Fluid Mechanics (CT-213)

- ***Course Instructor***

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Recommended Books

Text Book:

- **Fluid Mechanics With Engineering Applications (10th Edition)**

by *E. John Finnemore & Joseph B. Franzini*

Reference Books:

- **A textbook of Hydraulics, Fluid Mechanics and Hydraulic Machines (19th Edition)** *by R.S. Khurmi*
- **Applied Fluid Mechanics (6th Edition)** *by Robert L. Mott*
- **Fluid Mechanics** *by A.K Jain*

Marks Distribution

- Sessional - 20%
  - Quiz – 10%
  - Assignments/ Class Project/ Presentation – 10%
- Mid Term - 30%
- Final Exam - 50%

Properties of Fluids

Lecture - 1

Fluid

- A **fluid** is defined as:

  "A substance that continually deforms (flows) under an applied **shear stress** regardless of the magnitude of the applied stress".

- It is a subset of the phases of matter and includes liquids, gases, plasmas and, to some extent, plastic solids.

Fluid Mechanics

- It is the science of the mechanics of solids and gasses and is based on fundamental principles that are employed in the mechanics of solids.
- Fluid mechanics is divided in three branches
- Fluid statics: the study of mechanics of fluids at rest
- Kinematics: deals with velocities and stream lines without considering force and energy
- Hydrodynamics: deals with the relation with velocities and accelerations and the forces exerted by or upon fluids in motion.

Fluid Vs Solid Mechanics

- **Fluid mechanics:**

  "The study of the physics of materials which take the shape of their container." Or

  "Branch of Engg. science that studies fluids and forces on them."

- **Solid Mechanics:**

  "The study of the physics of materials with a defined rest shape."

- Fluid Mechanics can be further subdivided into **fluid statics**, the study of fluids at rest, and **kinematics**, the study of fluids in motion and **fluid dynamics**, the study of effect of forces on fluid motion.
- In the modern discipline called **Computational Fluid Dynamics** (CFD), computational approach is used to develop solutions to fluid mechanics problems.

Distinction between a Solid and a Fluid

Solid

- *Definite Shape* and *definite volume.*
- *Does not flow easily.*
- *Molecules* are closer.
- *Attractive forces* between the molecules are large enough to retain its shape.
- An **ideal Elastic Solid** deform under load and comes back to original position upon removal of load.
- **Plastic Solid** does not comes back to original position upon removal of load, means permanent deformation takes place.

Fluid

- *Indefinite Shape* and *Indefinite volume & it assumes the shape* of the container which it occupies.
- *Flow Easily.*
- *Molecules* are far apart.
- *Attractive forces* between the molecules are smaller.
- *Intermolecular cohesive forces* in a fluid are not great enough to hold the various elements of fluid together. Hence Fluid will flow under the action of applied stress. The flow will be continuous as long as stress is applied.

Distinction between a Gas and Liquid

- The molecules of a **gas** are much farther apart than those of a liquid.
- Hence a gas is very compressible, and when all external pressure is removed, it tends to expand indefinitely.
- A gas is therefore in equilibrium only when it is completely enclosed.

- A **liquid** is relatively incompressible.
- If all pressure, except that of its own vapor pressure, is removed, the cohesion between molecules holds them together, so that the liquid does not expand indefinitely.
- Therefore a liquid may have a free surface.

SI Units

Quantity	Basic Definition	Standard SI Units	Other Units Often Used
Length	—	meter (m)	millimeter (mm); kilometer (km)
Time	—	second (s)	hour (h); minute (min)
Mass	Quantity of a substance	kilogram (kg)	$N \cdot s^2/m$
Force or weight	Push or pull on an object	newton (N)	$kg \cdot m/s^2$
Pressure	Force/area	N/m^2 or pascal (Pa)	kilopascals (kPa); bar
Energy	Force times distance	$N \cdot m$ or Joule (J)	$kg \cdot m^2/s^2$
Power	Energy/time	$N \cdot m/s$ or J/s	watt (W); kW
Volume	$(\text{Length})^3$	m^3	liter (L)
Area	$(\text{Length})^2$	m^2	mm^2
Volume flow rate	Volume/time	m^3/s	L/s; L/min; m^3/h
Weight flow rate	Weight/time	N/s	kN/s; kN/min
Mass flow rate	Mass/time	kg/s	kg/h
Specific weight	Weight/volume	N/m^3	$kg/m^2 \cdot s^2$
Density	Mass/volume	kg/m^3	$N \cdot s^2/m^4$

FPS Units

Quantity	Basic Definition	Standard U.S. Units	Other Units Often Used
Length	—	feet (ft)	inches (in); miles (mi)
Time	—	second (s)	hour (h); minute (min)
Mass	Quantity of a substance	slugs	$lb \cdot s^2/ft$
Force or weight	Push or pull on an object	pound (lb)	kip (1000 lb)
Pressure	Force/area	lb/ft^2 or psf	lb/in^2 or psi; kip/in^2 or ksi
Energy	Force times distance	$lb \cdot ft$	$lb \cdot in$
Power	Energy/time	$lb \cdot ft/s$	horsepower (hp)
Volume	$(Length)^2$	ft^3	gallon (gal)
Area	$(Length)^3$	ft^2	in^2
Volume flow rate	Volume/time	ft^3/s or cfs	gal/min (gpm); ft^3/min (cfm)
Weight flow rate	Weight/time	lb/s	lb/min; lb/h
Mass flow rate	Mass/time	slugs/s	slugs/min; slugs/h
Specific weight	Weight/volume	lb/ft^3	
Density	Mass/volume	$slugs/ft^3$	

Important Terms

- **Density (ρ):**
  Mass per unit volume of a substance.
  - kg/m^3 in SI units
  - $Slug/ft^3$ in FPS system of units

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

- **Specific weight (γ):**
  Weight per unit volume of substance.
  - N/m^3 in SI units
  - lbs/ft^3 in FPS units

$$\gamma = \frac{w}{V}$$

- Density and Specific Weight of a fluid are related as:

$$\gamma = \rho g$$

- Where g is the gravitational constant having value $9.8 m/s^2$ or $32.2\ ft/s^2$.

Important Terms

- **Specific Volume (v):**

  Volume occupied by unit mass of fluid.

- It is commonly applied to gases, and is usually expressed in cubic feet per slug (m^3/kg in SI units).
- Specific volume is the reciprocal of density.

$$Specific Volume = v = 1/\rho$$

Important Terms

- **Specific gravity:**

It can be defined in either of two ways:

a. Specific gravity is the ratio of the density of a substance to the density of water at 4°C.

b. Specific gravity is the ratio of the specific weight of a substance to the specific weight of water at 4°C.

$$s_{\text{liquid}} = \frac{\gamma_l}{\gamma_w} = \frac{\rho_l}{\rho_w}$$

Example

The specific wt. of water at ordinary temperature and pressure is 62.4lb/ft^3. The specific gravity of mercury is 13.56. Compute density of water, Specific wt. of mercury, and density of mercury.

Solution:

$$1.\ \rho_{water} = \gamma_{water} / g = 62.4/32.2 = 1.938\ \text{slugs/ft}^3$$

$$2.\ \gamma_{\text{mercury}} = s_{mercury}\gamma_{water} = 13.56x62.4 = 846 lb / ft^3$$

$$3.\ \rho_{\text{mercury}} = s_{mercury}\rho_{water} = 13.56x1.938 = 26.3 slugs / ft^3$$

(Where Slug = lb.sec^2/ ft)

Example

A certain gas weighs 16.0 N/m^3 at a certain temperature and pressure. What are the values of its density, specific volume, and specific gravity relative to air weighing 12.0 N/m^3

Solution:

$$1.\ \text{Density}\ \rho = \gamma / g$$

$$\rho = 16/9.81 = 1.6631\ \text{kg/m}^3$$

$$2.\ \text{Specific volume}\ \upsilon = 1/\rho$$

$$u = 1/1.631 = 0.613\ \text{m}^3/\text{kg}$$

$$3.\ \text{Specific gravity}\quad s = \gamma_f / \gamma_{air}$$

$$s = 16/12 = 1.333$$

Example

The specific weight of glycerin is 78.6 lb/ft^3. compute its density and specific gravity. What is its specific weight in kN/m^3

Solution:

1. Density $\rho = \gamma / g$

$$\rho = 78.6/32.2 = 2.44 \text{ slugs/ft}^3$$

2. Specific gravity $s = \gamma_l / \gamma_w$

$$s = 78.6/62.4 = 1.260$$

so $\rho = 1.260 \text{x} 1000 \text{ kg/m}^3$

$$\rho = 1260 \text{ Kg/m}^3$$

3. Specific weight in kN/m^3

$$\gamma = \rho \text{ x } g$$

$$\gamma = 9.81 \text{x} 1260 = 12.36 \text{ kN/m}^3$$

Example

Calculate the specific weight, density, specific volume and specific gravity of 1litre of petrol weights 7 N.

Solution:

Given Volume = 1 litre = 10^{-3} m^3

Weight = 7 N

1. Specific weight,

   w = Weight of Liquid/volume of Liquid

   $w = 7/10^{-3} = 7000\ N/m^3$

2. Density, $\rho = \gamma/g$

   $\rho = 7000/9.81 = 713.56\ kg/m^3$

Solution (Cont.):

3. Specific Volume = 1/ ρ

$= 1/713.56$

$= 1.4 \times 10^{-3}\ m^3/kg$

4. Specific Gravity = s =

Specific Weight of Liquid/Specific Weight of Water

= Density of Liquid/Density of Water

s = 713.56/1000 = 0.7136

Example

If the specific gravity of petrol is 0.70.Calculate its Density, Specific Volume and Specific Weight.

Solution:

Given

Specific gravity = s = 0.70

1. Density of Liquid, ρ = s x density of water

= 0.70x1000

= 700 kg/m^3

2. Specific Volume = $1/\rho$

= 1/700

= 1.43×10^{-3}

3. Specific Weight, = 700x9.81 = 6867 N/m^3

Viscosity

- **Viscosity is a measure of the resistance of a fluid to deform under shear stress.**
- It is commonly perceived as thickness, or resistance to flow.
- Viscosity describes a fluid's internal resistance to flow and may be thought of as a measure of fluid friction. Thus, water is "thin", having a lower viscosity, while vegetable oil is "thick" having a higher viscosity.
- The friction forces in flowing fluid result from the cohesion and momentum interchange between molecules.
- All real fluids (except super-fluids) have some resistance to shear stress, but a fluid which has no resistance to shear stress is known as an **ideal fluid**.
- It is also known as **Absolute Viscosity** or **Dynamic Viscosity.**

Dynamic Viscosity

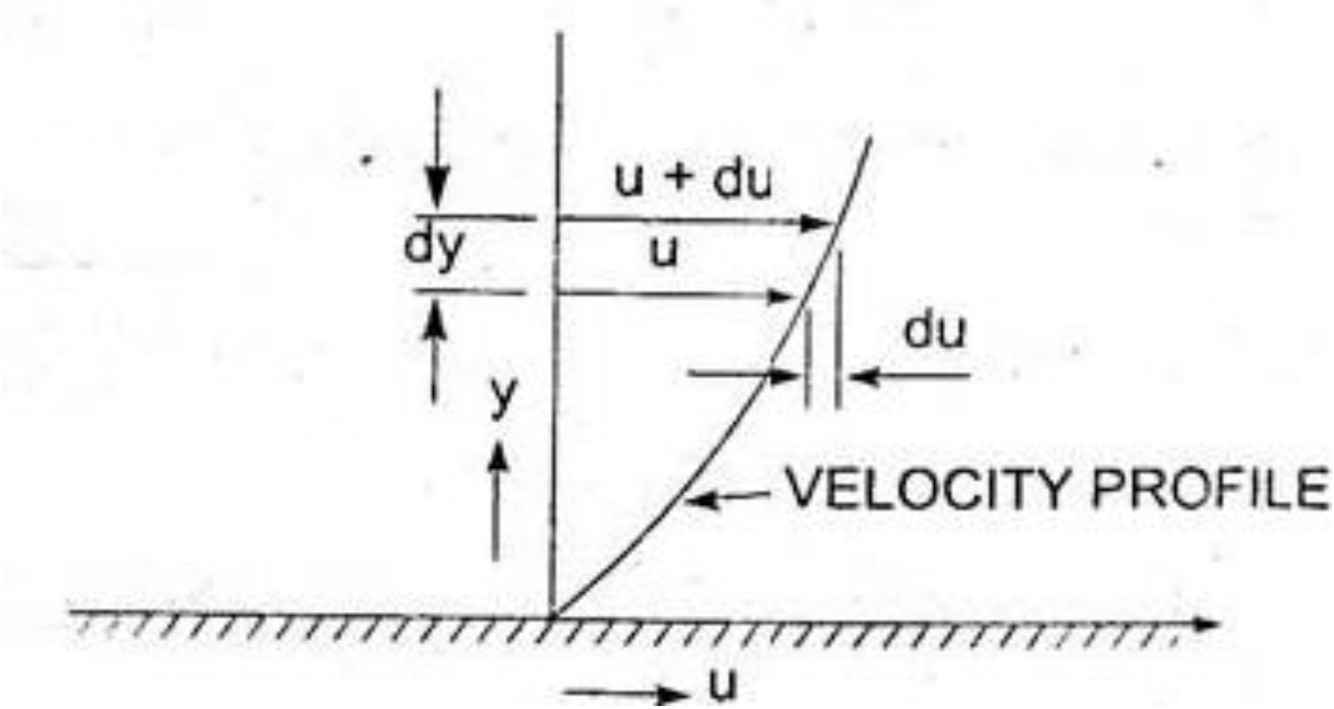
- As a fluid moves, a shear stress is developed in it, the magnitude of which depends on the viscosity of the fluid.
- *Shear stress*, denoted by the Greek letter (tau), τ, can be defined as *the force required to slide one unit area layer of a substance over another*.
- Thus, τ is a *force divided by an area* and can be measured in the units of N/m^2 (Pa) or lb/ft^2.

Viscosity

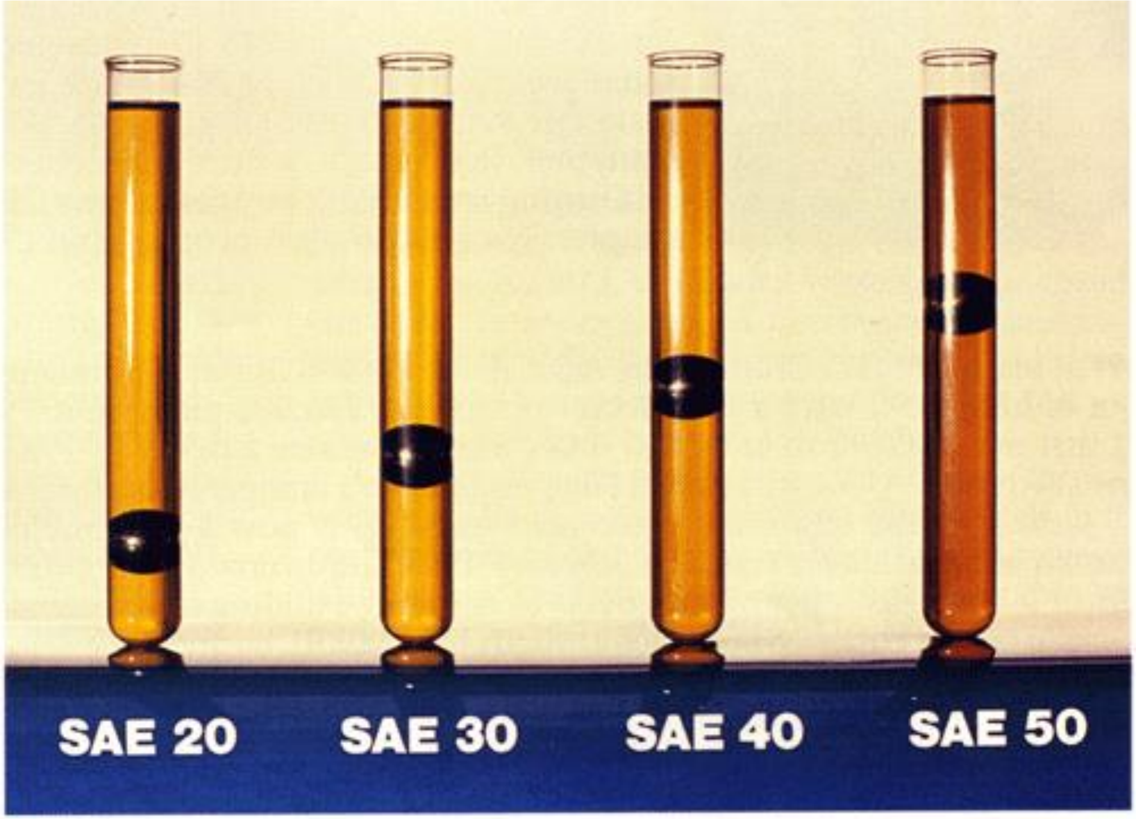
- **Viscosity is also defined as the property of the fluid which case the resistance in movement of one layer over another.**
- When two layers of fluid a distance *dy* apart, move one over another at different velocities, say *u* and *u+du* as shown in *fig*. a shear stress is developed between the layers of fluid. This shear stress is directly proportional to rate of change of velocity with respect to y.

$$\tau \; \alpha \frac{du}{dy} \; or \; \tau = \mu \frac{du}{dy}$$

Viscosity



Viscosity



Steel balls of equal weight dropped into test tubes filled with motor oils fall at different rates. Their rate of fall depends on the viscosity of the oil. The ball travelling through the light SAE 20 oil has travelled farthest, while the ball in the heavy SAE 50 has travelled least.

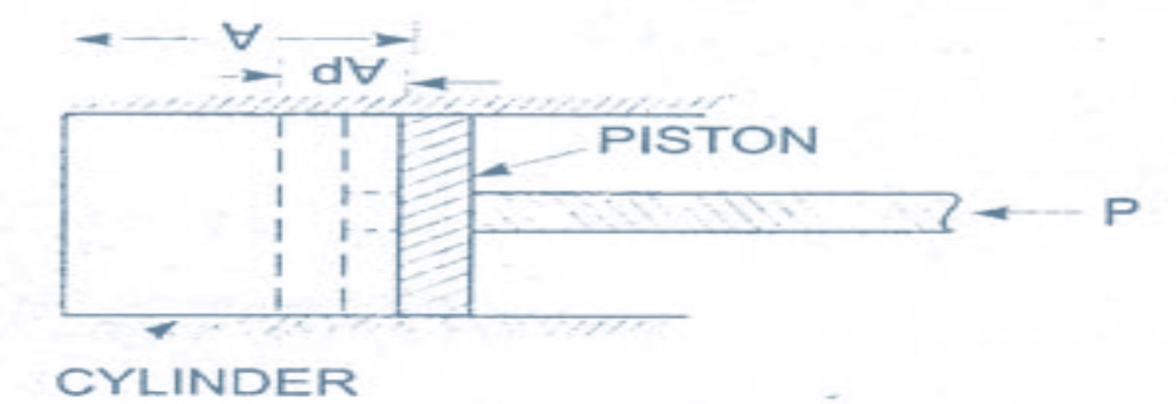
Compressibility

- It is defined as:

  "Change in Volume due to change in Pressure."

- The compressibility of a liquid is inversely proportional to Bulk Modulus (K) (volume modulus of elasticity).
- Compressibility is reciprocal of Bulk Modulus.
- Let a cylinder fitted with a piston as shown in fig.
- Let V is volume of gas enclosed in a cylinder and p is the pressure applied. Let the pressure is increased to $p+\Delta p$ and volume is decreased to $V- \Delta V$.

Compressibility



- Volumetric Strain= -ΔV/V
- Compressibility= 1/K=(-ΔV/V)/ Δp
- Bulk modulus of a substance measures resistance of a substance to uniform compression.
- Where; v is the specific volume and p is the pressure.
- **Units: Psi, MPa** , As v/dv is a dimensionless ratio, the units of E and p are identical.

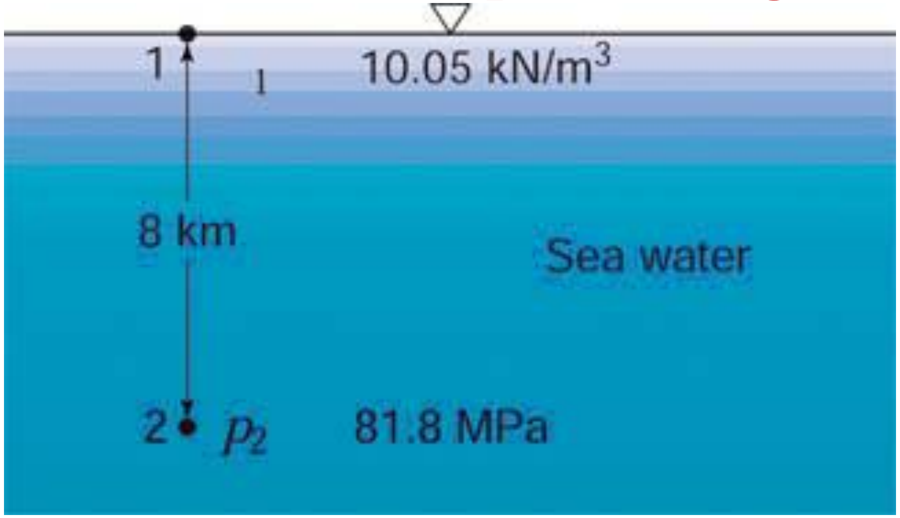
Example

At a depth of 8km in the ocean the pressure is 81.8Mpa. Assume that the specific weight of sea water at the surface is 10.05 kN/m^3 and that the average volume modulus is 2.34 x 10^9 N/m^3 for that pressure range.

(a) What will be the change in specific volume between the surface and at that depth?

(b) What will be the specific volume at that depth?

(c) What will be the specific weight at that depth?



Solution:

$$(a) \quad v_1 = 1/p_1 = g/\gamma_1$$

$$= 9.81/10050 = 0.000976 m^3/kg$$

$$\Delta v = -0.000976(81.8x10^6 - 0)/(2.34x10^9)$$

$$= -34.1x10^{-6} m^3/kg$$

$$(b) \quad v_2 = v_1 + \Delta v = 0.000942 m^3/kg$$

$$(c) \quad \gamma_2 = g/v_2 = 9.81/0.000942 = 10410 N/m^3$$

Using Equation :

$$E_v = \frac{-\Delta p}{(\Delta v/v)}$$

$$\frac{dv}{v} \approx -\frac{\Delta p}{E_v}$$

$$\frac{v_2 - v_1}{v_1} \approx -\frac{p_2 - p_1}{E_v}$$

Dynamic Viscosity

- The fact that the shear stress in the fluid is directly proportional to the velocity gradient can be stated mathematically as

$$\tau = \frac{F}{A} = \mu \frac{U}{Y} = \mu \frac{du}{dy}$$

- where the constant of proportionality μ (the Greek letter miu) is called the *dynamic viscosity* of the fluid. The term *absolute viscosity* is sometimes used.

Unit System	Dynamic Viscosity Units
International System (SI)	$N \cdot s/m^2$, $Pa \cdot s$, or $kg/(m \cdot s)$
U.S. Customary System	$lb \cdot s/ft^2$ or $slug/(ft \cdot s)$
cgs system (obsolete)	poise = $dyne \cdot s/cm^2$ = $g/(cm \cdot s)$ = 0.1 $Pa \cdot s$
	centipoise = poise/100 = 0.001 $Pa \cdot s$ = 1.0 $mPa \cdot s$

Kinematic Viscosity

- The kinematic viscosity ν is defined as:

  "Ratio of absolute viscosity to density."

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

Unit System	Kinematic Viscosity Units
International System (SI)	m^2/s
U.S. Customary System	ft^2/s
cgs system (obsolete)	stoke = $cm^2/s = 1 \times 10^{-4}\ m^2/s$
	centistoke = stoke/100 = $1 \times 10^{-6}\ m^2/s = 1\ mm^2/s$

Types of fluids:

- Ideal Fluid
- Real Fluid
- Newtonian Fluids
- Non- Newtonian Fluids
- Ideal Plastic Fluids.

Ideal Fluid

- An *ideal* fluid may be defined as:

  "A fluid in which there is *no friction i.e* Zero viscosity."

- Although such a fluid does not exist in reality, many fluids approximate frictionless flow at sufficient distances, and so their behaviors can often be conveniently analyzed by assuming an ideal fluid.

Real Fluid

- In a *real fluid*, either liquid or gas, tangential or shearing forces always come into being whenever motion relative to a body takes place, thus giving rise to fluid friction, because these forces oppose the motion of one particle past another.
- These friction forces give rise to a fluid property called *viscosity*.

Newtonian Fluid

- A **Newtonian fluid; where stress is directly proportional to rate of strain, and** (named for Isaac Newton) is a fluid that flows like water, its stress versus rate of strain curve is linear and passes through the origin. The constant of proportionality is known as the viscosity.
- A simple equation to describe Newtonian fluid behavior is

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

- Where μ = absolute viscosity/Dynamic viscosity or simply viscosity

  τ = shear stress

- A Non-**Newtonian fluid; where stress is not directly proportional to rate of change of strain,**
- **Ideal Plastic Fluid**: A **fluid** in which shear stress is more than the yield value and shear stress is proportional to the rate of shear strain (or velocity gradient)

Types of Fluids

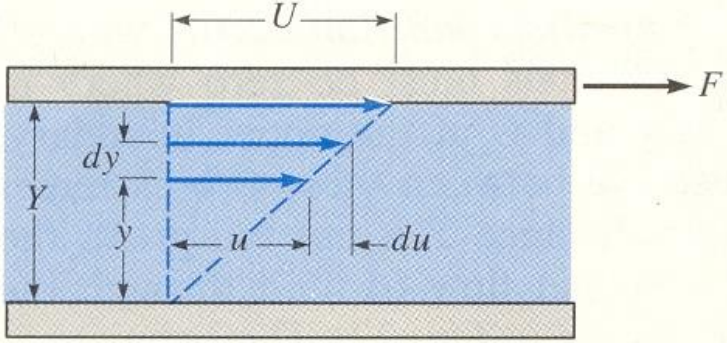


Figure 2.5

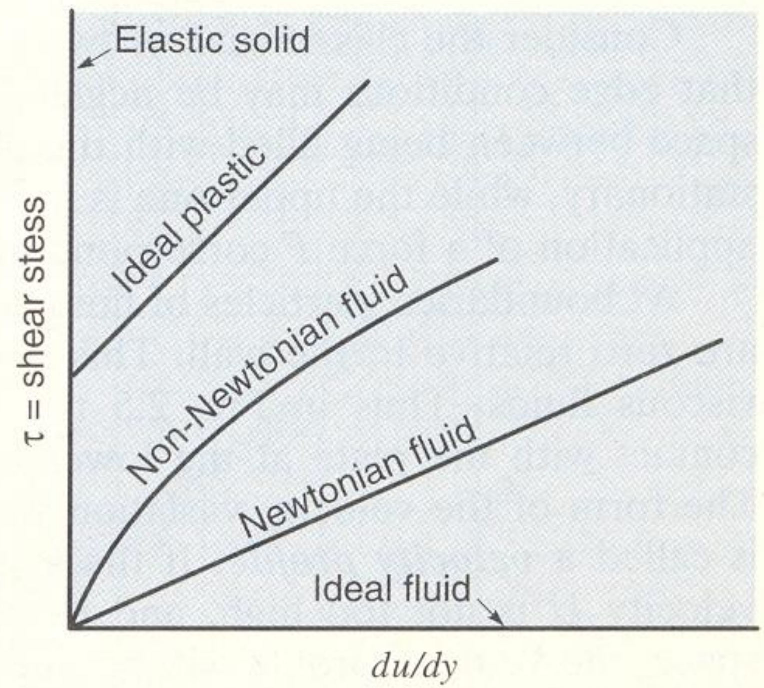


Figure 2.6

Example

Find the kinematic viscosity of liquid in stokes whose specific gravity is 0.85 and dynamic viscosity is 0.015 poise.

Solution:

Given $S = 0.85$

$\mu = 0.015$ poise

$= 0.015 \times 0.1\ Ns/m^2 = 1.5 \times 10^{-3}\ Ns/m^2$

We know that S = density of liquid/density of water

density of liquid = S x density of water

$\rho = 0.85 \times 1000 = 850\ kg/m^3$

Kinematic Viscosity ,

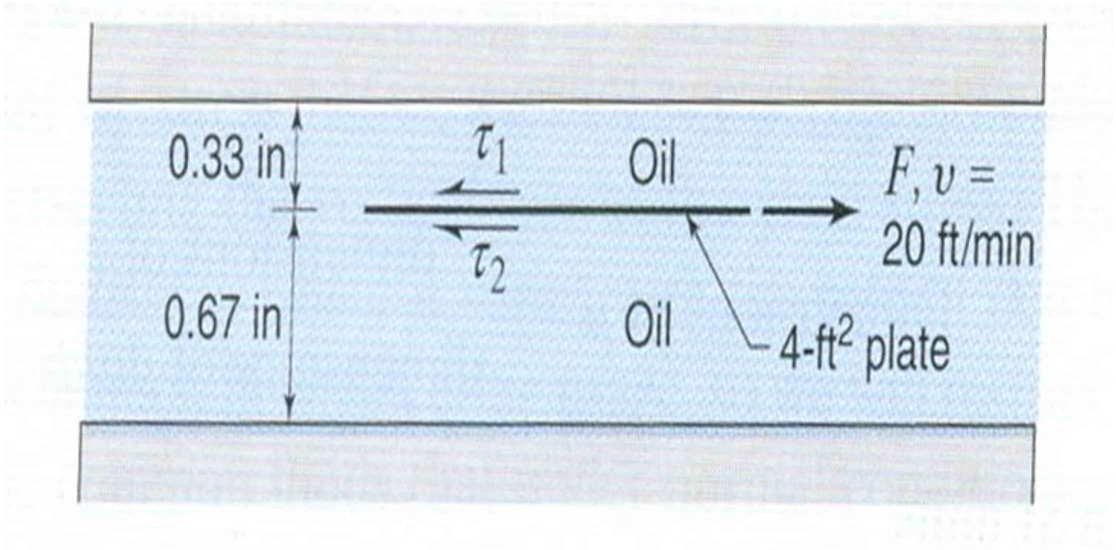
$\upsilon = \mu/\rho = 1.5 \times 10^{-3}/850$

$= 1.76 \times 10^{-6}\ m^2/s = 1.76 \times 10^{-6} \times 10^4 cm^2/s$

$= 1.76 \times 10^{-2}$ stokes.

Example

A 1 in wide space between two horizontal plane surface is filled with SAE 30 Western lubricating oil at 80 F. What force is required to drag a very thin plate of 4 sq.ft area through the oil at a velocity of 20 ft/min if the plate is 0.33 in from one surface.



Solution:

$$\mu = 0.0063\ \text{lb.sec/ft}^2 (From - A.1)$$

$$\tau = \frac{F}{A} = \mu \frac{U}{Y} = \mu \frac{du}{dy}$$

$$\tau_1 = 0.0063 * (20/60)/(0.33/12) = 0.0764 lb/ft^2$$

$$\tau_2 = 0.0063 * (20/60)/(0.67/12) = 0.0394 lb/ft^2$$

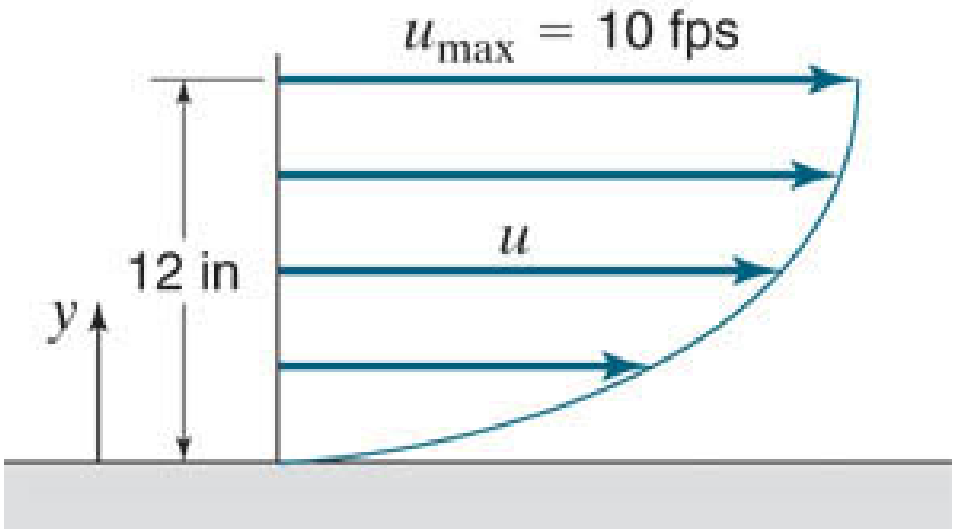
$$F_1 = \tau_1 A = 0.0764 * 4 = 0.0305 lb$$

$$F_2 = \tau_2 A = 0.0394 * 4 = 0.158 lb$$

$$Force = F_1 + F_2 = 0.463 lb$$

Example

Assuming a velocity distribution as shown in fig., which is a parabola having its vertex 12 in from the boundary, calculate the shear stress at y= 0, 3, 6, 9 and 12 inches. Fluid's absolute viscosity is 600 P.



1. If the velocity distribution over a plate is given by $u = \frac{2}{3}y - y^2$ in which velocity is in m/s and y is in m above the plate. Find the shear stress at y=0 and y=0.15 m. take dynamic viscosity as 8.63 poise.
2. Solve Related topic problems from book.

Solution

μ $=600$ P= 600 x 0.1=60 N-s/m^2 =60 x (1x2.204/9.81 x 3.28$^{2)}$

=60 x 0.020885=1.253 lb-sec/ft^2

Parabola Equation **$Y=aX^2$**

120-u= a(12-y) ^{2}

u=0 at y=0 so a= 120/12$^{2=}$5/6

u=120-5/6(12-y) ^{2} du/dy=5/3(12-y)

τ=μ du/dy

y (in)	0	3	6	9	12
du/dy	20	15	10	5	0
τ	0.251	0.1880	0.1253	0.0627	0

Variation of Viscosity with Temperature:

- Temperature affects the viscosity.
- The viscosity of liquid decreases with increase in temperature while viscosity of gasses increases with increases in temperature.
- The relation between temperature and viscosity is given as
- $\mu = \mu_o \left(\frac{1}{1+\alpha t+\beta t^2}\right)$ For Liquids
- $\mu = \mu_o + \alpha t - \beta t^2$ For Gasses
- Where β and α are constants
- μ= Viscosity at *ith* C^o , in poise.
- μ_o= Viscosity at *0* C^o , in poise.

Variation of Viscosity with Temperature:

Constants	Liquid	Gasses
α	0.03368	0.1189×10^{-9}
β	0.000221	0.000000056
μ_o	1.79×10^{-3} poise	0.000017 poise

Surface Tension

- Cohesion: "Attraction between molecules of same surface"
  It enables a liquid to resist tensile stresses.
- Adhesion: "Attraction between molecules of different surface"
  It enables to adhere to another body.
- "Surface Tension is the property of a liquid, which enables it to resist tensile stress".
- At the interface between liquid and a gas i.e at the liquid surface, and at the interface between two immiscible (not mixable) liquids, the attraction force between molecules form an imaginary surface film which exerts a tension force in the surface. This liquid property is known as Surface Tension.

Surface Tension

- As a result of surface tension, the liquid surface has a tendency to reduce its surface as small as possible. That is why the water droplets assume a nearly spherical shape.
- This property of surface tension is utilized in manufacturing of lead shots.

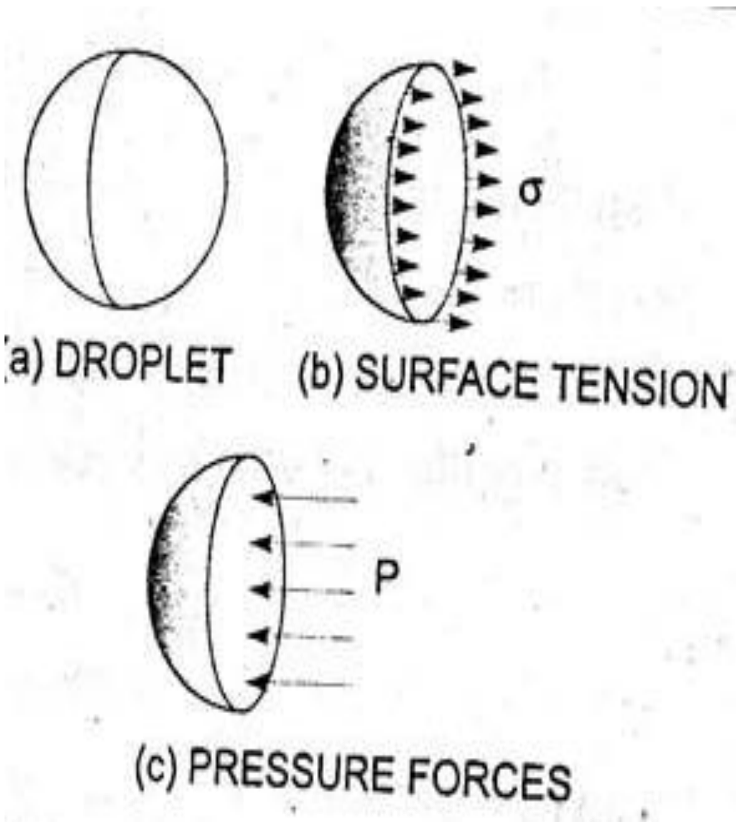
Surface Tension on liquid droplet

- Consider a small sphere of droplet of a liquid of radius r, on entire surface tensile stress will be acting due to surface tension.
- Let droplet is cut off into two parts, the forces acting on one half will be

I. Tensile force along the circumference of the cut off portion as shown=σπd

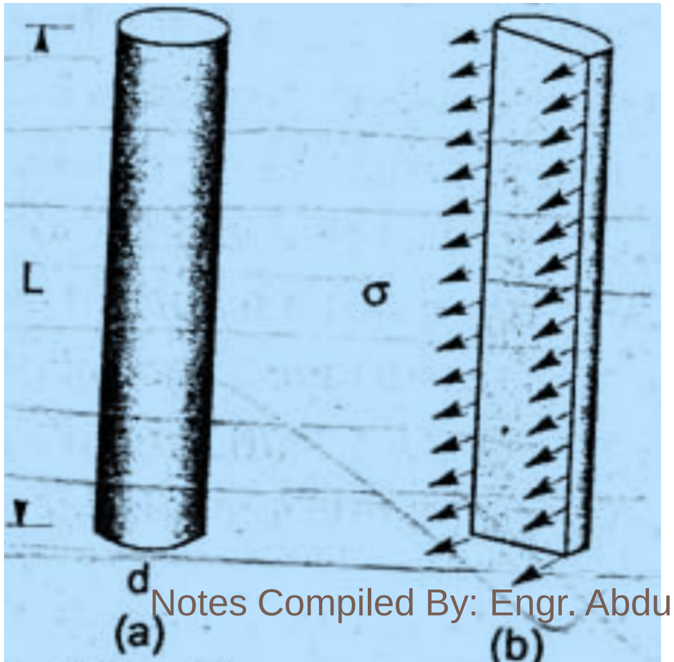
II. Pressure force on the area $\pi d^2/4$= pxA=p.$\pi d^2/4$

- Equating both eq. we have $p = \frac{4\sigma}{d}$
- Surface Tension on bubble =$p = \frac{8\sigma}{d}$



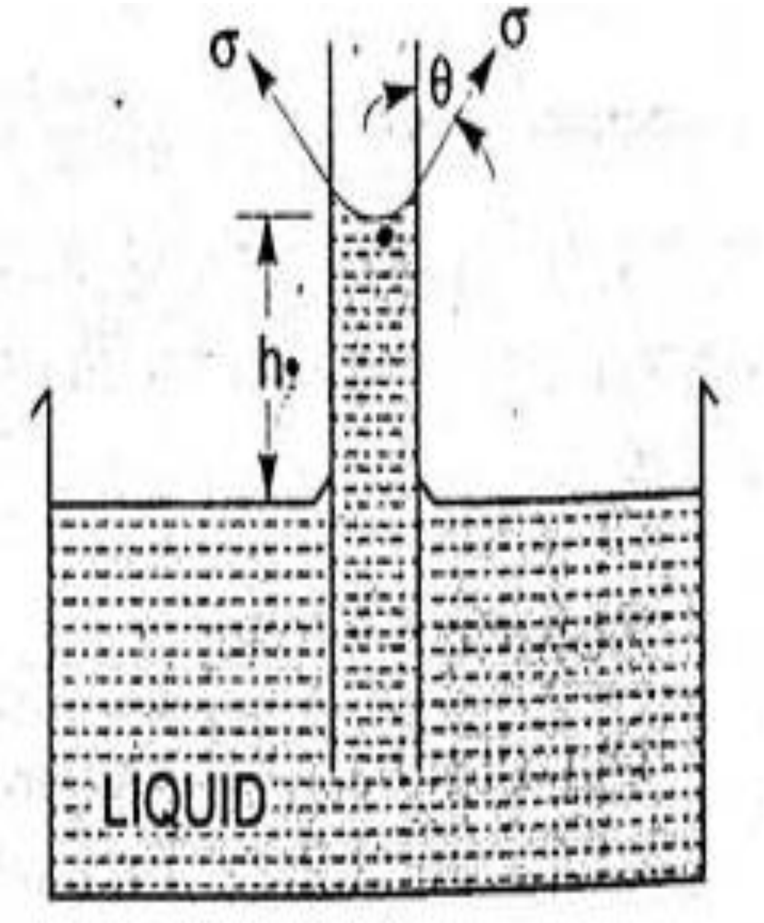
Surface Tension on liquid Jet

- Consider a liquid jet of dia D and length L as shown in fig.
- Consider the equilibrium condition
- Force due to pressure = force due to surface tension
- pxLxD=σx2L
- $p = \frac{2L\sigma}{LD}$



Capillary Rise

- **Capillary Rise**: The phenomenon of rising water in the tube of smaller diameter is called capillary rise.
- $h = \dfrac{4\sigma cos\theta}{\rho g d}$



Thermodynamic Properties

- Fluids consists of liquid and gasses.
- Gasses are more compressible than that of liquids.
- With change in temp and pressure, there is large change in its density.
- $\frac{p}{\rho} = RT$
- R is gas constant.
- R=29.3 kg-f/kg-K
- R=287 j/kg-K

Metric to U.S. System Conversions, Calculations, Equations, and Formulas

- Millimeters (mm) x 0.03937 = inches (")(in)
- Centimeters (cm) x 0.3937 = inches (")(in)
- Meters (m) x 39.37 = inches (")(in)
- Meters (m) x 3.281 = feet (')(ft)
- Meters (m) x 1.094 = yards (yds)
- Kilometers (km) x 0.62137 = miles (mi)
- Kilometers (km) x 3280.87 = feet (')(ft)
- Liters (l) x 0.2642 = gallons (U.S.)(gals)

Calculations, Equations & Formulas

- Bars x 14.5038 = pounds per square inch (PSI)
- Kilograms (kg) x 2.205 = Pounds (P)
- Kilometers (km) x 1093.62 = yards (yds)
- Square centimeters x 0.155 = square inches
- Liters (l) x 0.0353 = cubic feet
- Square meters x 10.76 = square feet
- Square kilometers x 0.386 = square miles
- Cubic centimeters x 0.06102 = cubic inches
- Cubic meters x 35.315 = cubic feet

Calculations, Equations & Formulas

- Inches (")(in) x 25.4 = millimeters (mm)
- Inches (")(in) x 2.54 = centimeters (cm)
- Inches (")(in) x 0.0254 = meters (m)
- Feet (')(ft) x 0.3048 = meters (m)
- Yards (yds) x 0.9144 = meters (m)
- Miles (mi) x 1.6093 = kilometers (km)
- Feet (')(ft) x 0.0003048 = kilometers (km)

Calculations, Equations & Formulas

- Gallons (gals) x 3.78 = liters (l)
- Cubic feet x 28.316 = liters (l)
- Pounds (P) x 0.4536 = kilograms (kg)
- Square inches x 6.452 = square centimeters
- Square feet x 0.0929 = square meters
- Square miles x 2.59 = square kilometers
- Acres x 4046.85 = square meters
- Cubic inches x 16.39 = cubic centimeters
- Cubic feet x 0.0283 = cubic meters

Calculations, Equations & Formulas

- MKS units of Absolute Viscosity=kgf-sec/m^2=98.1 poise
- CGS units of Absolute Viscosity=1 poise=dyne-sec/cm^2
- SI units= Ns/m^2=Pa.sec
- 1 poise= 0.1 Ns/m^2
- 1 centipoise= 1/100 poise
- 1 stoke= cm^2/s


QUESTIONS