

CHAPTER 1

Fluids and their Properties



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Objectives of this Chapter:

- Define the nature of a fluid.
- Show where fluid mechanics concepts are common with those of solid mechanics and indicate some fundamental areas of difference.
- Introduce viscosity and show what are Newtonian and non-Newtonian fluids
- Define the appropriate physical properties and show how these allow differentiation between solids and fluids as well as between liquids and gases.

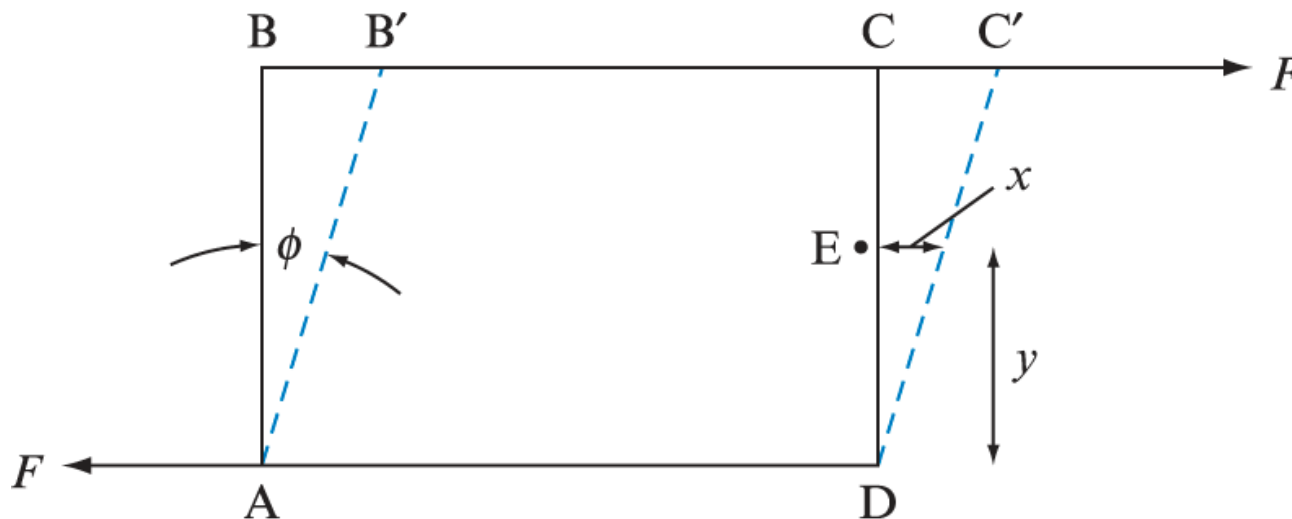
1.1 Fluids :

- We normally recognize **three states of matter**:
 - Solid.
 - Liquid.
 - Gas.

} have common characteristic and both called **fluids**
- Fluids in contrast to solids, **lack the ability to resist deformation**.
- They flow (move) under the action of such forces, and deforms continuously as the force is applied.
- A solid can resist deformation, which may cause some displacement but the solid does not continue to move indefinitely.

1.1 Fluids: (cont.)

- The deformation is caused by **shearing forces** which act tangentially to a surface.
- F** acting tangentially on a **rectangular** (solid lined) element **$ABDC$** . This is a shearing force and produces the (dashed lined) **rhombus** element **$AB'C'D$** .



1.1 Fluids: (cont.)

- A Fluid is a substance which **deforms continuously**, or flows, when subjected to **shearing forces**.
- If a fluid is **at rest there are no shearing forces acting**. All forces must **be perpendicular** to the planes which they are acting.

Fluid Flow		Shear stress - Yes
Fluid Rest		Shear stress - No

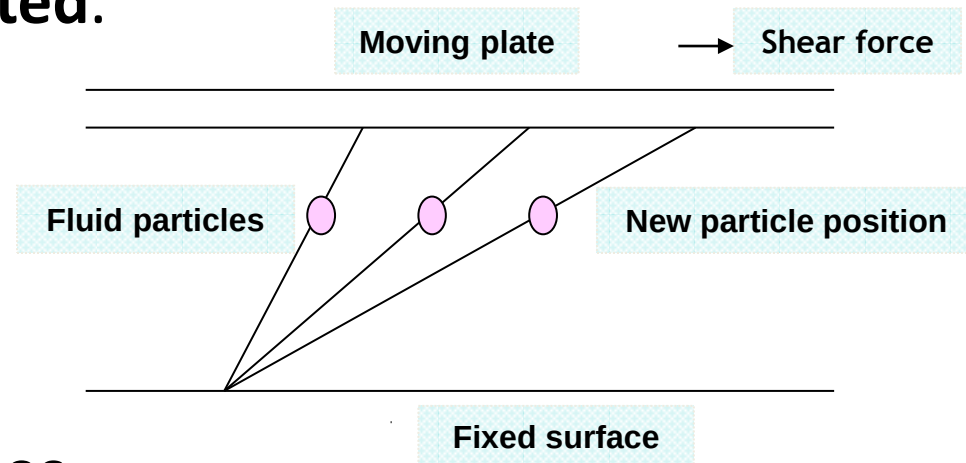
1.1 Fluids: (cont.)

There are two aspects of fluid mechanics which make it different to solid mechanics:

- The ***nature*** of fluid is much different to that of solid.
- In fluids we usually deal with ***continuous streams*** of fluid without a beginning or end. In solids we only consider ***individual elements***.

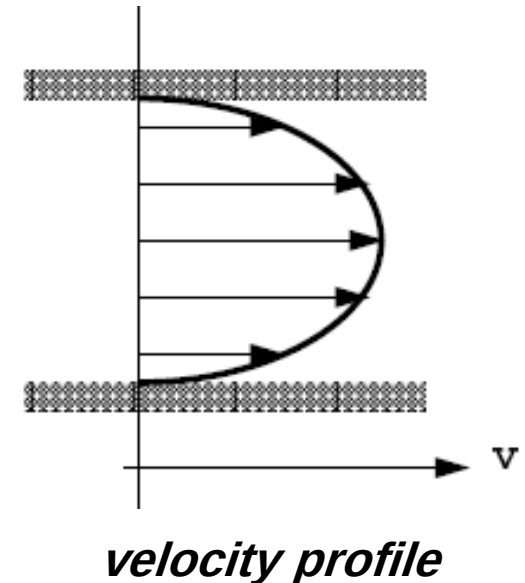
1.2 Shear stress in moving fluid:

- If fluid is in motion, shear stresses are developed.
- This occurs **if the particles of the fluid move relative to each other** with different velocities, causing the shape of the fluid to become **distorted**.
- On the other hand, if the velocity of the fluid is the **same at every point**, no shear stress will be produced, **the fluid particles are at rest relative to each other**.



1.2 Shear stress in moving fluid:

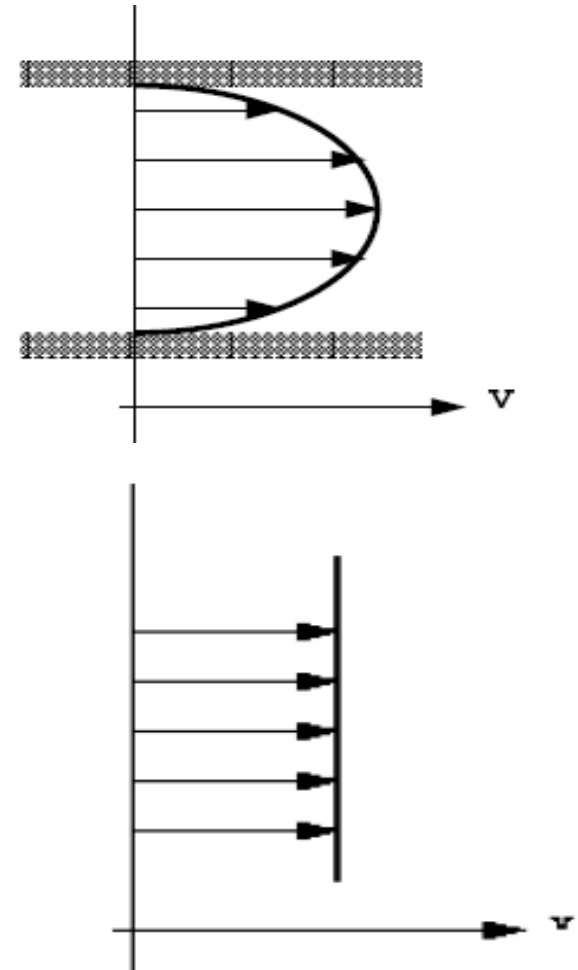
- In practice we are concerned with **flow past solid boundaries**; aeroplanes, cars, pipe walls, river channels
- Fluid next to the wall will have **zero** velocity. (The fluid “sticks” to the wall.)
- Moving away from the wall velocity increases to a **maximum**.
- Plotting the velocity across the section gives “ **velocity profile** ”
- Change in velocity with distance is “ **velocity gradient** ”



$$\text{Velocity gradient} = \frac{dv}{dy}$$

1.2 Shear stress in moving fluid:

- Because particles of fluid next to each other are moving with different velocities there are shear forces in the moving fluid i.e. shear forces are **normally** present in a moving fluid.
- On the other hand, if a fluid is a long way from the boundary and all the particles are traveling with the same velocity. Therefore, **the fluid particles are at rest relative to each other.**

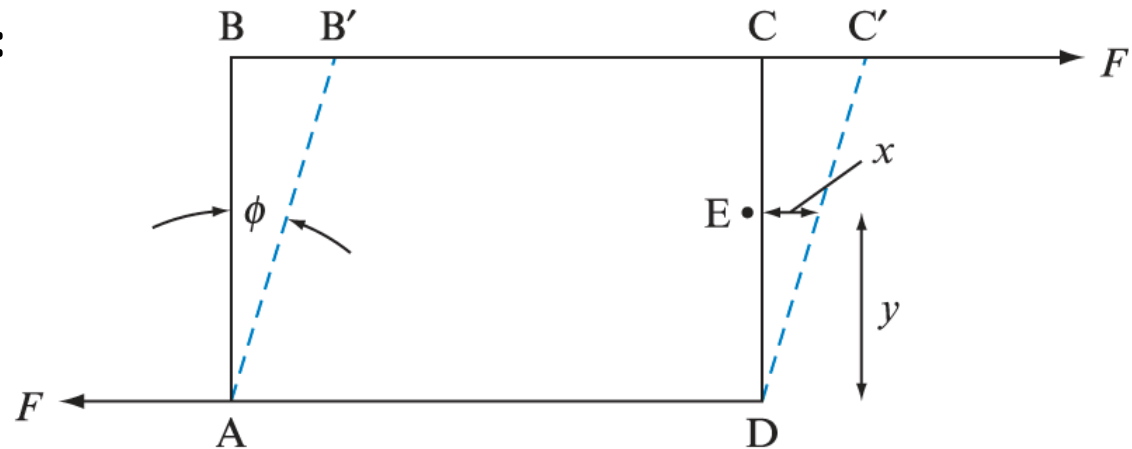


1.2 Shear stress in moving fluid:

The shearing force acts on:

$$\text{Area} = A = BC \times s$$

$$\begin{aligned} \tau &= \text{Shear Stress} \\ &= \frac{F}{A} \end{aligned}$$



The **deformation** which shear stress causes is measured by the angle ϕ , and is known as **shear strain**.

In a **solid** shear strain, ϕ , is constant for a fixed shear stress τ .
In a **fluid** ϕ increases for as long as τ is applied - the fluid flows.

1.2 Shear stress in moving fluid:

It has been found experimentally that:

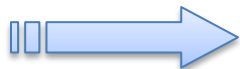
the **rate of shear strain** (shear strain per unit time, ϕ/time) is **directly proportional** to the **shear stress**.

$$\text{Shear strain, } \phi = \frac{x}{y}$$

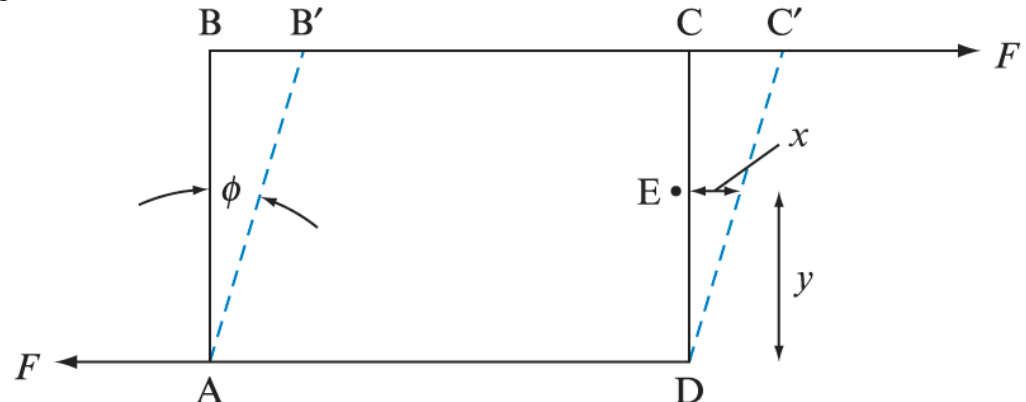
$$\text{Rate of shear strain} = \frac{x}{yt} = \frac{v}{y} \text{ (Velocity gradient)}$$

$$\tau = \text{constant} \frac{v}{y}$$

Dynamic Viscosity



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



1.2 Shear stress in moving fluid:

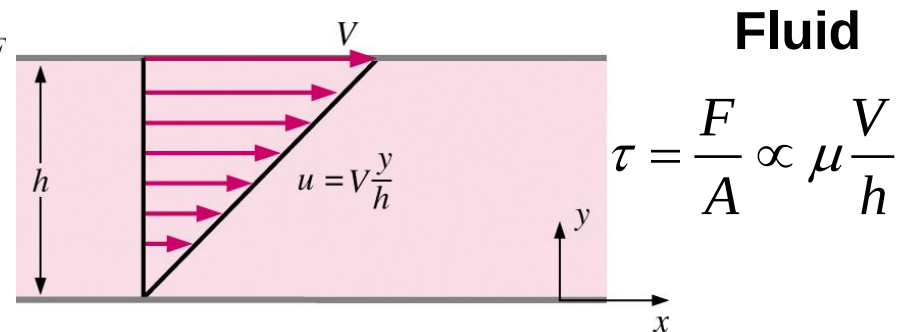
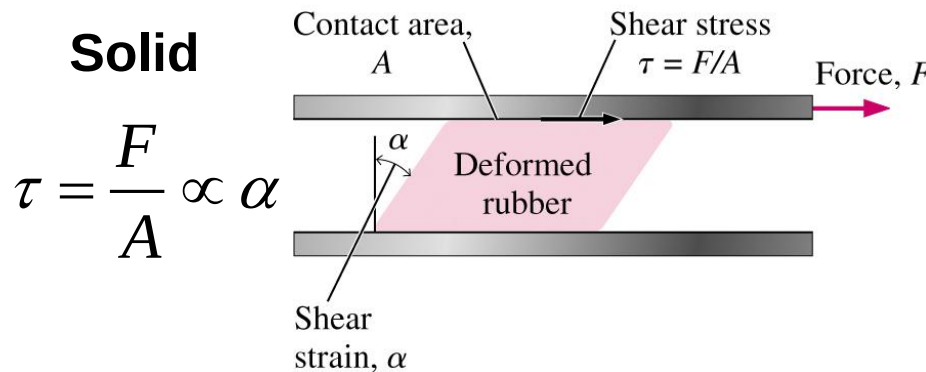
$$\tau = \mu \frac{dv}{dy}$$

This is known as **Newton's law of viscosity**.

μ : depends on fluid under consideration

1.3 Differences between solids & fluid

Solid	Fluid
The strain is a function of the applied stress	The rate of strain is proportional to the applied stress.
The strain is independent of the time over which the force is applied and (if the elastic limit is not reached) the deformation disappears when the force is removed	Continues to flow as long as the force is applied and will not recover its original form when the force is removed.



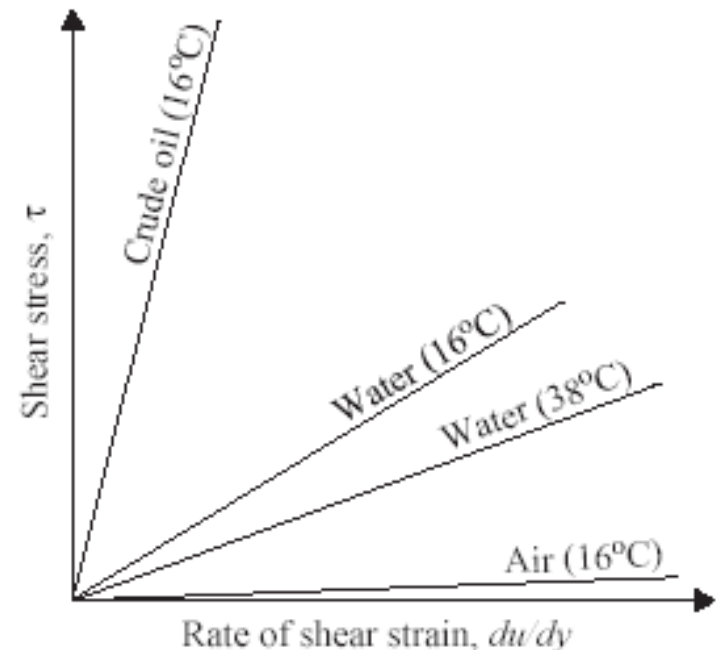
1.4 Newtonian & Non-Newtonian Fluid

Newtonian Fluids

Fluid ^{obey} $\dashrightarrow$ Newton's law of viscosity ^{refer} $\dashrightarrow$ Newtonian fluids

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

- A **linear relationship** between shear stress and the velocity gradient.
- The viscosity μ is **constant**.
- Most common fluids are Newtonian.



Example:

Air, Water, Oil, Gasoline, Alcohol, Kerosene, Benzene, Glycerine

1.4 Newtonian & Non-Newtonian Fluid

Non-Newtonian Fluids

Do not obey
 Fluid — — —▶ Newton's law of viscosity — — —▶ Non-Newtonian fluids

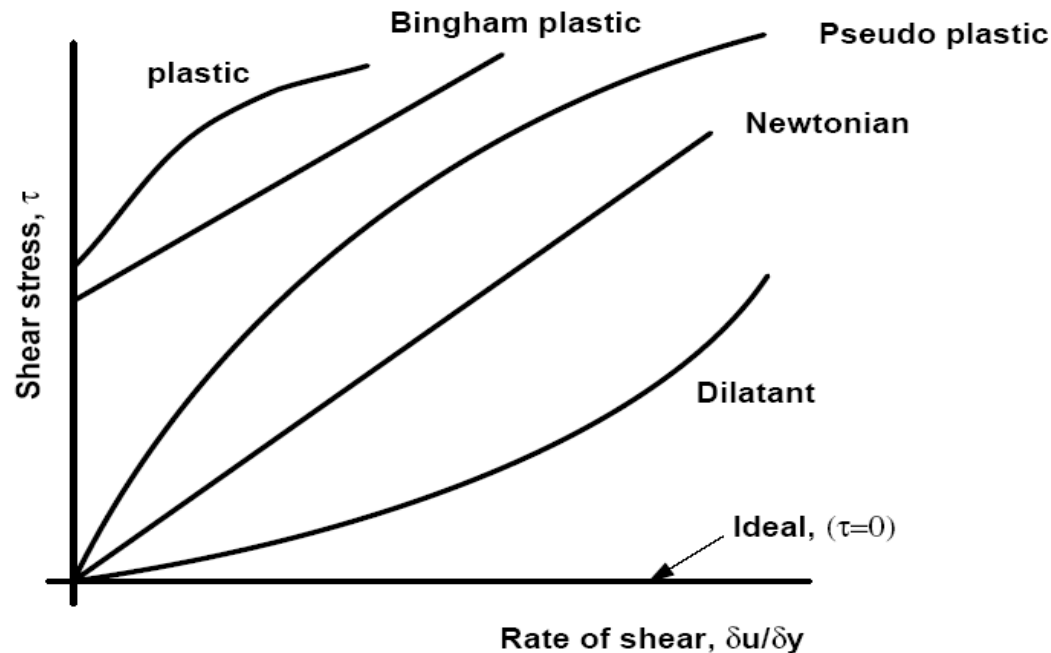
- Slope of the curves for non-Newtonian fluids varies.
- There are several categories of Non-Newtonian Fluid.
- These categories are based on the relationship between shear stress and the velocity gradient.

- The general relationships is: $\tau = A + B \left(\frac{dv}{dy} \right)^n$

where A , B and n are constants.

For Newtonian fluids $A = 0$, $B = \mu$ and $n = 1$.

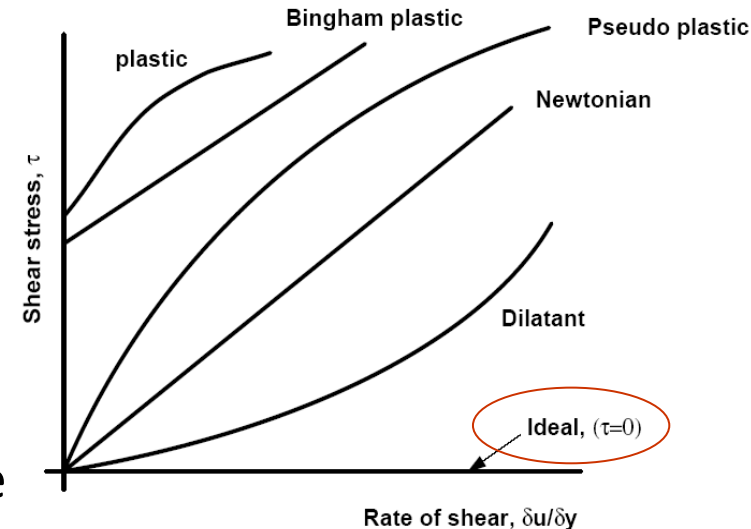
1.4 Newtonian & Non-Newtonian Fluid



- **Plastic:** Shear stress must reach a certain minimum before flow commences.
- **Bingham plastic:** As with the plastic above, a minimum shear stress must be achieved. With this classification $n = 1$. An example is sewage sludge, toothpaste, and jellies.

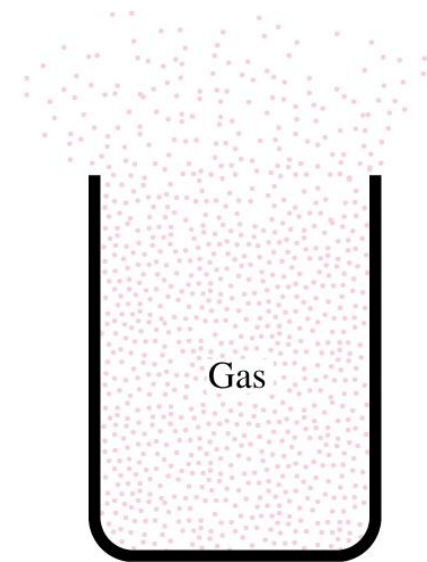
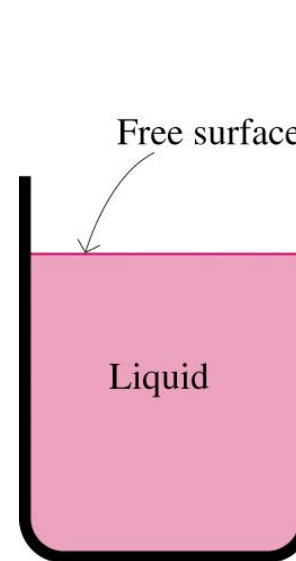
1.4 Newtonian & Non-Newtonian Fluid

- **Pseudo-plastic:** No minimum shear stress necessary and the viscosity decreases with rate of shear, e.g. colloidal substances like clay, milk and cement.
- **Dilatant substances;** Viscosity increases with rate of shear e.g. quicksand.
- **Thixotropic substances:** Viscosity decreases with length of time shear force is applied e.g. thixotropic jelly paints.
- **Rheopectic substances:** Viscosity increases with length of time shear force is applied
- **Viscoelastic materials:** Similar to Newtonian but if there is a sudden large change in shear they behave like plastic.



1.5 Liquids and Gases:

Liquid	Gases
Difficult to compress and often regarded as incompressible	Easily to compress – changes of volume is large, cannot normally be neglected and are related to temperature
Occupies a fixed volume and will take the shape of the container	No fixed volume , it changes volume to expand to fill the containing vessels
A free surface is formed if the volume of container is greater than the liquid.	Completely fill the vessel so that no free surface is formed.



1.8 Properties of Fluids:

There are **many ways** of expressing density:

A. Mass density:

ρ = Mass per unit volume

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

Where:

M = mass of fluid, V = volume of fluid

Units: kg/m^3

Dimensions: ML^{-3}

Typical values:

Water = 1000 kg/m^3 , Mercury = 13546 kg/m^3

Air = 1.23 kg/m^3 , Paraffin Oil = 800 kg/m^3

1.8 Properties of Fluids:

B. Specific Weight :

- Specific Weight w is defined as:

$$w = \gamma = \text{weight per unit volume}$$

Where:

$$\gamma = \rho g = \frac{W}{V}$$

W = weight of fluid, V = volume of fluid

Units: N/m^3

Dimensions: $ML^{-2}T^{-2}$

Typical values:

Water = 9814 N/m^3 , Mercury = 132943 N/m^3

Air = 12.07 N/m^3 , Paraffin Oil = 7851 N/m^3

1.8 Properties of Fluids:

B. Relative Density :

- Relative Density (or specific gravity) σ , is defined as the ratio of mass density of a substance to some standard mass density.
- For solids and liquids this standard mass density is the maximum mass density for water (which occurs at 4°C)

$$\sigma = SG = \frac{\rho_{Sub}}{\rho_{water \text{ at } 4^{\circ}C}}$$

Units: none, as it is a ratio

Dimensions: 1

Typical values:

Water = 1 , Mercury = 13.5, Paraffin Oil = 0.8

1.8 Properties of Fluids:

D. Specific Volume :

- Specific Volume, v , is defined as the reciprocal of mass density.

$$v = \frac{1}{\rho}$$

Units: m^3/kg

1.9 Properties of Fluids: Viscosity

- Viscosity, μ , is the property of a fluid, due to **cohesion and interaction between molecules**, which offers resistance to shear deformation.
- The ease with which a fluid pours is an indication of its viscosity. (The viscosity is measure of the “fluidity” of the fluid).
- Fluid with a **high viscosity** such as oil **deforms more slowly** than fluid with a low viscosity such as water.
- **There are two ways of expressing viscosity:**
 - A. Coefficient of **Dynamic Viscosity**
 - B. Coefficient of **Kinematic Viscosity**

A. Coefficient of Dynamic Viscosity

- The Coefficient of Dynamic Viscosity, μ , is defined as the shear force, per unit area, (or shear stress τ), required to drag one layer of fluid with unit velocity past another layer a unit distance away.

$$\mu = \tau / \frac{dv}{dy} = \frac{\text{Force}}{\text{Area}} / \frac{\text{Velocity}}{\text{Distance}} = \frac{\text{Force} \times \text{Time}}{\text{Area}} = \frac{\text{Mass}}{\text{Length} \times \text{Area}}$$

- Units:** N.s/m² or kg/m.s (kg m⁻¹ s⁻¹)

(Note that m is often expressed in Poise, P , where $10 P = 1 \text{ N.s/m}^2$)

- Dimensions:** $ML^{-1}T^{-1}$

- Typical values:**

Water = $1.14(10^{-3}) \text{ Ns/m}^2$, Air = $1.78(10^{-5}) \text{ Ns/m}^2$

Mercury = 1.552 Ns/m^2 , Paraffin Oil = 1.9 Ns/m^2

B. Coefficient of Kinematic Viscosity

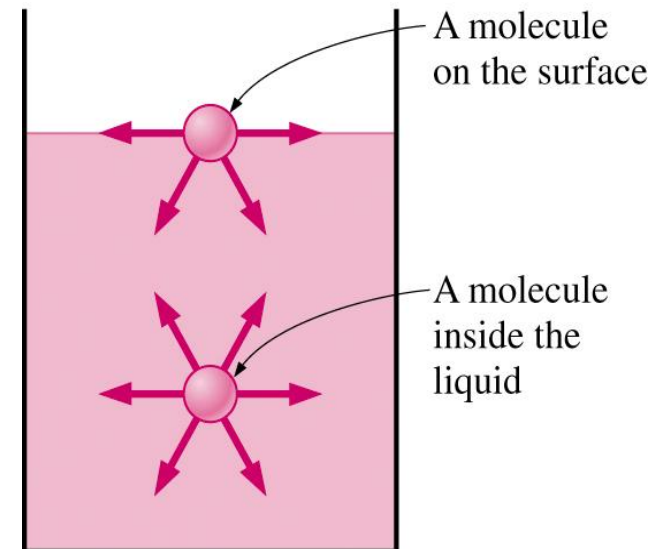
- Kinematic Viscosity, ν , is defined as the ratio of dynamic viscosity to mass density.

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

- **Units:** m^2/s
(Note that ν is often expressed in Stokes, St, where $10^4 \text{ St} = 1 \text{ m}^2/\text{s}$)
- **Dimensions:** $ML^{-1}T^{-1}$
- **Typical values:**
Water = $1.14(10^{-6}) \text{ m}^2/\text{s}$, Air = $1.46(10^{-5}) \text{ m}^2/\text{s}$,
Mercury = $1.145(10^{-4}) \text{ m}^2/\text{s}$, Paraffin Oil = $2.375(10^{-3}) \text{ m}^2/\text{s}$

1.12 Surface Tension

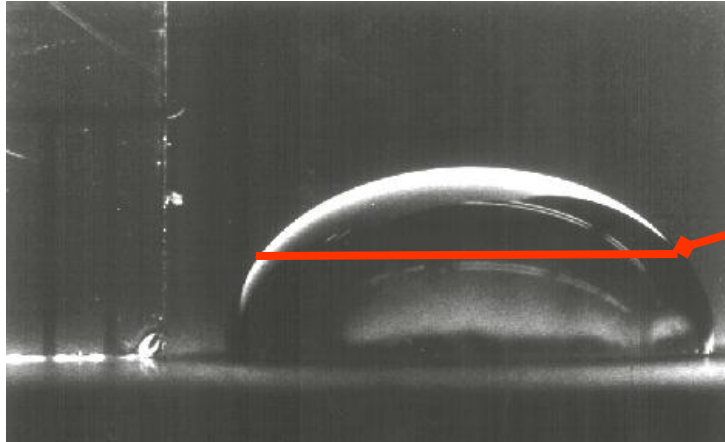
- Liquid droplets behave like small spherical balloons filled with liquid, and the surface of the liquid acts like a stretched elastic membrane under tension.
- The pulling force that causes this is due to the attractive forces between molecules called **surface tension σ**
- **In the body of the liquid**, a molecule is surrounded by other molecules and intermolecular forces are symmetrical and in equilibrium.
- **At the surface of the liquid**, a molecule has this force acting only through 180° . Thus, The surface molecules being pulled inward towards the bulk of the liquid.



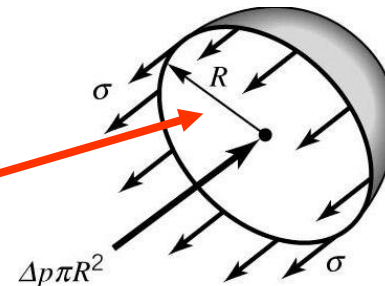
- This effect causes the **liquid surface to behave like a very thin membrane under tension.**
- Surface tension is defined as **force per unit length**, and its unit is **N/m** .

1.12 Surface Tension: Spherical drop

Real Fluid Drops



Mathematical Model



R is the radius of the droplet, σ is the surface tension, Δp is the pressure difference between the inside and outside pressure.

The force developed around the edge due to **surface tension** along the line:

$$F_{\sigma} = 2\pi R\sigma$$

This force is balanced by the force produced from the **pressure difference** Δp :

$$F_{\Delta p} = \pi R^2 \Delta p$$

1.12 Surface Tension: Spherical drop

Now, equating the Surface Tension Force to the Pressure Force, we can estimate $\Delta p = p_i - p_e$:

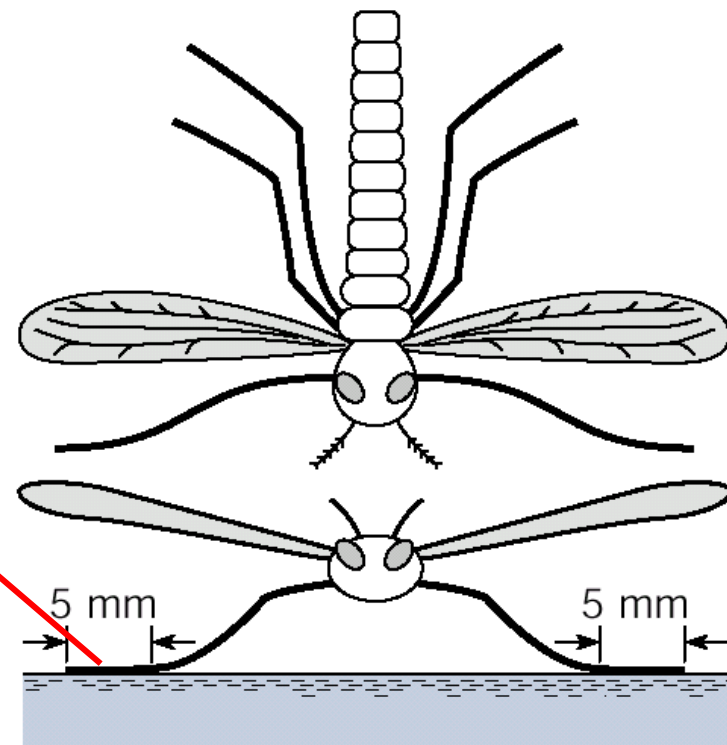
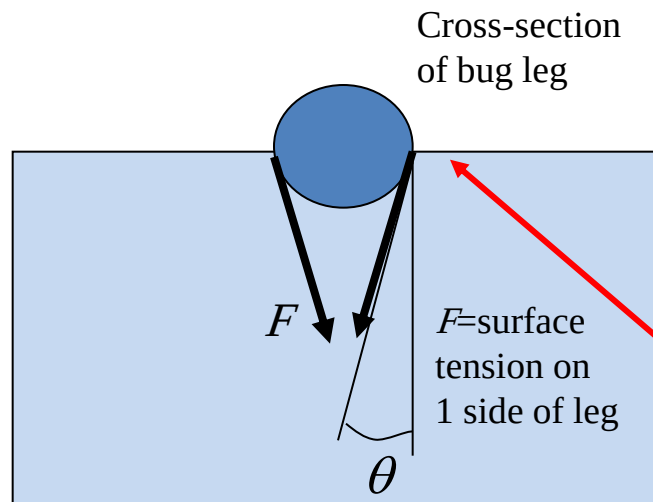
$$\Delta p = \frac{2\sigma}{R}$$

This indicates that the **internal pressure in the droplet is greater than the external pressure** since the right hand side is entirely positive.

The surface tension forces **is neglected** in many engineering problems since it is **very small**.

1.12 Surface Tension

Bug Problem



Approximate Physical Properties of Common Liquids at Atmospheric Pressure

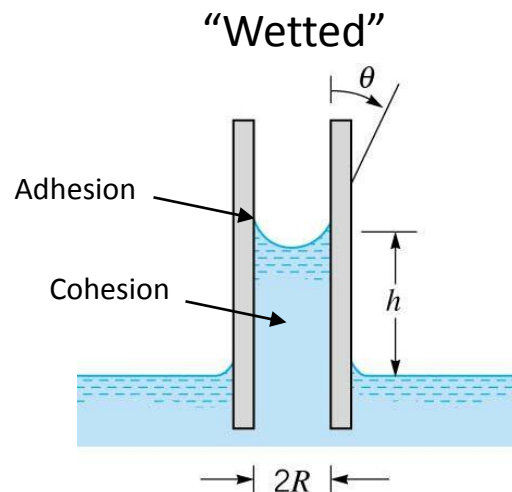
Liquid and temperature	Density kg/m ³ (slugs/ft ³)	Specific gravity (S) water at 4°C is ref.	Specific weight, N/m ³ (lbf/ft ³)	Dynamic viscosity, N · s/m ² (lbf · s/ft ²)	Kinematic viscosity, m ² /s (ft ² /s)	Surface tension, N/m* (lbf/ft)
Ethyl alcohol ⁽³⁾⁽¹⁾ 20°C (68°F)	799 (1.55)	0.79	7,850 (50.0)	1.2×10^{-3} (2.5×10^{-5})	1.5×10^{-6} (1.6×10^{-5})	2.2×10^{-2} (1.5×10^{-3})
Carbon tetrachloride ⁽³⁾ 20°C (68°F)	1,590 (3.09)	1.59	15,600 (99.5)	9.6×10^{-4} (2.0×10^{-5})	6.0×10^{-7} (6.5×10^{-6})	2.6×10^{-2} (1.8×10^{-3})
Glycerine ⁽³⁾ 20°C (68°F)	1,260 (2.45)	1.26	12,300 (78.5)	6.2×10^{-1} (1.3×10^{-2})	5.1×10^{-4} (5.3×10^{-3})	6.3×10^{-2} (4.3×10^{-3})
Kerosene ⁽²⁾⁽¹⁾ 20°C (68°F)	814 (1.58)	0.81	8,010 (51)	1.9×10^{-3} (4×10^{-5})	2.37×10^{-6} (2.55×10^{-5})	2.9×10^{-2} (2.0×10^{-3})
Mercury ⁽³⁾⁽¹⁾ 20°C (68°F)	13,550 (26.3)	13.55	133,000 (847)	1.5×10^{-3} (3.2×10^{-5})	1.2×10^{-7} (1.3×10^{-6})	4.8×10^{-1} (3.3×10^{-2})
Sea water 10°C at 3.3% salinity	1,026 (1.99)	1.03	10,070 (64.1)	1.4×10^{-3} (3×10^{-5})	1.4×10^{-6} (1.5×10^{-5})	
Oils—38°C (100°F)						
SAE 10W ⁽⁴⁾	870 (1.69)	0.87	8,530 (54.4)	3.6×10^{-2} (7.4×10^{-4})	4.1×10^{-5} (4.4×10^{-4})	
SAE 10W-30 ⁽⁴⁾	880 (1.71)	0.88	8,630 (55.1)	6.7×10^{-2} (1.4×10^{-3})	7.6×10^{-5} (8.2×10^{-4})	
SAE 30 ⁽⁴⁾	880 (1.71)	0.88	8,630 (55.1)	1.0×10^{-1} (2.0×10^{-3})	1.1×10^{-4} (1.2×10^{-3})	

*Liquid–air surface tension values.

SOURCES: (1) V.L. Streeter, *Handbook of Fluid Dynamics*, McGraw-Hill Book Company, New York, 1961; (2) V.L. Streeter, *Fluid Mechanics*, 4th ed., McGraw-Hill Book Company, New York, 1966; (3) J. Vennard, *Elementary Fluid Mechanics*, 4th ed., John Wiley & Sons, Inc., New York, 1961; (4) R. E. Bolz and G. L. Tuve, *Handbook of Tables for Applied Engineering Sciences*, CRC Press, Inc., Cleveland, 1973.

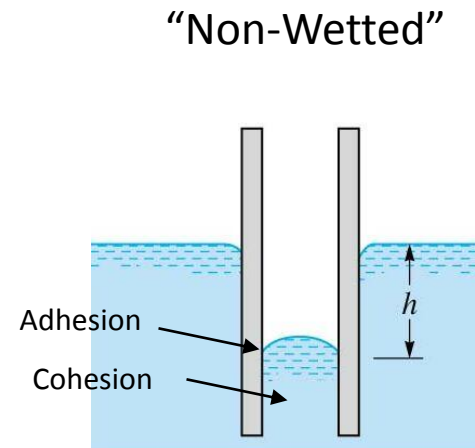
1.13 Capillarity:

- **Capillary effect** is the rise or fall of a liquid in a small-diameter tube.
- Capillary action in small tubes which **involve a liquid-gas-solid interface** is **caused by surface tension**.



Adhesion > Cohesion

Water



Cohesion > Adhesion

Mercury

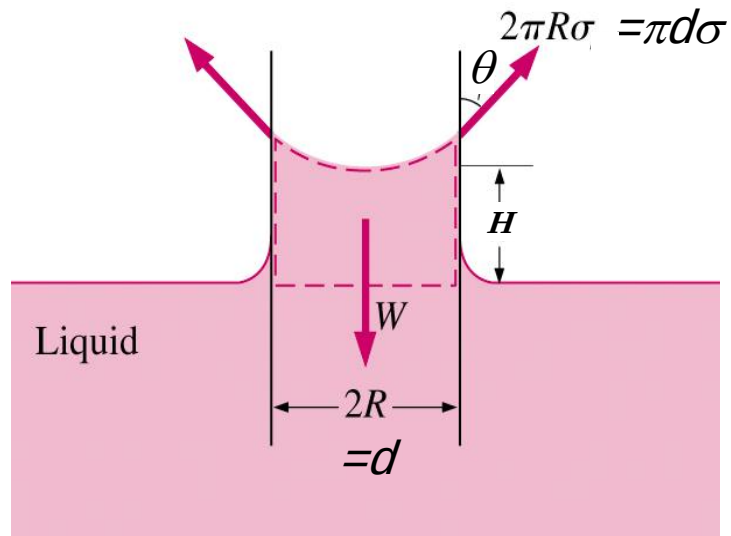
1.13 Capillarity:

H : is the height,

R : is the radius of the tube ($d=2R$)

θ : is the **angle of contact** between liquid and solid.

The weight of the fluid is balanced with the vertical force caused by surface tension.



➔ $\pi d \sigma \cos \theta = \rho g \frac{\pi}{4} d^2 H$

$$H = \frac{4\sigma \cos \theta}{\rho g d}$$

- For clean glass in contact with **water**, $\theta \approx 0^\circ$, and thus as R decreases, H increases, giving a higher rise. ($H= 5\text{mm}$ in a tube of 5mm diameter in water)
- For a clean glass in contact with **Mercury**, $\theta \approx 130^\circ$, and thus H is negative or there is a push down of the fluid. ($H= -1.4\text{mm}$ in a tube of 5mm diameter in mercury)

1.14 Compressibility & Bulk Modulus:

- All materials are compressible under the application of an external force
- The **compressibility of a fluid is expressed by its bulk modulus “K”**, which describes the variation of volume with change of pressure:

$$K = \frac{\text{Change in Pressure}}{\text{Volumetric Strain}}$$

- Thus, if the pressure intensity of a volume of fluid, V , is increased by Δp and the volume is changed by ΔV , then:

$$K = -\frac{\Delta p}{\Delta V/V} \quad \text{or} \quad K = \rho \frac{\Delta p}{\Delta \rho}$$

- The –ve sign indicate that the volume decrease as the pressure increase.
- Typical values: Water = $2.05 \times 10^9 \text{ N/m}^2$; Oil = $1.62 \times 10^9 \text{ N/m}^2$

1.14 Compressibility & Bulk Modulus:

- Large values of the bulk modulus indicate incompressibility.
- Incompressibility indicates large pressures are needed to compress the volume slightly.
- Most liquids are incompressible for most practical engineering problems.
- **Example:** 1 MPa pressure change = 0.05% volume change, Water is relatively incompressible.

Example:

A reservoir of oil has a mass of 825 kg. The reservoir has a volume of 0.917 m^3 . Compute the density, specific weight, and specific gravity of the oil.

Solution:

$$\rho_{oil} = \frac{\text{mass}}{\text{volume}} = \frac{m}{V} = \frac{825}{0.917} = 900 \text{ kg} / \text{m}^3$$

$$\gamma_{oil} = \frac{\text{weight}}{\text{volume}} = \frac{mg}{V} = \rho g = 900 \times 9.81 = 8829 \text{ N} / \text{m}^3$$

$$SG_{oil} = \frac{\rho_{oil}}{\rho_{w@4^\circ C}} = \frac{900}{1000} = 0.9$$

Example:

Water has a surface tension of 0.4 N/m. In a 3-mm diameter vertical tube, if the liquid rises 6 mm above the liquid outside the tube, **calculate the wetting angle.**

Solution

Capillary rise due to surface tension is given by;

$$h = \frac{4\sigma \cos \theta}{\rho g d}$$

$$\therefore \cos \theta = \frac{\gamma d h}{4\sigma} = \frac{9810 \times 0.003 \times 0.006}{4 \times 0.4}$$

$$\theta = 83.7^\circ$$

Example:

- **Given:** Pressure of 2 MPa is applied to a mass of water that initially filled 1000-cm³ volume.
- **Find:** Volume after the pressure is applied.
- **Solution:** $K = 2.2 \times 10^9 \text{ Pa}$

$$K = -\frac{\Delta p}{\Delta V / V}$$

$$\Delta V = -\frac{\Delta p}{K} V$$

$$= -\frac{2 \times 10^6 \text{ Pa}}{2.2 \times 10^9 \text{ Pa}} 1000 \text{ cm}^3$$

$$= -0.909 \text{ cm}^3$$

$$V_{\text{final}} = V + \Delta V$$

$$= 1000 - 0.909$$

$$V_{\text{final}} = 999.01 \text{ cm}^3$$

Example:

Find: Capillary rise between two vertical glass plates 1 mm apart.

- $\sigma = 7.3 \times 10^{-2} \text{ N/m}$
- l is into the page

Solution:

$$\Sigma F_{\text{vertical}} = 0$$

$$2\sigma l - h l t \gamma = 0$$

$$h = \frac{2\sigma}{t\gamma}$$

$$= \frac{2 * 7.3 \times 10^{-2}}{0.001 * 9810}$$

$$h = 0.0149 \text{ m}$$

$$h = 14.9 \text{ mm}$$

