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.

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	$(Length)^3$	m^3	liter (L)
Area	$(Length)^2$	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	$N \cdot s^2/m^4$

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.

$$SpecificVolume = v = 1/\rho$$

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:

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

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

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

(Where Slug = lb.sec2/ 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:

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

$$\rho = 16/9.81 = 16.631\ \text{kg/m}^3$$

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

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

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

$$s = 16/12 = 1.333$$

Example

The specific weight of glycerin is 78.6 lb/ft³. compute its density and specific gravity. What is its specific weight in kN/m³ Solution:

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

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

$$2.\ \text{Specific gravity}\quad s = \gamma_l / \gamma_w$$

$$s = 78.6/62.4 = 1.260$$

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

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

$$3.\ \text{Specific weight in kN/m}^3$$

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

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

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

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

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

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

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/ ρ

= 1/700

= 1.43×10^{-3}

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

Compressibility

- It is defined as:

  "Change in Volume due to change in Pressure."

- The compressibility of a liquid is inversely proportional to Bulk Modulus (volume modulus of elasticity).
- Bulk modulus of a substance measures resistance of a substance to uniform compression.

$$E_v = \frac{-dp}{(dv/v)}$$

$$E_v = -\left(\frac{v}{dv}\right)dp$$

- 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.

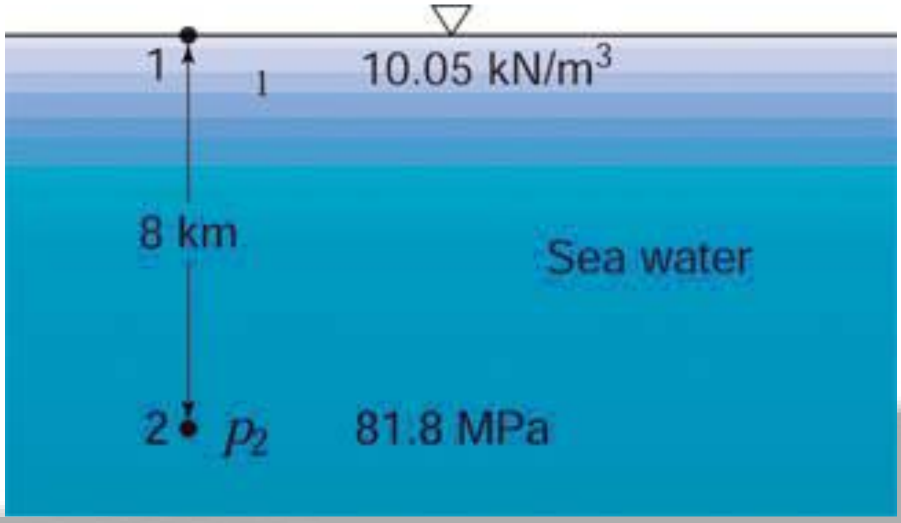
Example

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/m³ and that the average volume modulus is 2.34 x 10³ N/m³ for that pressure range.

(a) What will be the change in specific volume between that at 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 :

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

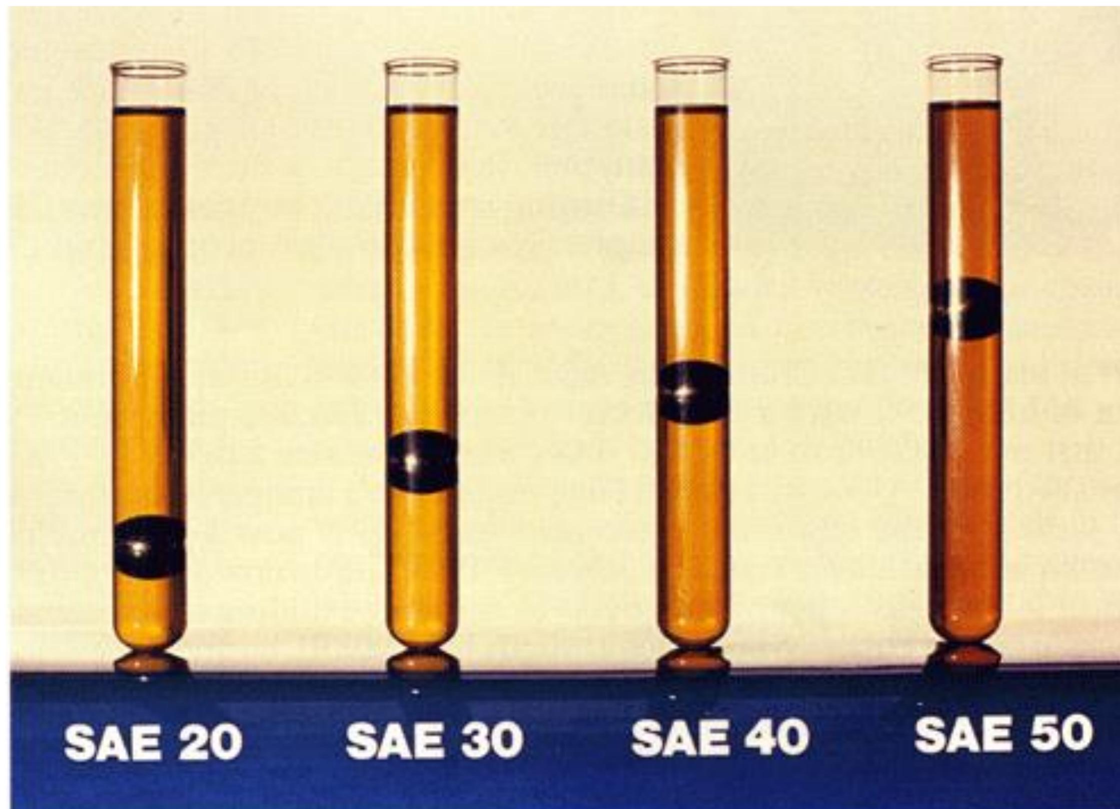
$$\frac{dv}{v} \approx -\frac{\Delta p}{E_v}$$

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

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.**

Viscosity



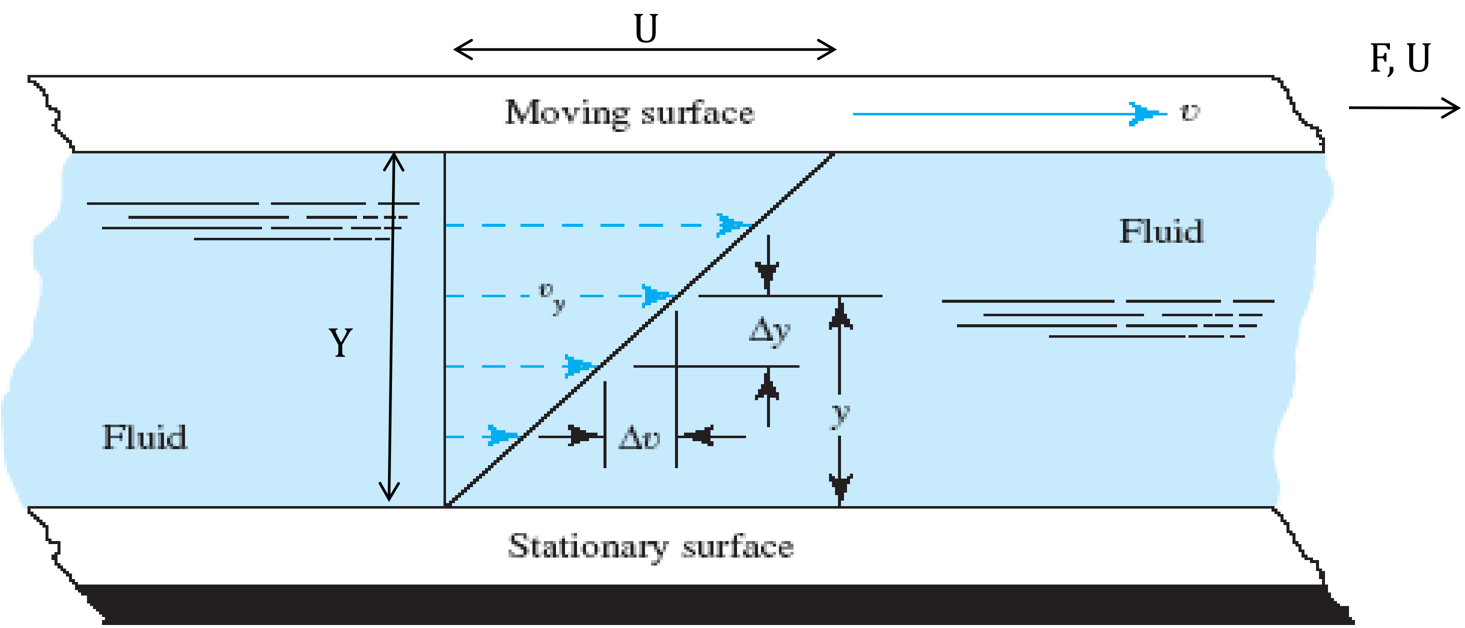
Steel balls of equal weight dropped into test tubes filled with motor oils fall at different rates. Their rate of fall depends on the viscosity of the oil. The ball travelling through the light SAE 20 oil has travelled farthest, while the ball in the heavy SAE 50 has travelled least.

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.

Dynamic Viscosity

- Figure shows the velocity gradient in a moving fluid.



- Experiments have shown that: $F \alpha \dfrac{AU}{Y}$

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·s/m^2, Pa·s, or kg/(m·s)
U.S. Customary System	lb·s/ft^2 or slug/(ft·s)
cgs system (obsolete)	poise = dyne·s/cm^2 = g/(cm·s) = 0.1 Pa·s
	centipoise = poise/100 = 0.001 Pa·s = 1.0 mPa·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 $= 1 \times 10^{-6}\ m^2/s = 1\ mm^2/s$

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

Newtonian Fluid

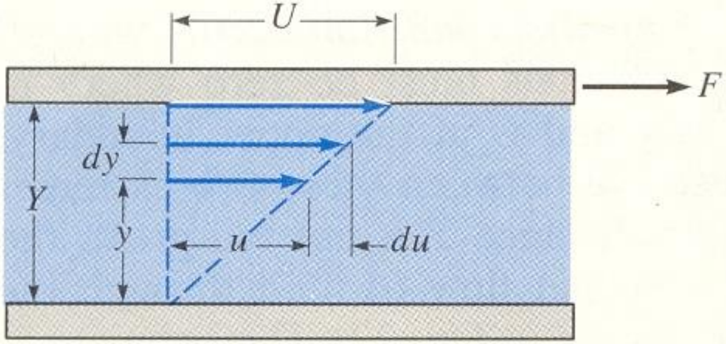


Figure 2.5

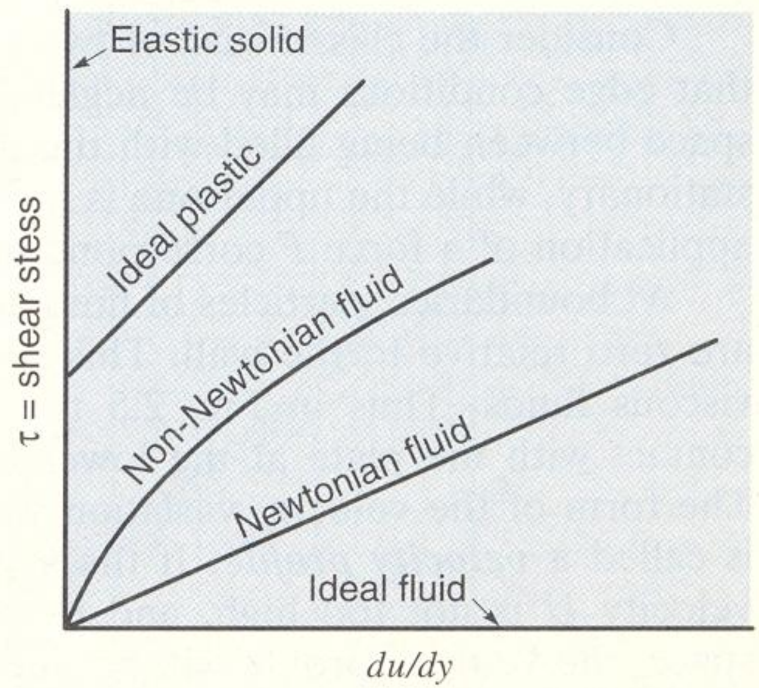


Figure 2.6

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 ,

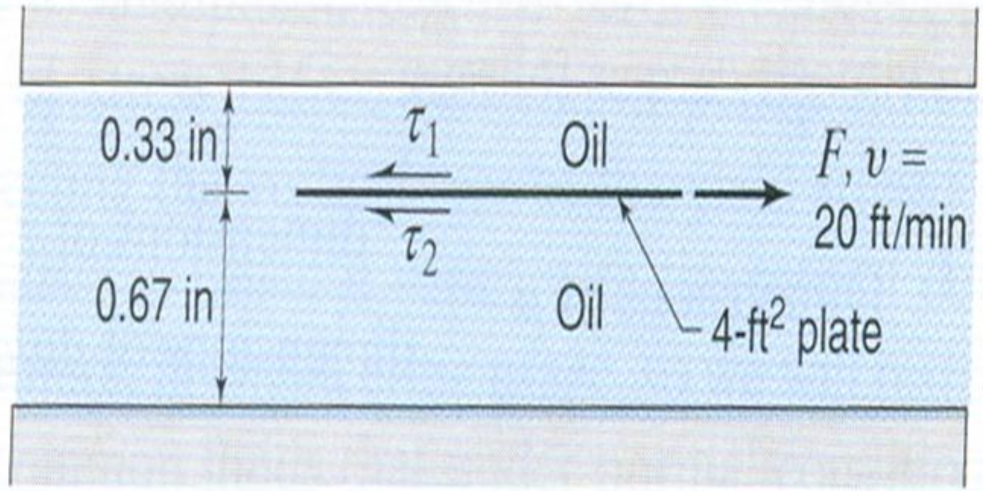
$\upsilon = \mu/\rho = 1.5 \times 10^{-3}/850$

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

$= 1.76 \times 10^{-2}$ 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/mm if the plate is 0.33 in from one surface.



Solution:

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

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

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

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

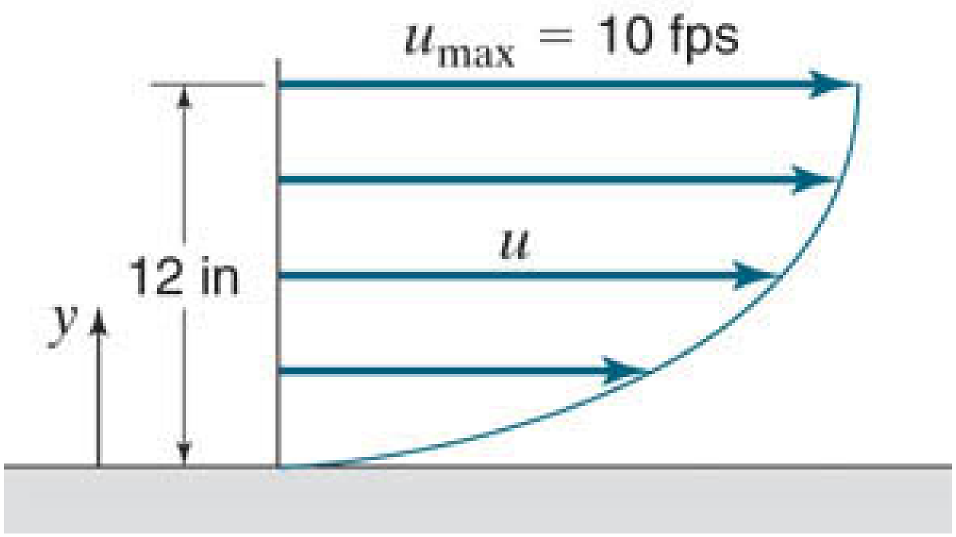
$$F_1 = \tau_1 A = 0.0764 * 4 = 0.0305 lb$$

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

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

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.



Solution

μ =600 P= 600 x 0.1=0.6 N-s/m^2 =0.6 x (1x2.204/9.81 x 3.28$^{2)}$

=0.6 x 0.020885=0.01253 lb-sec/ft^2

Parabola Equation $\mathbf{Y=aX^2}$

$120-u= a(12-y)^2$

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

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*.

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.
- Capillary Rise: The phenomenon of rising water in the tube of smaller diameter is called capillary rise.