrated with the help of a small diameter tube (known as capillary tube, **CT**) immersed in water and mercury.
- In case of water, rise of water level in the **CT** is observed whereas fall of **Hg** level in the **CT** is observed.
- Rise of level is known as capillary rise and the fall as capillary depression or fall.
- Concave meniscus is formed in case of water (adhesion > cohesion) whereas convex meniscus is formed in case of **Hg** (cohesion > adhesion).



(a) **Capillary rise** (b) **Capillary fall**

Phenomenon of Capillarity

- Capillary rise (or fall) can be determined by considering equilibrium condition of of liquid in the capillary tube.
- Under equilibrium,

Vertical component of force due to surface tension

= Weight due to liquid column of height **h** in capillary tube

$$\sigma \cos\theta \times \pi d = \gamma \frac{\pi}{4} d^2 \times h \qquad \Rightarrow h = \frac{4\sigma\cos\theta}{\gamma d}$$

- θ is the contact angle between the liquid and the tube
- For pure water in contact with a clean glass surface, **θ** is taken as 0^o and for mercury, θ lies between 130^o to 150^o depending upon the purity of mercury.
- Eq. shows that smaller is the diameter; greater is the capillary rise (or fall)
- With increase in diameter, capillary effect reduces.
- For tubes of diameters greater than 5 mm, capillary effect is negligible.
- To avoid a correction for the capillary effect, diameter of tubes used in piezometers and manometers for measuring pressure should be more than 5 mm.

TYPES OF FLUIDS

- Two types, viz. ideal and real.

Ideal fluids are those which have no viscosity, surface tension and compressibility.

- No resistance is encountered when these fluids flow. Also, known as inviscid or non-viscous fluids.
- Concept of ideal fluids is used to simplify the analysis of fluid flow problems compatible with experimental results.

Real fluids possess viscosity, **ST** and compressibility.

- Certain resistance is always encountered to these fluids when they flow.

- No real fluid is inviscid, but in many applications the influence of viscosity is neglected.
- Water and air, though real fluids, but treated as ideal fluids for all practical purposes without any appreciable error.
  - √ Real fluids are further of two types *i.e.* Newtonian and non-Newtonian fluid
- Newtonian fluids obey Newton's law of viscosity, i.e.a linear relationship exists between shear stress and velocity gradient. **Examples:** Water, air etc.
- Non-Newtonian fluids do not obey Newton's law of viscosity.
- A general relationship between shear stress and velocity gradient of different fluids may be expressed by the power law equation of type: $\tau = A\left(\frac{du}{dy}\right)^n + B$
- **A**, **B** and **n** are constants that depend upon the type of fluid.

For example,

(i) For ideal fluids, $\boldsymbol{\tau = 0}$ (As $\mu = 0$)

$$\therefore\ A = 0;\ B = 0$$

(ii) For Newtonian fluids, $\boldsymbol{\tau = \mu\ (du/dy)}$

$$\therefore\ A = \mu;\ B = 0;\ n = 1$$

(iii) For non-Newtonian fluids, $\boldsymbol{\tau = \mu\ (du/dy)^n}$

$$\therefore A = \mu,\ B = 0 \text{ and } \mathbf{n} \text{ can be either} > 1 \text{ or } < 1$$

(a) If **n > 1**, fluids are called dilatant fluids (shear thickening fluids, viscosity increases with rate of shear strain).

Examples: Concentrated solution of sugar in water, printing ink etc.

(b) If n < 1, fluids are called pseudo plastic fluids (shear thinning fluids, viscosity decreases with rate of shear strain).

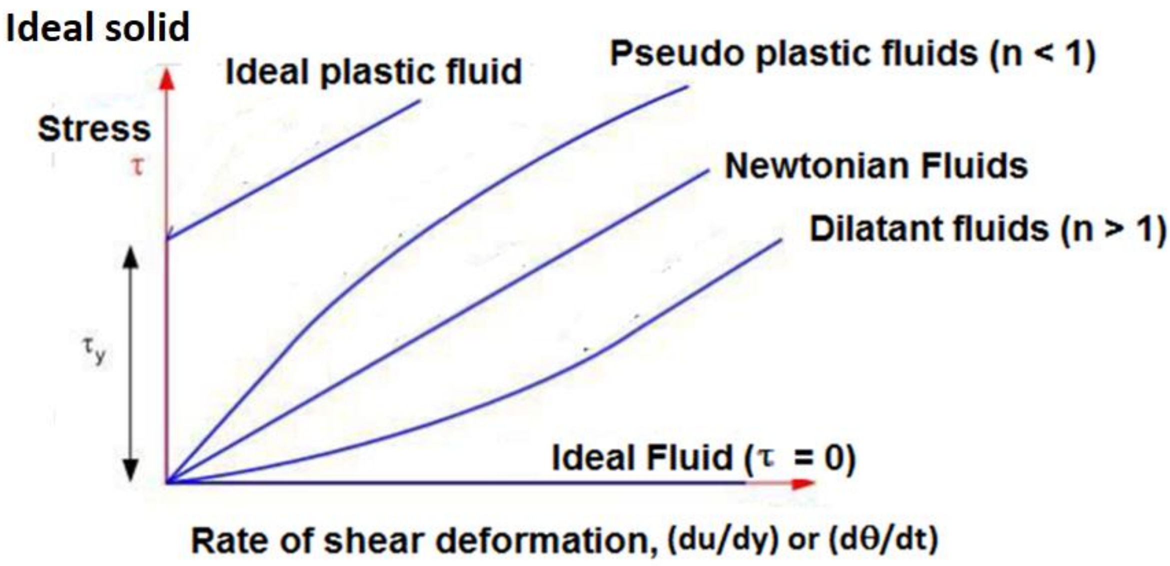
Examples: Milk, clay, blood, liquid cement etc.

(iv) An ideal plastic fluid has a definite yield stress and a constant linear relation between shear stress developed and the rate of deformation.

$$\boldsymbol{\tau = \tau_y + \mu\ (du/dy)}$$

$$\therefore\ A = \mu;\ B = \tau_y;\ n = 1$$

- Stress-Strain diagram for different fluids is shown in **Figure**:


Ideal solid
Ideal plastic fluid
Pseudo plastic fluids (n < 1)
Stress
τ
Newtonian Fluids
Dilatant fluids (n > 1)
τy
Ideal Fluid (τ = 0)
Rate of shear deformation, (du/dy) or (dθ/dt)