FLUID MECHANICS I

SEMM 2313

INTRODUCTION TO FLUID MECHANICS AND UNIT

CHARACTERISTIC OF FLUIDS

A fluid is defined as a substance that deforms continuously when acted on by a shearing stress at any magnitude.

In a fluid at rest, normal stress is called *"pressure"*.

Dimensions, Dimensional homogeneity and Units

Fluid has *qualitative* and *quantitative* characteristic.

Qualitative :

To identify the nature of fluid such as length, time, stress and velocity. Basically the qualitative aspects identities the nature or type of characteristic.

Quantitative :

Numerical measure of the characteristic. Quantitative requires both a number and a standard. Such standards are called *"unit"*.

3 kg

Number 3 is quantity and kg (kilogram) is a unit

Primary quantity :

L	: Length
T	: Time
M	: Mass
θ	: Temperature

Secondary quantity :

L^2	: Area
LT^{-1}	: Velocity
ML^{-3}	: Density

All theoretically derived equations are *"dimensionally homogeneous"*. The dimension of the left side of the equation must be the same as those on the right side, and all additive separate terms must have the same dimensions.

Example :

$$V = V_0 + at$$

$$LT^{-1} = LT^{-1} + (LT^{-2})(T)$$

TABLE 1.1

Dimensions Associated with Common Physical Quantities

	FLT System	*MLT* System
Acceleration	LT^{-2}	LT^{-2}
Angle	$F^0L^0T^0$	$M^0L^0T^0$
Angular acceleration	T^{-2}	T^{-2}
Angular velocity	T^{-1}	T^{-1}
Area	L^2	L^2
Density	$FL^{-4}T^2$	ML^{-3}
Energy	FL	ML^2T^{-2}
Force	F	MLT^{-2}
Frequency	T^{-1}	T^{-1}
Heat	FL	ML^2T^{-2}
Length	L	L
Mass	$FL^{-1}T^2$	M
Modulus of elasticity	FL^{-2}	$ML^{-1}T^{-2}$
Moment of a force	FL	ML^2T^{-2}
Moment of inertia (area)	L^4	L^4

UNIT

3 major systems that are commonly used in engineering.

1. *British Gravitational (BG) System*
   - Length – foot (ft)
   - Time – second (s)
   - Force – pound (lb)
   - Temperature – Fahrenheit (ºF)

2. *International System (SI)*
   - Length – meter (m)
   - Time – second (s)
   - Mass – kilogram (kg)
   - Temperature – Kelvin (K)

3. *English Engineering (EE) System*

- Length – foot (ft)
- Time – second (s)
- Mass – pound mass (lbm)
- Force – pound (lb or lbf)
- Temperature – Rankine (ºR)

The relation of Kelvin and Celsius is;

$$K = {}^{\circ}C + 273.15$$

TABLE 1.2

Prefixes for SI Units

Factor by Which Unit Is Multiplied	Prefix	Symbol
10^{12}	tera	T
10^{9}	giga	G
10^{6}	mega	M
10^{3}	kilo	k
10^{2}	hecto	h
10	deka	da
10^{-1}	deci	d
10^{-2}	centi	c
10^{-3}	milli	m
10^{-6}	micro	μ
10^{-9}	nano	n
10^{-12}	pico	p
10^{-15}	femto	f
10^{-18}	atto	a

MEASURES OF FLUID MASS AND WEIGHT

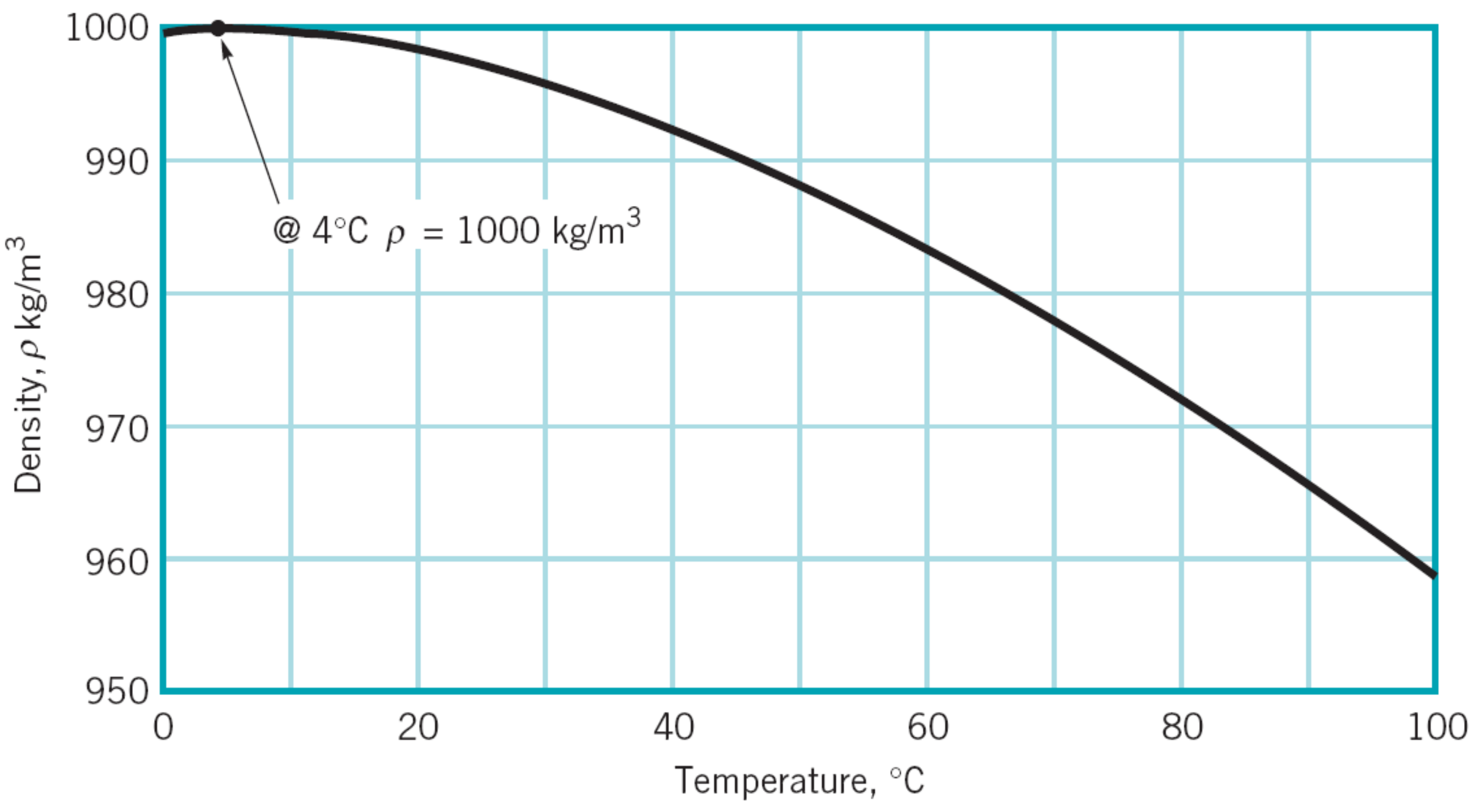
Density

Designated by the Greek symbol ρ (rho).
Defined as its mass per unit volume.

$$\rho = \frac{mass}{volume} = \frac{kg}{m^3}$$

Specific volume, is the volume per unit mass. This property is not commonly used in fluid mechanics but is used widely in thermodynamics.

$$\upsilon = \frac{volume}{mass} = \frac{1}{\rho}$$



The changes of density of water over temperatures.

If not given, we could take the density of water is 1000 kg/m^3

■ TABLE 1.6
Approximate Physical Properties of Some Common Liquids (SI Units)

Liquid	Temperature (°C)	Density, ρ (kg/m^3)	Specific Weight, γ (kN/m^3)	Dynamic Viscosity, μ (N · s/m^2)	Kinematic Viscosity, ν (m^2/s)	Surface Tension,[a] σ (N/m)	Vapor Pressure, p_v [N/m^2 (abs)]	Bulk Modulus,[b] E_v (N/m^2)
Carbon tetrachloride	20	1,590	15.6	9.58 E − 4	6.03 E − 7	2.69 E − 2	1.3 E + 4	1.31 E + 9
Ethyl alcohol	20	789	7.74	1.19 E − 3	1.51 E − 6	2.28 E − 2	5.9 E + 3	1.06 E + 9
Gasoline[c]	15.6	680	6.67	3.1 E − 4	4.6 E − 7	2.2 E − 2	5.5 E + 4	1.3 E + 9
Glycerin	20	1,260	12.4	1.50 E + 0	1.19 E − 3	6.33 E − 2	1.4 E − 2	4.52 E + 9
Mercury	20	13,600	133	1.57 E − 3	1.15 E − 7	4.66 E − 1	1.6 E − 1	2.85 E + 10
SAE 30 oil[c]	15.6	912	8.95	3.8 E − 1	4.2 E − 4	3.6 E − 2	—	1.5 E + 9
Seawater	15.6	1,030	10.1	1.20 E − 3	1.17 E − 6	7.34 E − 2	1.77 E + 3	2.34 E + 9
Water	15.6	999	9.80	1.12 E − 3	1.12 E − 6	7.34 E − 2	1.77 E + 3	2.15 E + 9

[a]In contact with air.

[b]Isentropic bulk modulus calculated from speed of sound.

[c]Typical values. Properties of petroleum products vary.

Specific weight

Designated by the Greek symbol γ (gamma).

Defined as its weight per unit volume.

$$\gamma = \frac{weight}{volume} = \frac{mg}{volume} = \frac{kg \cdot g}{m^3} = \rho g$$

Specific gravity

Designated as SG.

Defined as the ratio of the density of the fluid to the density of water at some specified temperature.

Usually, the specified temperature is taken as 4ºC.

$$SG = \frac{\rho}{\rho_{H_2O@4^\circ C}}$$

Ideal gas law

Gases are highly compressible in comparison to liquids, with changes in gas density directly related to changes in pressure and temperature through the equation.

$$P = \rho R T$$

P : pressure

ρ : density

R : gas constant

T : temperature

The pressure in the ideal gas law must be expressed as an absolute pressure (abs), which means that it is measured relative to absolute zero pressure (a pressure that would only occur in a perfect vacuum).

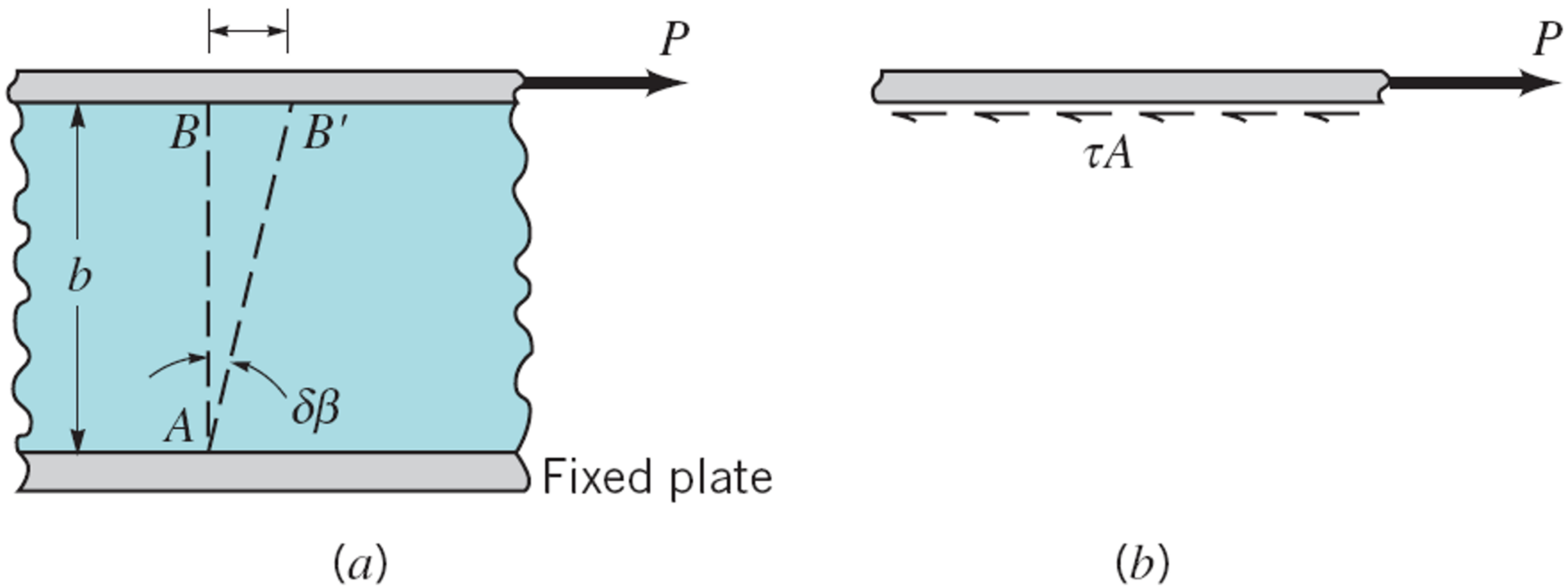
Standard sea-level atmospheric pressure is 14.696 psi and 101.325 kPa, respectively.

$$P_{atm} = 101.325 \ \text{kPa}$$

VISCOSITY

The property of viscosity is described the *"fluidity"* of the fluid.

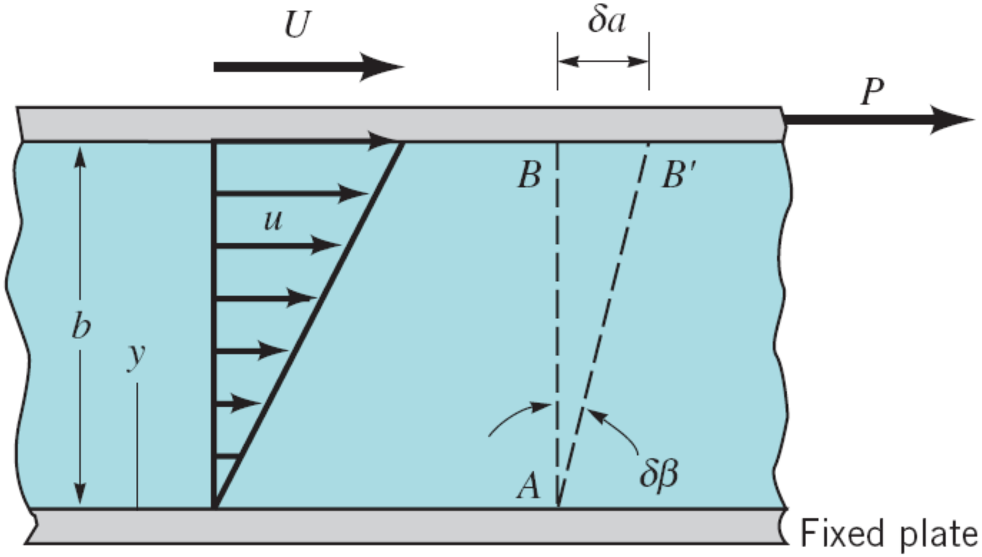
To resist the applied force, P, a shearing stress, τ, would be developed at the plate-material interface.



The equilibrium is ;

$$P = \tau A$$

It revealed that as the shearing stress, τ, is increased by increasing P.



We can say that shear stress, τ, has direct proportion with the velocity gradient – that is ;

$$\tau \propto \frac{du}{dy}$$

The shearing stress and velocity gradient can be related with a relationship of the form ;

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

μ (miu) is a dynamic viscosity. Dynamic viscosity also called as absolute viscosity.

Unit is kg/m.s or N.s/m^2 or Pa.s or Poise (P) or centipoise (cP)

1 Pa.s = 10 Poise

Relation between dynamic viscosity and kinematic viscosity can be written as ;

$$\mu = \rho \upsilon$$

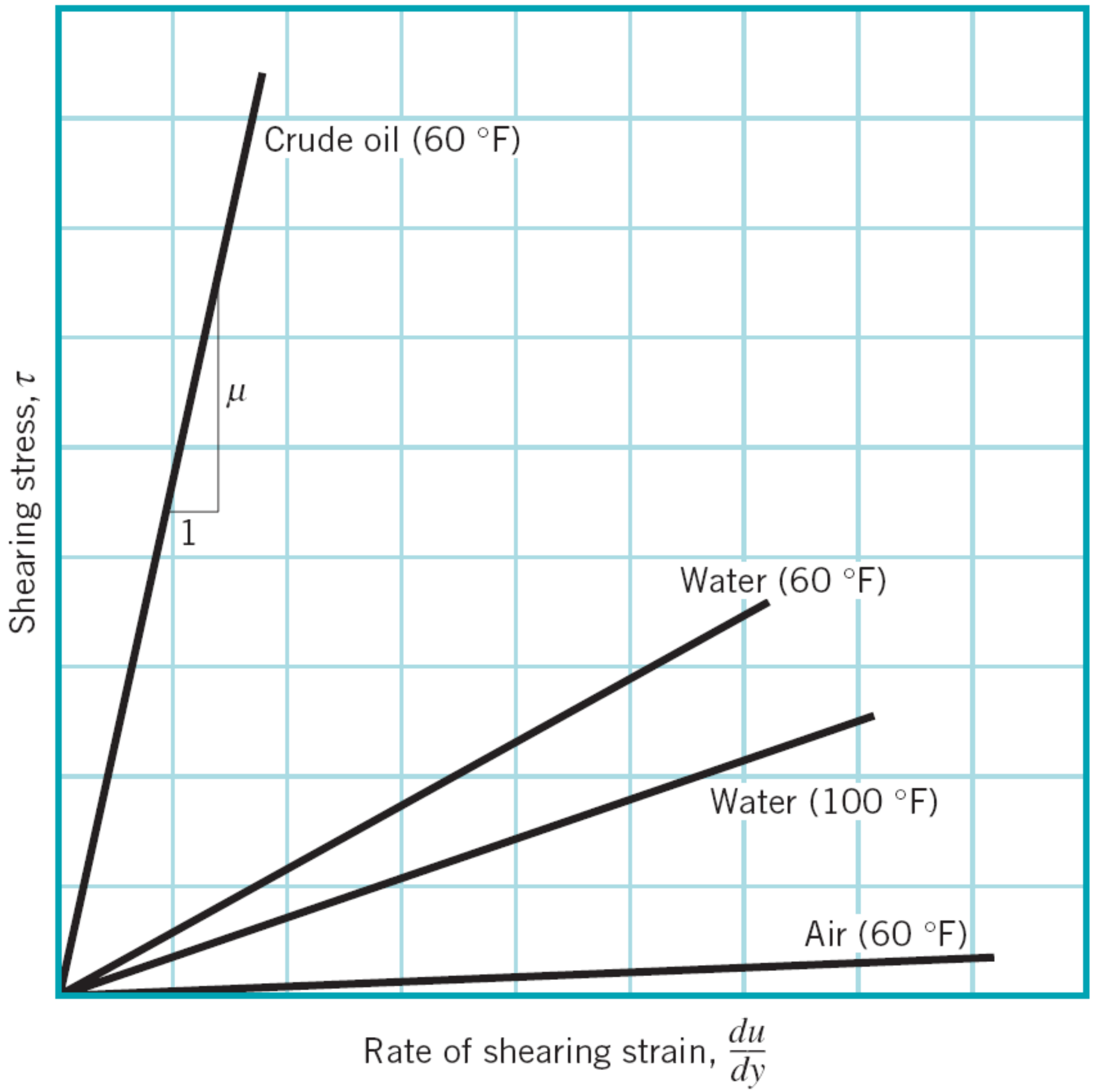
υ (nu) is a kinematic viscosity.

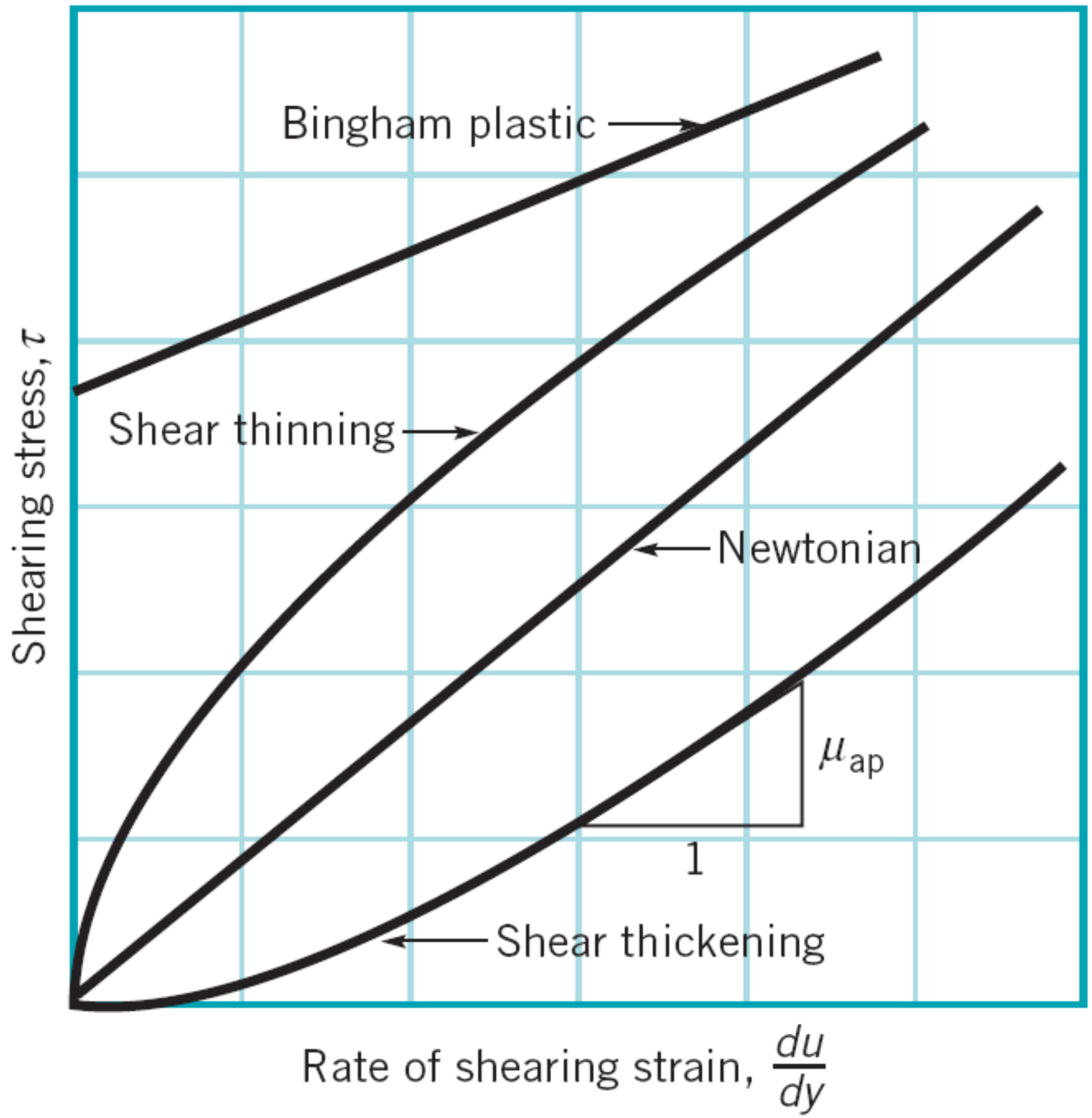
Unit is m^2/s or Stokes (St) or centiStokes (cSt)

$$1 \quad m^2/s \quad = \quad 10{,}000 \quad cSt$$

Fluids for which the shearing stress is *linearly* related to the rate of shearing strain are designated as *Newtonian fluids*.

Fluids for which the shearing stress is not linearly related to the rate of shearing strain are designated as *non-Newtonian fluids*.


Crude oil (60 °F)
μ
1
Water (60 °F)
Water (100 °F)
Air (60 °F)
Shearing stress, τ
Rate of shearing strain, du/dy



Bingham plastic
Shear thinning
Newtonian
μ_{ap}
1
Shear thickening
Shearing stress, τ
Rate of shearing strain, $\frac{du}{dy}$

BULK MODULUS

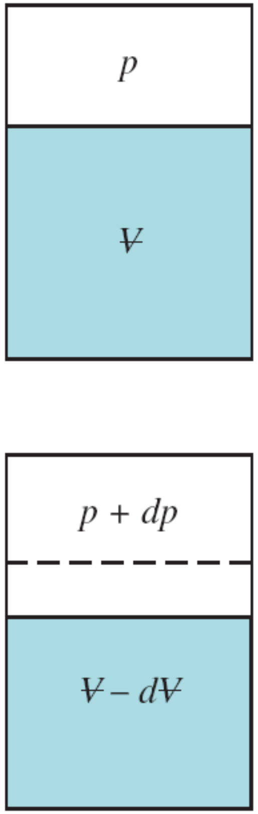
A property that is commonly used to characterize compressibility is the bulk modulus.

Defined as ;

$$E_{\upsilon} = -\frac{dP}{dV/V} = \frac{dP}{d\rho/\rho}$$

we conclude that liquids can be considered as *incompressible* for most practical engineering applications.

COMPRESSION & EXPANSION OF GAS



When gases are compressed (or expanded) the relationship between pressure and density depends on the nature of the process.

If the compression or expansion takes place under constant temperature conditions (isothermal process), then ;

$$\frac{P}{\rho} = \text{constant}$$

If the compression or expansion is frictionless and no heat is exchanged with the surroundings (isentropic process), then ;

$$\frac{P}{\rho^k} = \text{constant}$$

k is the ratio of the specific heat at constant pressure, c_p, to the specific heat at constant volume, c_v.

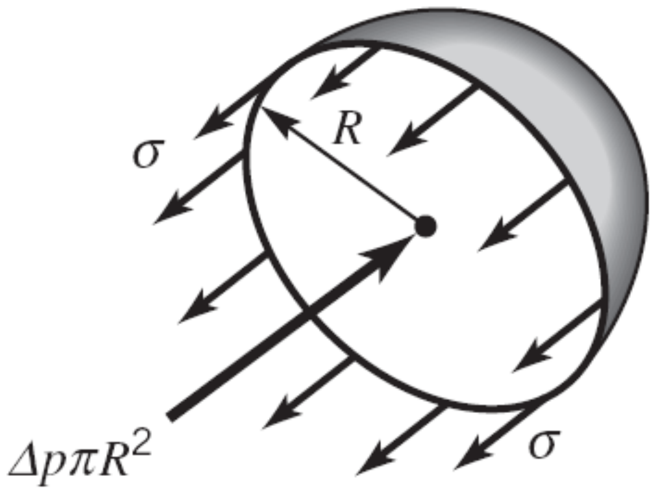
$$k = {}^{c_p}\!\big/_{c_v}$$

SURFACE TENSION

The intensity of the molecular attraction per unit length along any line in the surface is called the surface tension.

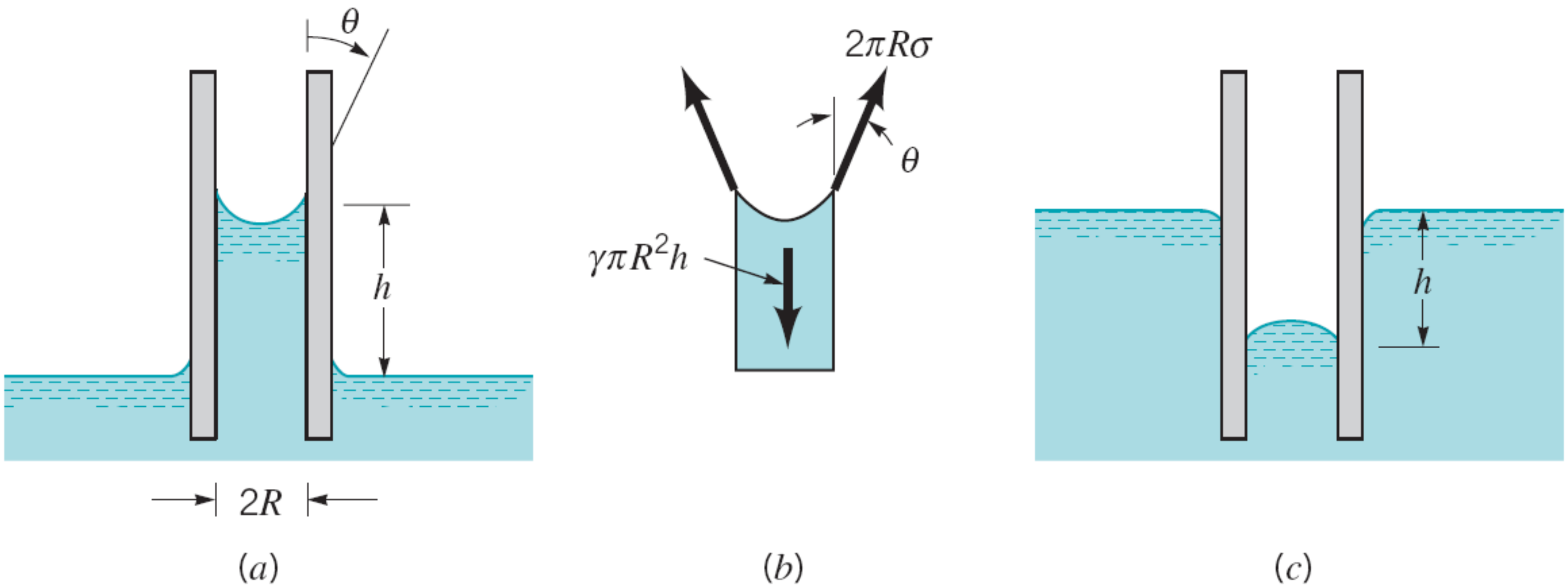
Designated by the Greek symbol, σ (sigma)

Unit is N/m.



The forces balance of half-cut spherical is shown as ;

$$2\pi \mathrm{R}\sigma = \Delta P \pi R^2$$



The forces balance of capillary action is shown as ;

$$2\pi R\sigma\cos\theta = \rho g h \pi R^2$$

VISCOSITY

VISCOSITY

The property of viscosity is described the *“fluidity”* of the fluid.

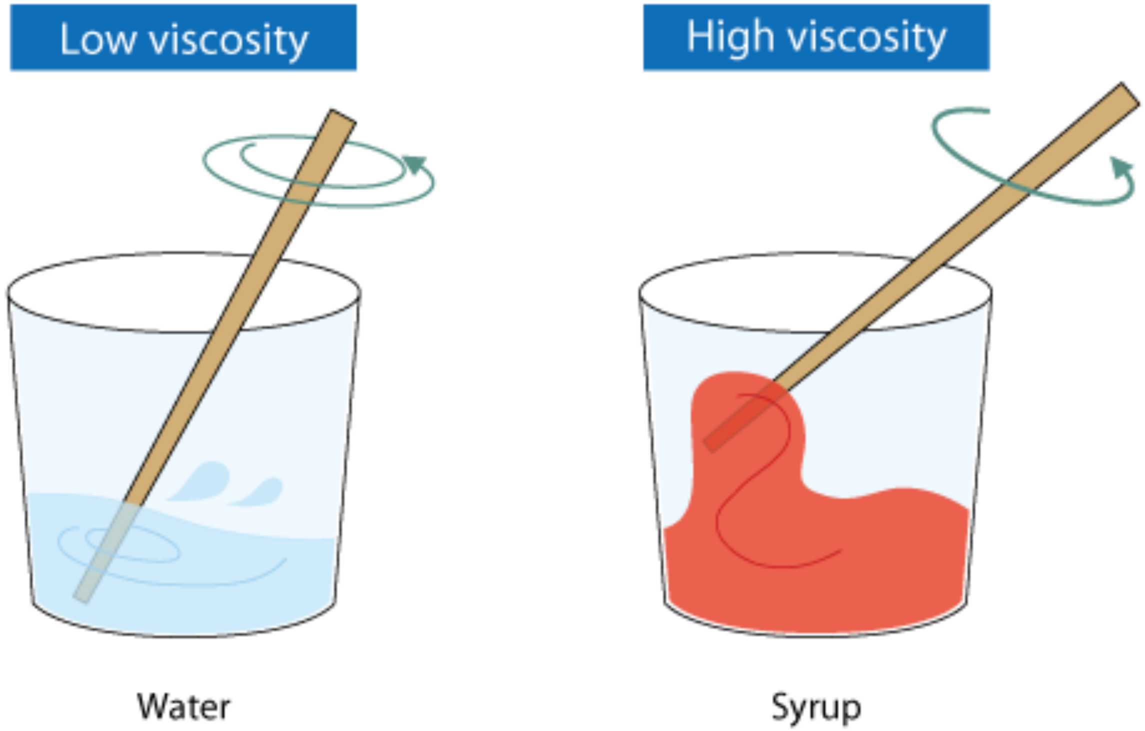
Viscosity is a physical property of fluids. It shows resistance to flow.

In a simple example, water has a low viscosity, as it is "thin".

Maple syrup has a high viscosity, as they are "thick".

A way to test for viscosity is the speed at which the substance runs down a slope. Maple syrup would reach the bottom very slowly, and water would be much quicker.

Another method to test the viscosity



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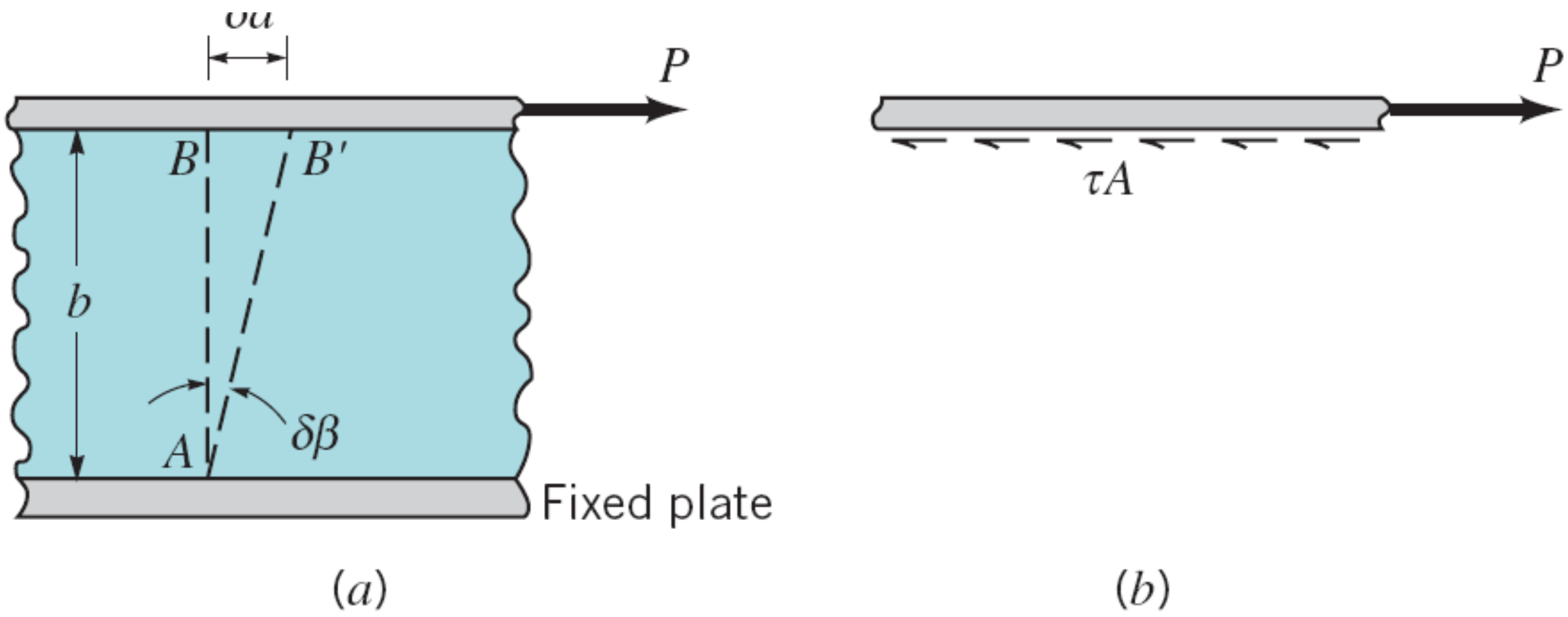

The equilibrium is ;

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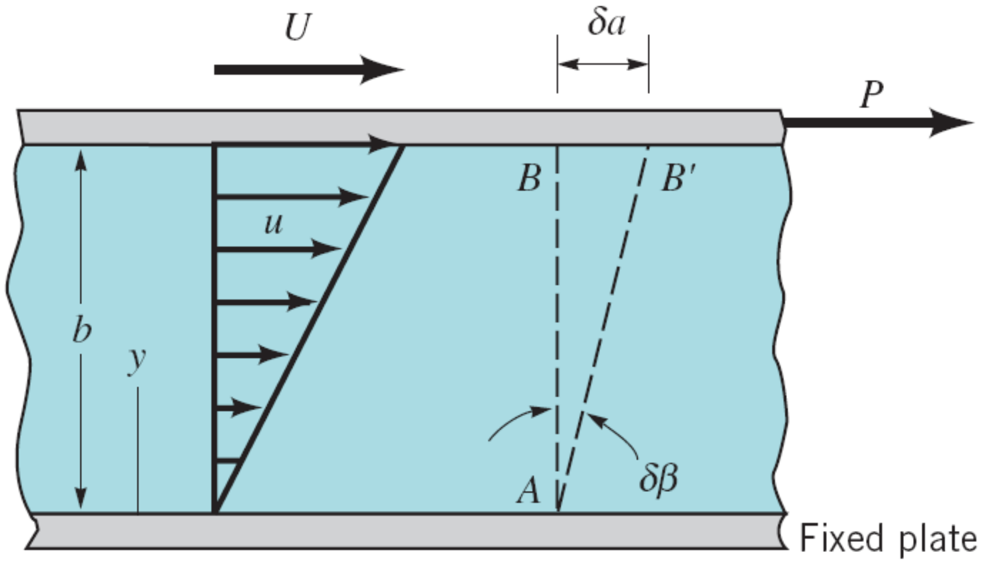
It revealed that we need more P (to move the plate) as the shearing stress, τ, is increased.



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Velocity profile

The velocity profile indicates the magnitude of the velocity as a function of position. In this course, we are focusing in flow on flat plate and flow in pipe.

A major feature of the velocity profile is the no slip condition at the surface. That is, the velocity goes to zero ($V = 0$) at the surface.

It is because the outermost molecules of fluid as stuck to the surfaces past which it flows.

In the other word, fluid molecule stick very hard on surface and gives velocity equal to zero.

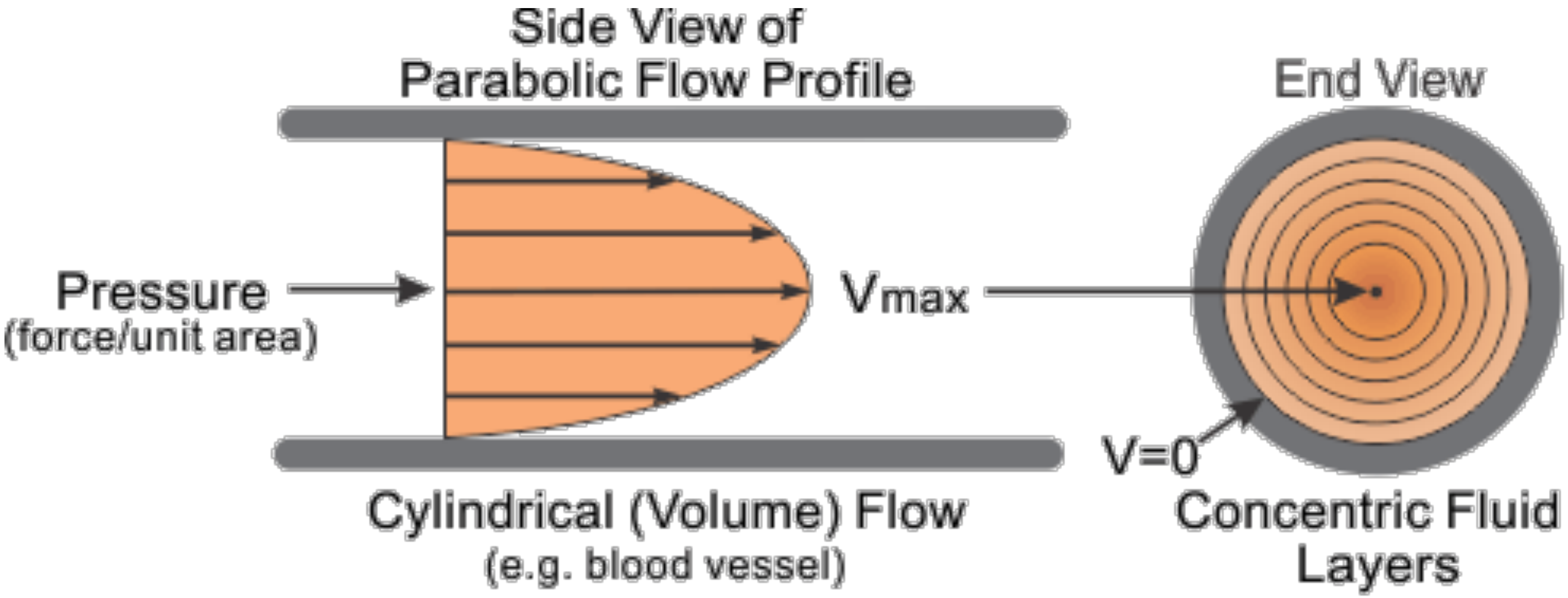
Physical justification:

Particles close to a surface do not move along with a flow when adhesion is stronger than cohesion. At the fluid-solid interface, the force of attraction between the fluid particles and solid particles (adhesive forces) is greater than that between the fluid particles (cohesive forces).

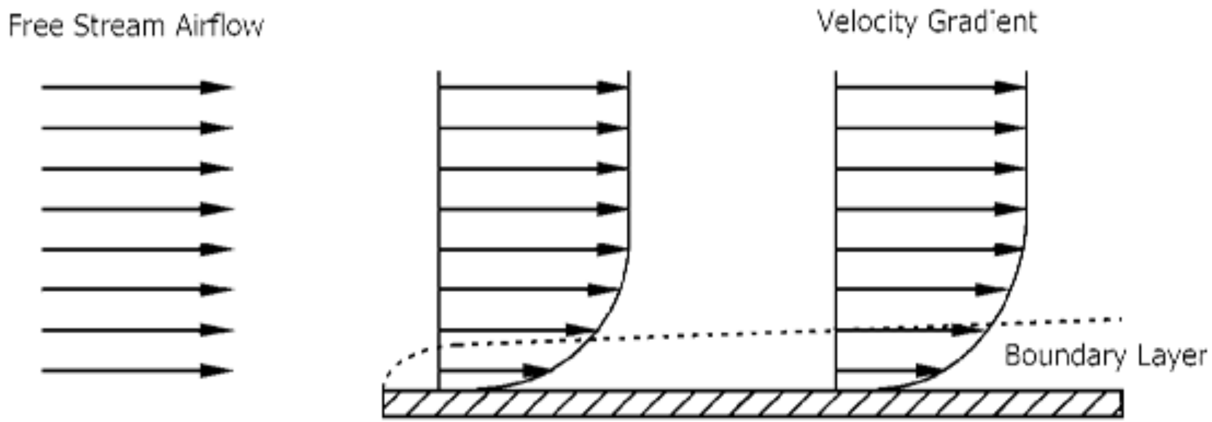
This force imbalance brings down the fluid velocity to zero.

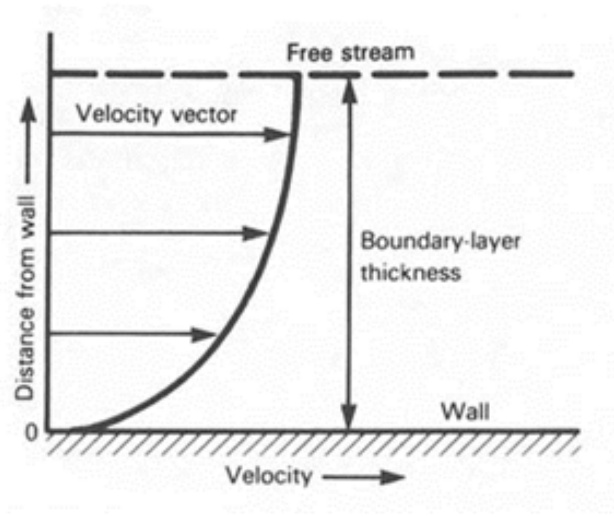
The no slip condition is only defined for viscous flows and where continuum concept is valid.

Velocity profile for flow in pipe:



Velocity profile for flow on thin flat plate:





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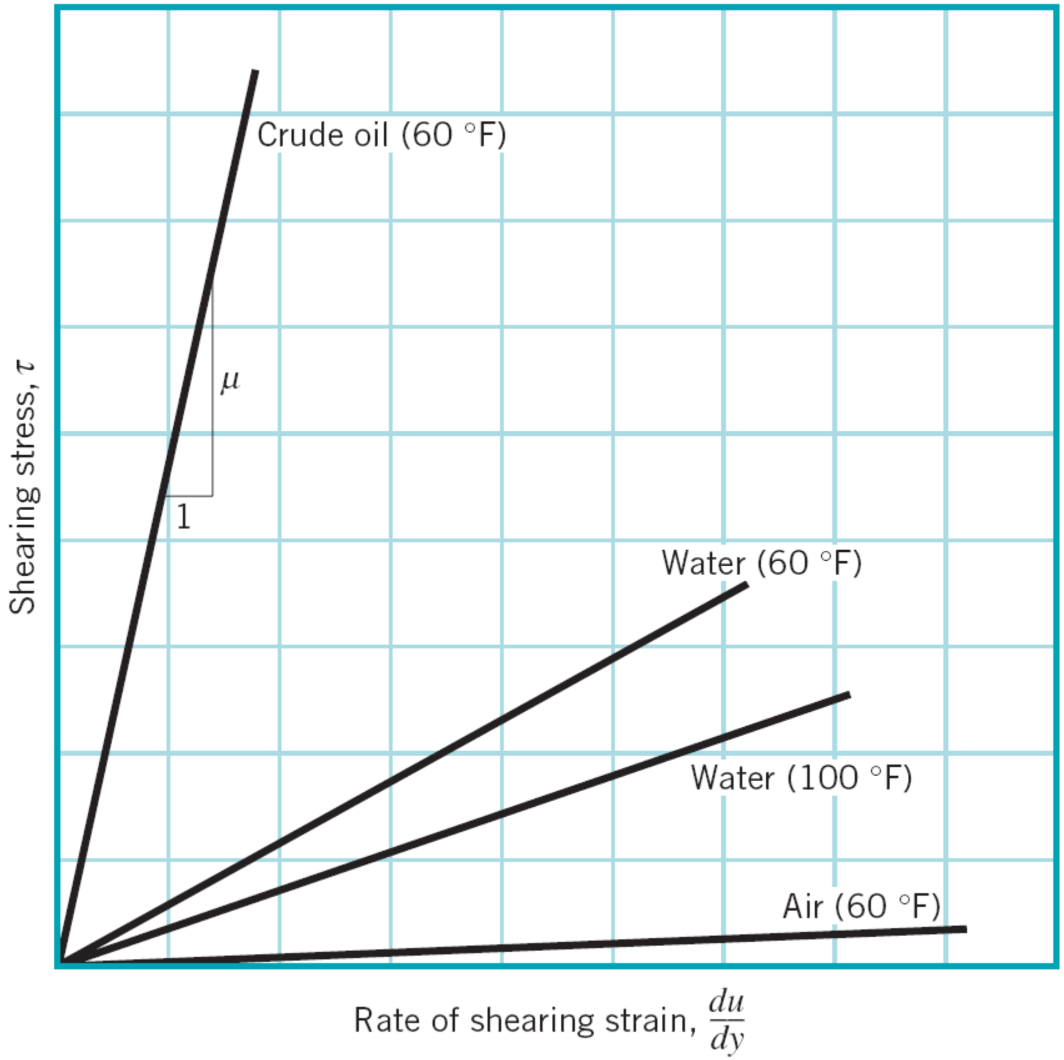
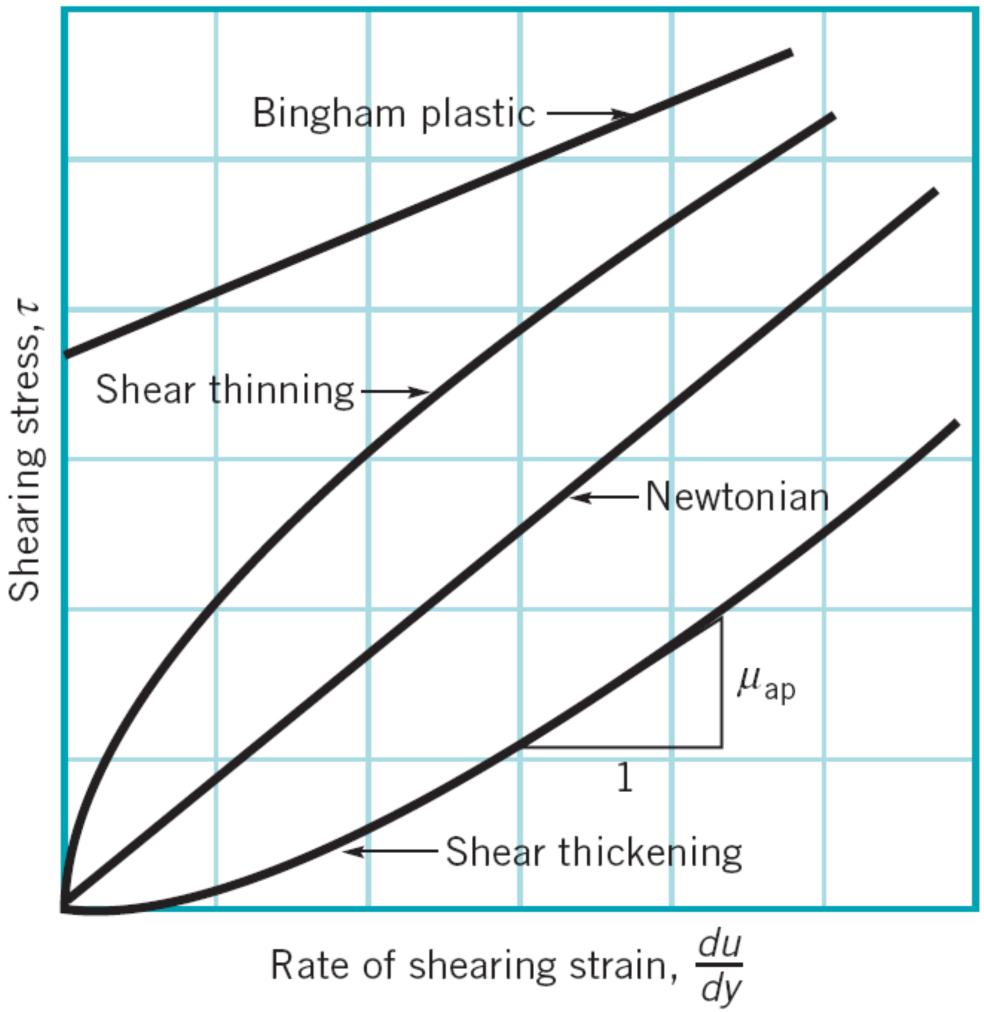


The relation of shearing stress for Newtonian fluid.



The relation of shearing stress for non-Newtonian fluid.

Shear thinning

In fluid mechanics, shear thinning is the non-Newtonian behavior of fluids whose viscosity decreases under shear strain.

Modern paints are examples of pseudoplastic materials. When modern paints are applied, the shear created by the brush or roller will allow them to thin and wet out the surface evenly. Once applied, the paints regain their higher viscosity, which avoids drips and runs.

Ketchup is a prominent example of a shear thinning material, being viscous when at rest, but flows at speed when agitated by squeezing, shaking or striking the bottle.

Whipped cream is also an example of a shear thinning material. When whipped cream is sprayed out of its canister, it flows out smoothly from the nozzle due to the low viscosity at high flow rate. However, after whipped cream is sprayed into a spoon, it does not flow, and its increased viscosity allows it to be rigid.

Shear thickening

A shear thickening or dilatant fluid is one in which viscosity increases with the rate of shear strain.

This can readily be seen with a mixture of cornstarch and water which acts in counterintuitive ways when struck or thrown against a surface.

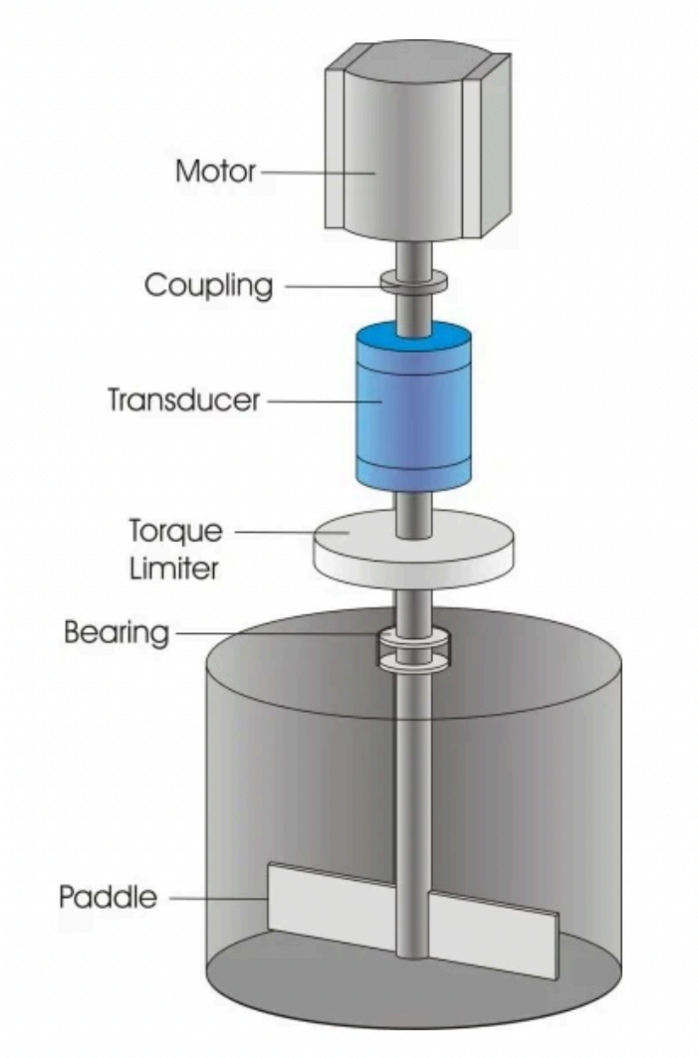
Sand that is completely soaked with water also behaves as a dilatant material. This is the reason why when walking on wet sand, a dry area appears directly underfoot.[2]

A viscometer is an instrument used to measure the viscosity of a fluid.

Rotational viscometer is usually used to measure the dynamic viscosity.

It has mechanism as shown here.

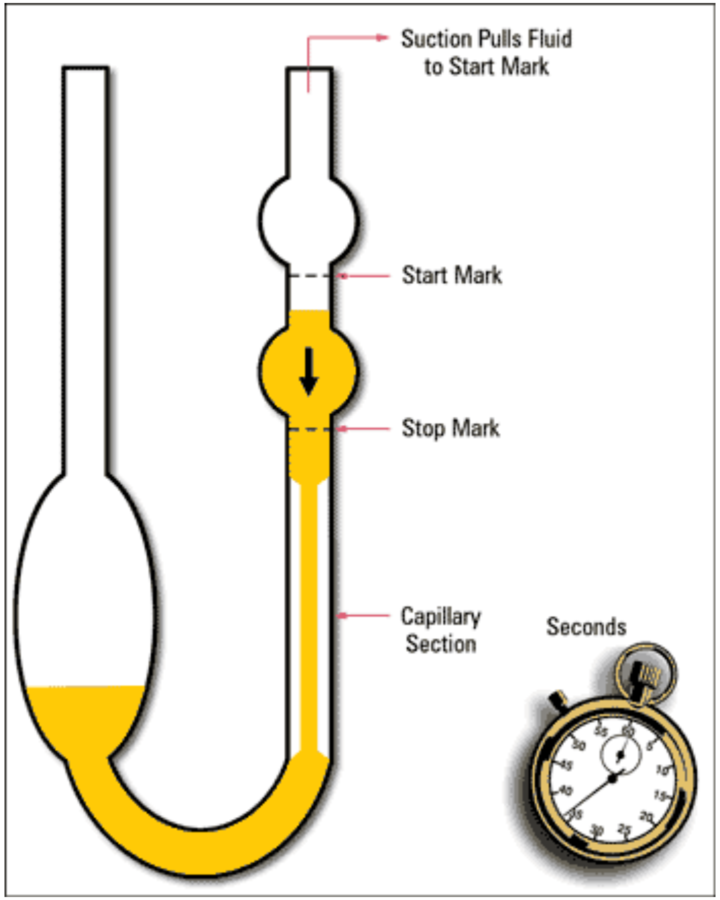
The more viscous a liquid is, the higher the force required to rotate the paddle. This torque value will be recorded and calibrated to obtain the dynamic viscosity value.



A glass capillary viscometers or Ostwald viscometers is usually used to measure the kinematic viscosity.

The time required for the test liquid to flow through a capillary of a known diameter of a certain factor between two marked points is measured.

By multiplying the time taken by the factor of the viscometer, the kinematic viscosity is obtained.



The more viscous a liquid is, the longer it takes for the liquid to flow from the “start mark” to the “stop mark”.

This time value will be used to calculate the kinematic viscosity value.

Often the value of kinematic viscosity can be obtained from a table prepared based on the time taken.

Engine oil

10W-50 is a heavy-duty multi-grade oil crafted to support an engine's maximum performance at a very high operating temperature.

10W-50 follows the Society of Automotive Engineers (SAE) format for a multi-grade oil, where W stands for winter.

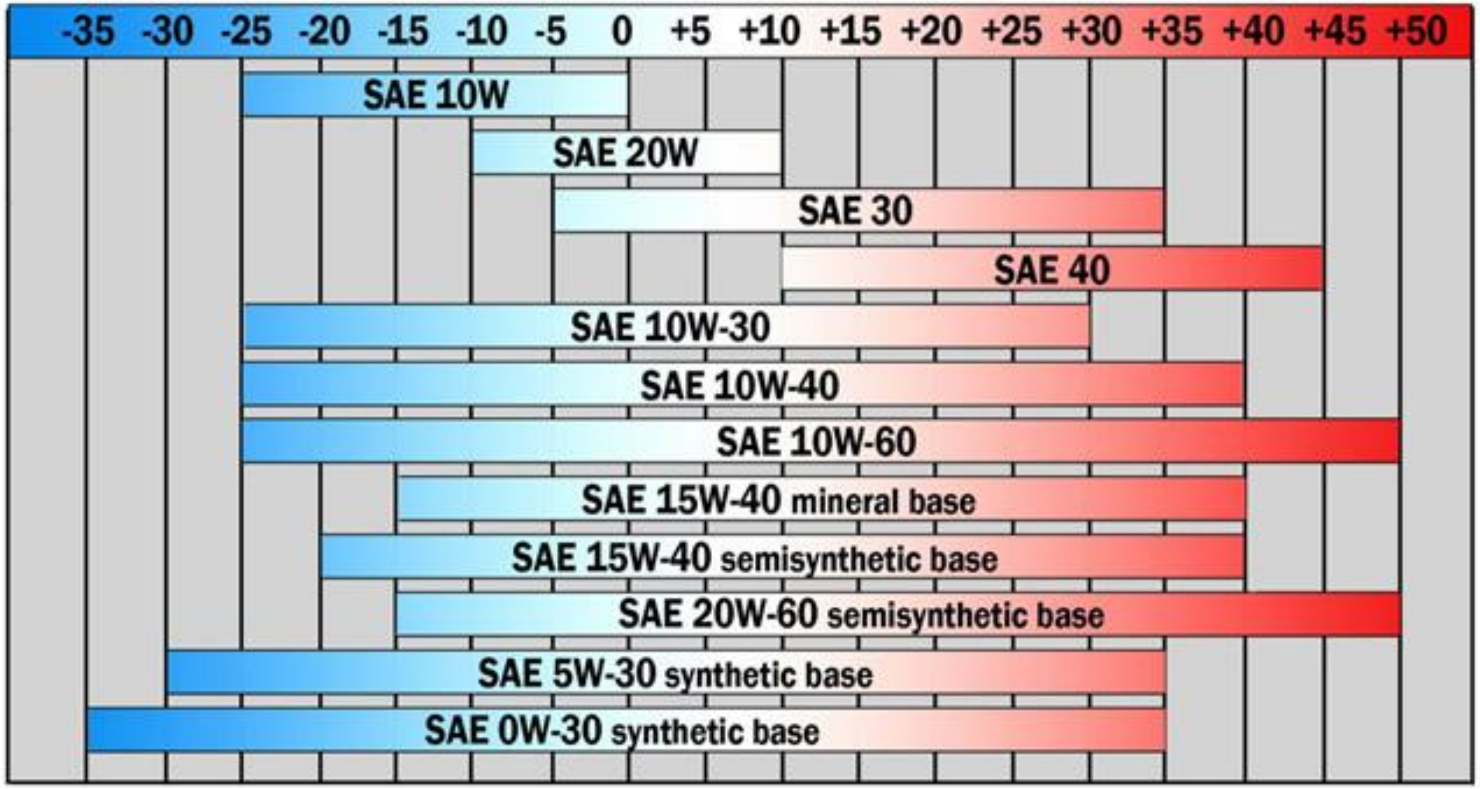
The number preceding the W (i.e.,10) denotes the oil flow at 0°C. The lower this number, the better the W oil will perform in winter (by not thickening).

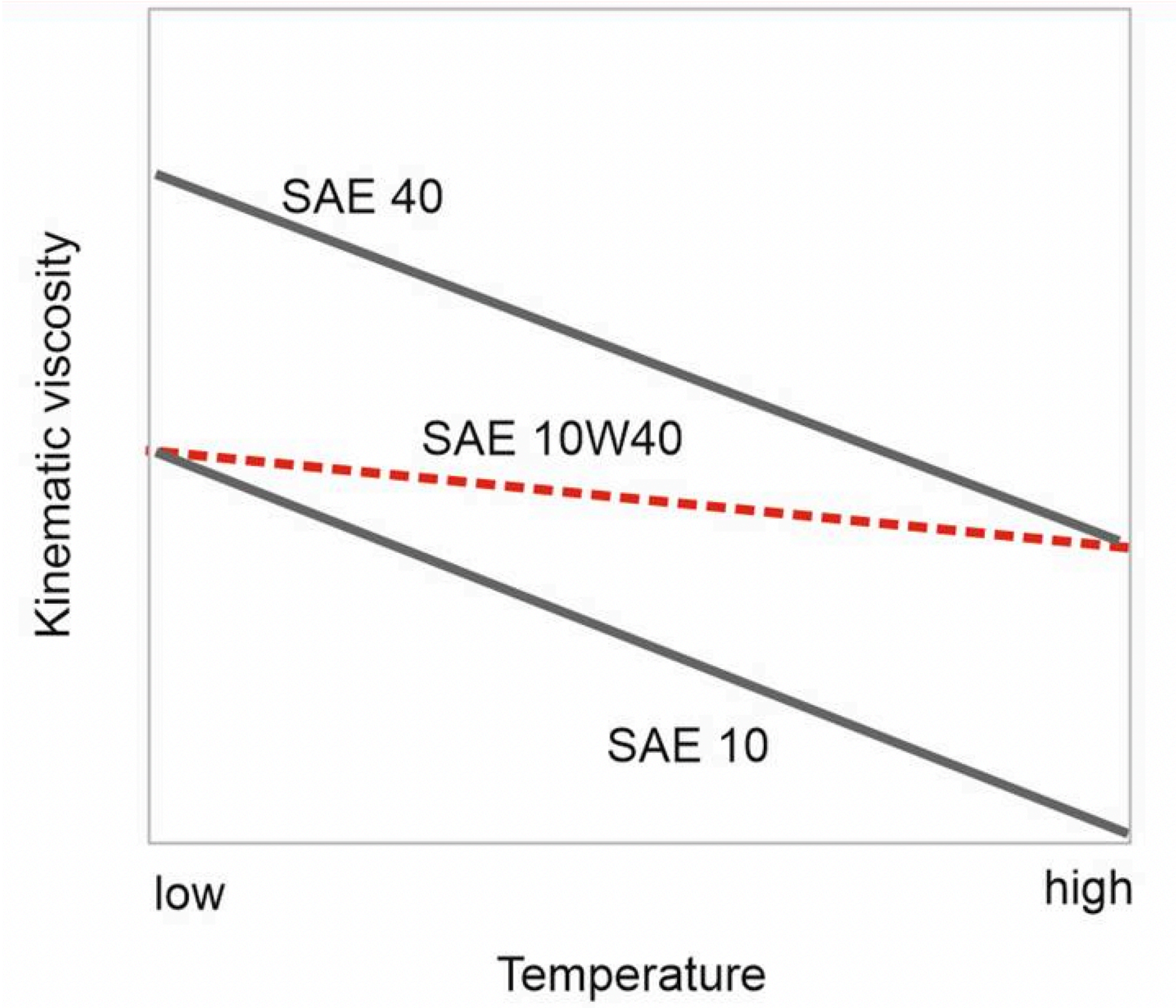
The number after W (i.e., 50) stands for the viscosity rating at peak temperatures. The higher this number, the better is the oil's resistance against thinning at a high temperature.

Meaning, 10W-50 motor oil acts like an SAE 10W weight oil under 0°C (32°F), and an SAE 50 weight engine oil at 100°C (212°F).

SAE Grades

For Engine Oils Recommended in Relation with the Outside Temperatures (°C)




SAE 40
SAE 10W40
SAE 10
Kinematic viscosity
low
high
Temperature

TUTORIAL

PROBLEMS FOR CHAPTER 1 – FLUID PROPERTIES

QUESTION 1

According to information found in an old hydraulics book, the energy loss per unit weight of fluid flowing through a nozzle connected to a hose can be estimated by the formula

$$h = (0.04 \sim 0.09)\left(\frac{D}{d}\right)^4\left(\frac{V^2}{2g}\right)$$

where h is the energy loss per unit weight, D the hose diameter, d the nozzle tip diameter, V the fluid velocity in the hose, and g the acceleration of gravity. Do you think this equation is valid in any system of units? Explain.

QUESTION 2

The “no-slip” condition means that a fluid “sticks” to a solid surface. This is true for both fixed and moving surfaces. Let two layers of fluid be dragged along by the motion of an upper plate as shown in Figure 1. The bottom plate is stationary. The top fluid puts a shear stress on the upper plate, and the lower fluid puts a shear stress on the bottom plate. Determine the ratio of these two shear stresses.

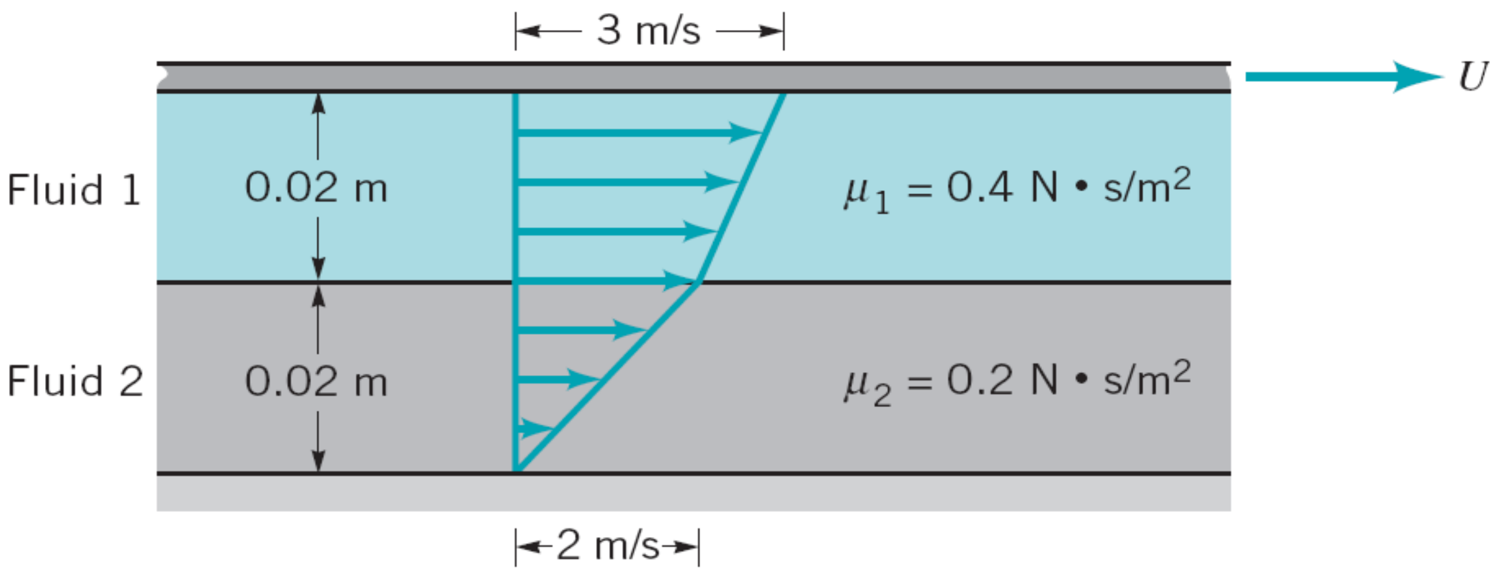


Figure 1

QUESTION 3

A 25-mm-diameter shaft is pulled through a cylindrical bearing as shown in Figure 2. The lubricant that fills the 0.3-mm gap between the shaft and bearing is an oil having a kinematic viscosity of 8.0×10^{-4} m²/s and a specific gravity of 0.91. Determine the force P required to pull the shaft at a velocity of 3 m/s. Assume the velocity distribution in the gap is linear.

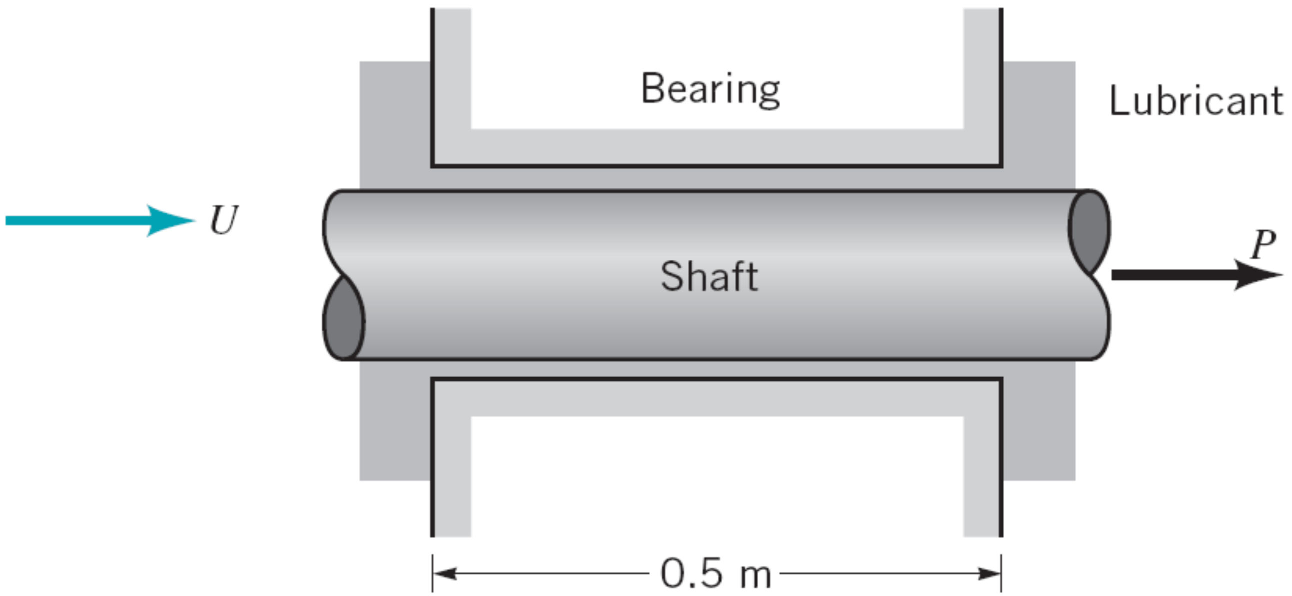


Figure 2

QUESTION 4

A layer of water flows down an inclined fixed surface with the velocity profile shown in Figure 3. Determine the magnitude and direction of the shearing stress that the water exerts on the fixed surface for $U = 2$ m/s and $h = 0.1$ m.

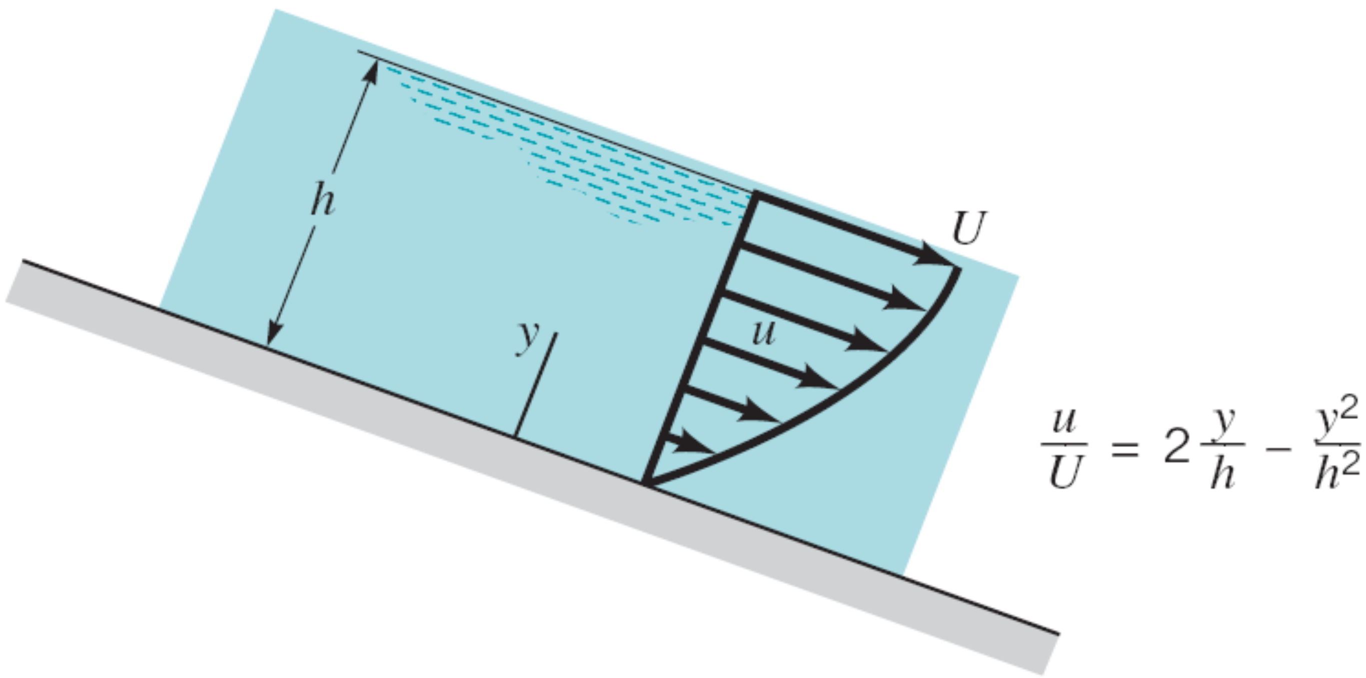
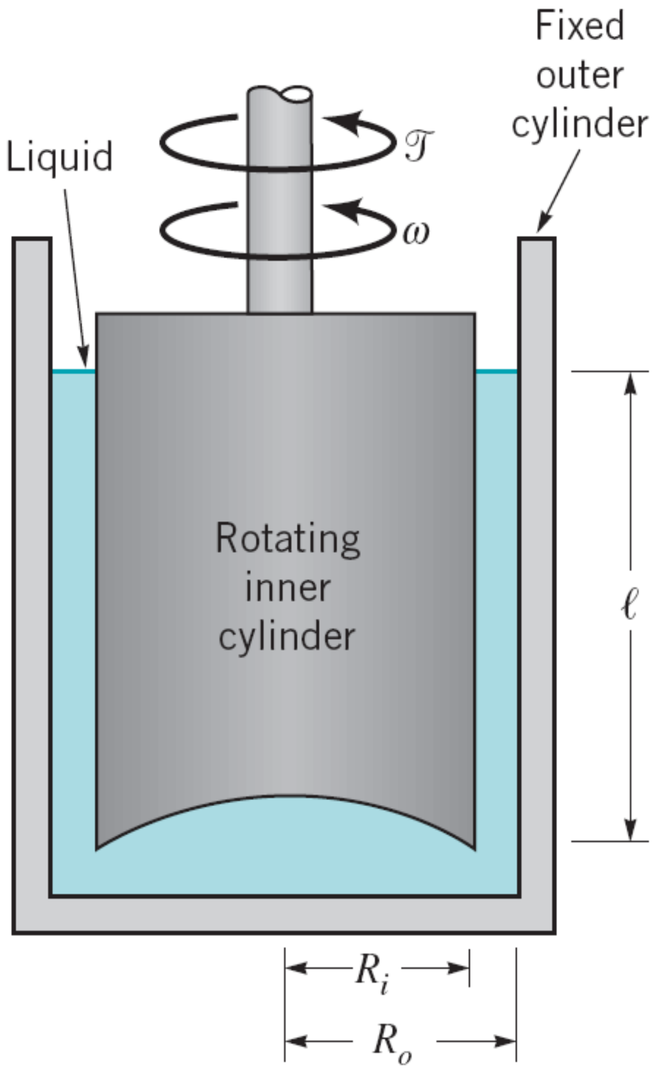


Figure 3

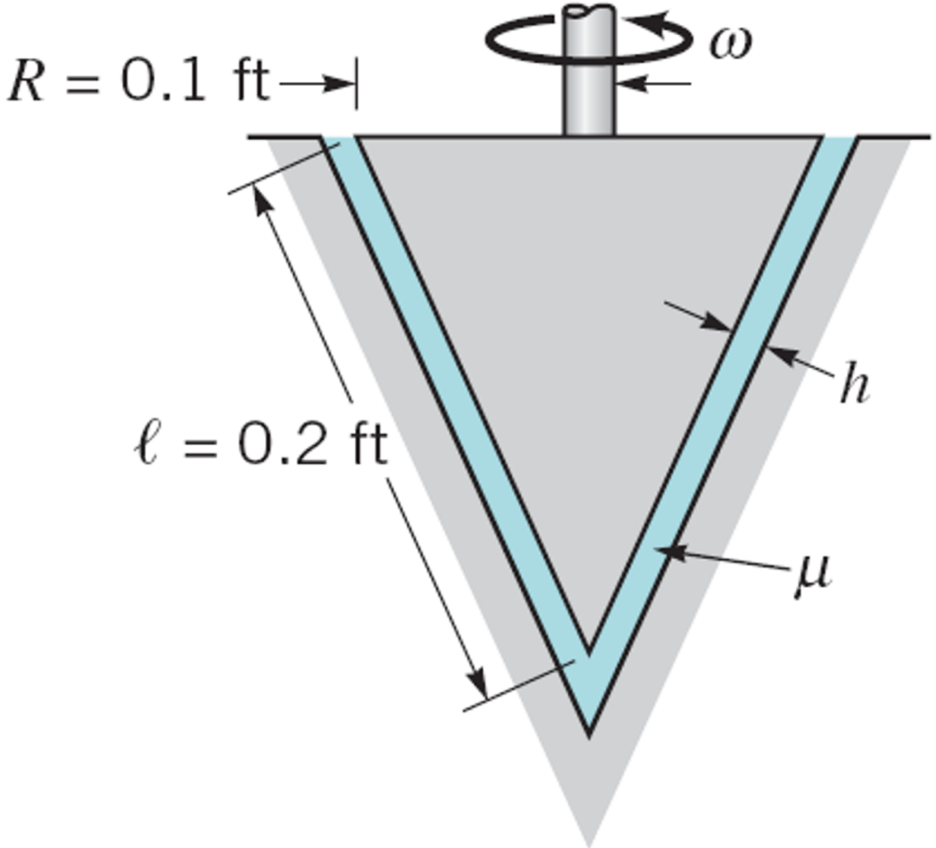
QUESTION 5

The viscosity of liquids can be measured using a *rotating cylinder viscometer* of the type illustrated in Figure 4. In this device the outer cylinder is fixed and the inner cylinder is rotated with an angular velocity, ω. The torque T required to develop ω is measured and the viscosity is calculated from these two measurements. Develop an equation relating μ, ω, T, ℓ, R_o, and R_i. Neglect end effects and assume the velocity distribution in the gap is linear.



QUESTION 6

A conical body rotates at a constant angular velocity in rpm in a container as shown in the figure. A uniform gap (*h*) between the cone and the container is filled with oil that has a specific dynamic viscosity. Determine the torque required to rotate the cone.



QUESTION 7

A 12 cm diameter circular plate is placed over a fixed bottom plate with a 1 mm gap between the two plates filled with glycerin as shown in Figure 6. Determine the torque required to rotate the circular plate slowly at 12 rpm. Assume that the velocity distribution in the gap is linear and that the shear stress on the edge of the rotating plate is negligible.

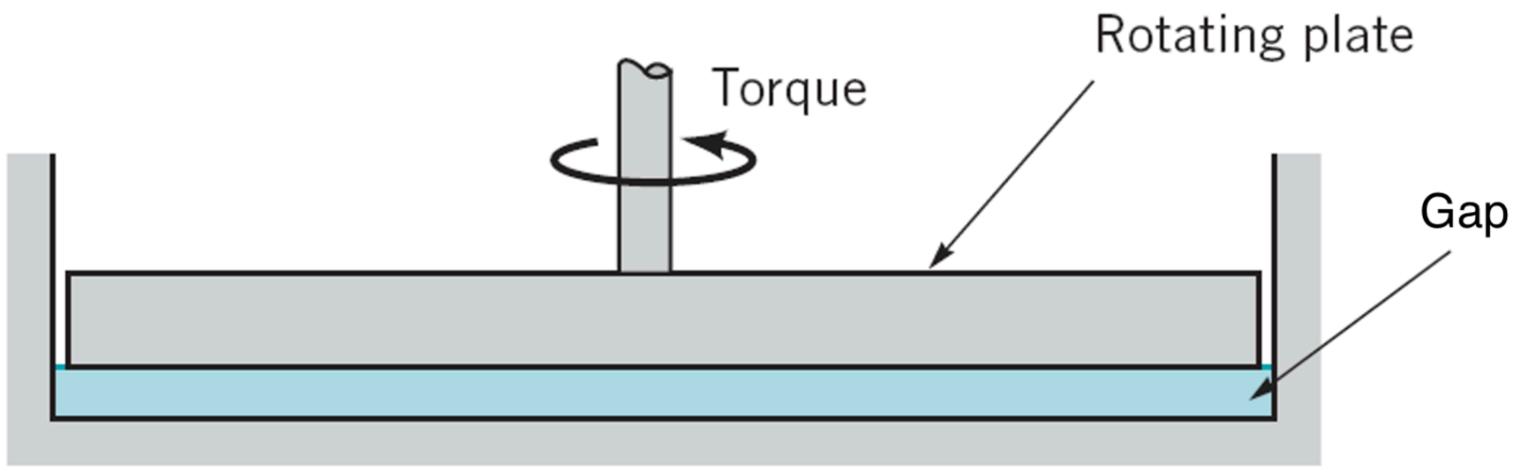


Figure 6

QUESTION 8

Figure below show's shaft rotates at 2000 rpm. An oil with a viscosity of μ=0.5 Pa.s fills the 0.2-mm gap between rotating shaft and stationary housing. Determine the total power required to overcome the viscous resistance.

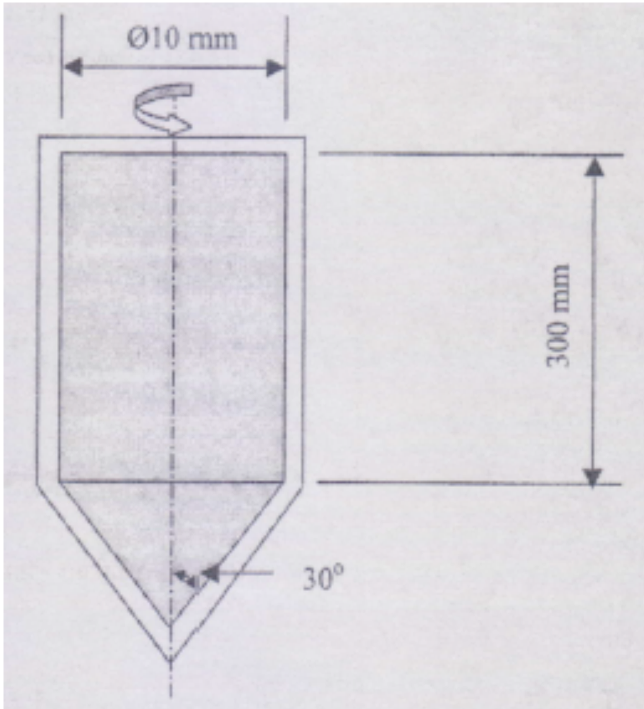


Figure Q1

QUESTION 9

A Newtonian fluid having a specific gravity of 0.9 and kinematics viscosity (ν) of $4 \times 10^{-4}\ m^2/s$ form a boundary layer near a solid wall of cubic velocity profile. The boundary layer thickness (δ) is 6mm, and the maximum velocity is 10 m/s. Determine the shear stress (τ) in the boundary layer at y equal to 0 mm and 3 mm. Calculate the drag force.

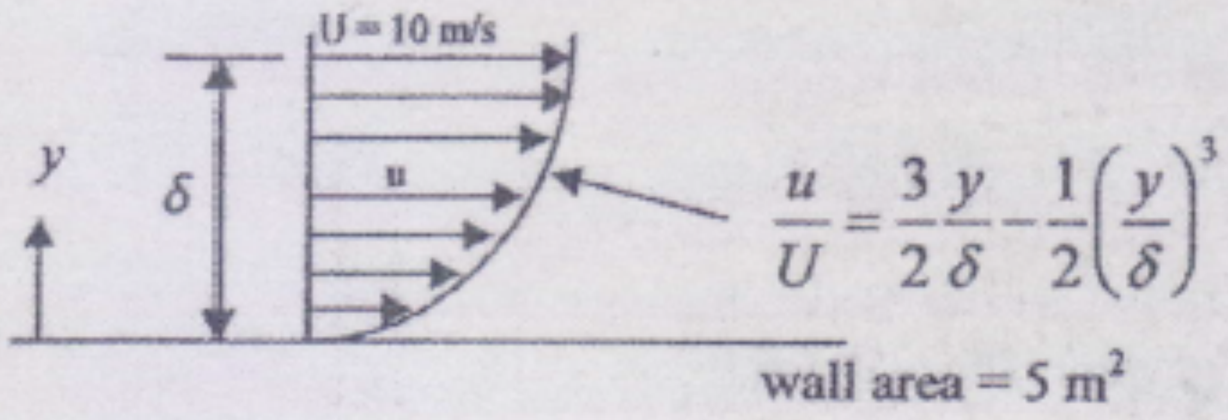


Fig.Q1b