FLUID MECHANICS

Chapter 1: **Introduction**

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Introduction

- Fluid mechanics is a study of the behavior of fluids, either at rest (fluid statics) or in motion (fluid dynamics).
- The analysis is based on the fundamental laws of mechanics, which relate continuity of mass and energy with force and momentum.
- An understanding of the properties and behavior of fluids at rest and in motion is of great importance in engineering.

Application Areas of Fluid Mechanics

Fluid dynamics is used extensively in the design of artificial hearts. Shown here is the Penn State Electric Total Artificial Heart.

Natural flows and weather

Power plants

Boats

Aircraft and spacecraft

Human body

Cars


Wind turbines


Piping and plumbing systems


Industrial applications

Objectives

1. Identify the units for the basic quantities of time, length, force and mass.
2. Properly set up equations to ensure consistency of units.
3. Define the basic fluid properties.
4. Identify the relationships between specific weight, specific gravity and density, and solve problems using their relationships.

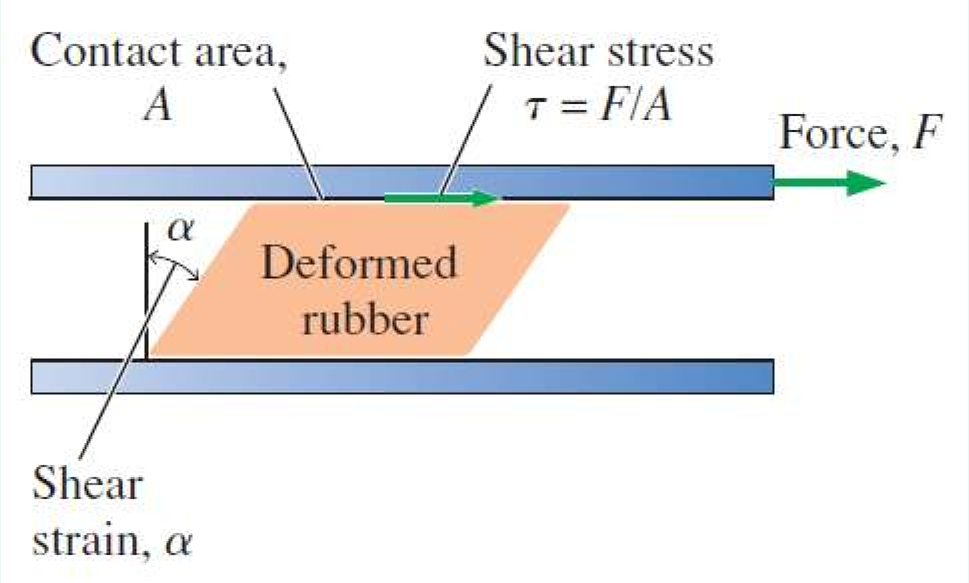
What is a Fluid?

Fluid: [A substance in the liquid or gas phase]

A fluid deforms continuously under the influence of a shear stress, no matter how small.

In solids, stress is proportional to *strain*, but in fluids, stress is proportional to *strain rate*.

When a constant shear force is applied, a solid eventually stops deforming at some fixed strain angle, whereas a fluid never stops deforming and approaches a constant *rate* of strain.



Deformation of a rubber block placed between two parallel plates under the influence of a shear force. The shear stress shown is that on the rubber—an equal but opposite shear stress acts on the upper plate.

UNIT SYSTEMS

- **We will work with SI unit systems in FLUID MECHANICS:**
  - **International System (SI)**
  - **U.S. Customary (USCS)**

- **SI UNITS**

In the SI system, the unit of force, the *Newton,* is derived unit. The meter, second and kilogram are base units.

- **U.S. CUSTOMORY**

In the US Customary system, the unit of mass, the *slug*, is a derived unit. The foot, second and pound are base unit.

Units and Dimensions

- A **dimension** is informally defined as the minimum number of coordinates needed to specify any point within it (without numerical values)
- The ***primary quantities*** which are also referred to as ***basic dimensions***, such as ***L*** for length, ***T*** for time, ***M*** for mass and **Q** for temperature.
- This dimension system is known as the ***MLT*** system where it can be used to provide qualitative description for ***secondary quantities***, or ***derived dimensions***, such as area (L), velocity (LT^{-1}) and density (ML^{-3}).
- In some countries, the ***FLT*** system is also used, where the quantity ***F*** stands for force.

Units and Dimensions

- An example is a kinematic equation for the velocity *V* of a uniformly accelerated body,

$$V = V_0 + at$$

where V_0 is the initial velocity, *a* the acceleration and *t* the time interval. In terms for dimensions of the equation, we can expand that:

$$LT^{-1} = LT^{-1} + LT^{-2} \bullet T$$

Basic Dimensions & Units

The SI system consists of **six** primary units, from which all quantities may be described but in fluid mechanics we are generally only interested in the **top four** units from this table.

Quantity	SI Unit	Dimension
length	metre, m	L
mass	kilogram, kg	M
time	second, s	T
temperature	Kelvin, K	θ
current	ampere, *A*	I
luminosity	candela	Cd

Derived Units

Quantity	SI Unit		Dimension
velocity	m/s	ms^{-1}	LT^{-1}
acceleration	m/s^2	ms^{-2}	LT^{-2}
force	N $kg\ m/s^2$	$kg\ ms^{-2}$	$M\ LT^{-2}$
energy (or work)	Joule J N m, $kg\ m^2/s^2$	$kg\ m^2 s^{-2}$	ML^2T^{-2}
power	Watt W N m/s $kg\ m^2/s^3$	Nms^{-1} $kg\ m^2 s^{-3}$	ML^2T^{-3}
pressure (or stress)	Pascal P, N/m^2, $kg/m/s^2$	Nm^{-2} $kg\ m^{-1}s^{-2}$	$ML^{-1}T^{-2}$
density	kg/m^3	$kg\ m^{-3}$	ML^{-3}
specific weight	N/m^3 $kg/m^2/s^2$	$kg\ m^{-2}s^{-2}$	$ML^{-2}T^{-2}$
relative density	a ratio no units		1 no dimension
viscosity	$N\ s/m^2$ kg/m s	$N\ sm^{-2}$ $kg\ m^{-1}s^{-1}$	$M\ L^{-1}T^{-1}$
surface tension	N/m $kg\ /s^2$	Nm^{-1} $kg\ s^{-2}$	MT^{-2}

Table summarizes these unit systems.

Name	Length	Time	Mass	Force
International System of Units (SI)	meter (m)	second (s)	kilogram (kg)	$\boxed{\text{newton*}}$ (N) $\left(\frac{\text{kg}\cdot\text{m}}{\text{s}^2}\right)$
U.S. Customary (FPS)	foot (ft)	second (s)	$\boxed{\text{slug*}}$ $\left(\frac{\text{lb}\cdot\text{s}^2}{\text{ft}}\right)$	pound (lb)

*Derived unit.

FLUID PROPERTIES

Properties involving the Mass or Weight of the Fluid

Specific Weight, γ

The gravitational force per unit volume of fluid, or simply "weight per unit volume".

- Water at 20 ^{o}C has a specific weight of 9.79 kN/m^3.

Mass Density, ρ

The "mass per unit volume" is mass density. Hence it has units of kilograms per cubic meter.

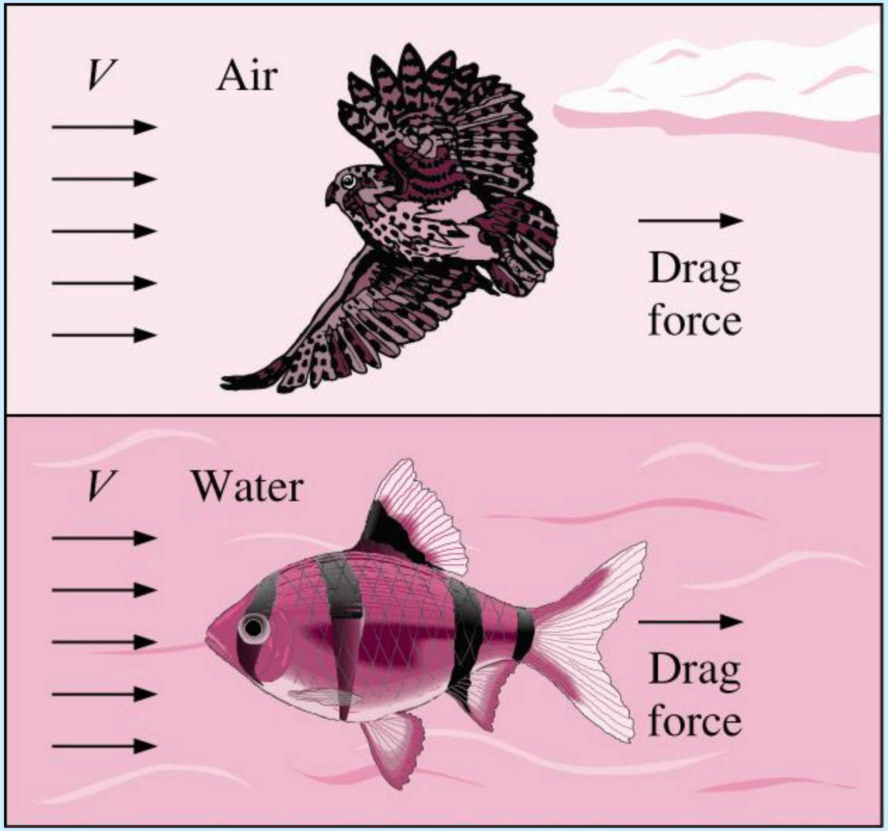
- The mass density of water at 4 ^{o}C is 1000 kg/m^3 while it is 1.20 kg/m^3 for air at 20 ^{o}C at standard pressure.

Specific Gravity, S

- The ratio of specific weight of a given liquid to the specific weight of water at a standard reference temperature (4 °C)is defined as *specific gravity*, S.
- The specific weight of water at atmospheric pressure is 9810 N/m^3.
- The specific gravity of mercury at 20 °C is

$$S_{Hg} = \frac{133\,\text{kN/m}^3}{9.81\,\text{kN/m}^3} = 13.6$$

Viscosity



- Viscosity is a property that represents the internal resistance of a fluid to motion.
- The force a flowing fluid exerts on a body in the flow direction is called the drag force, and the magnitude of this force depends, in part, on viscosity.

- **Viscosity is a property that represents the internal resistance of a fluid to motion, or The property of a fluid to resist the growth of shear deformation.**
- **The viscosity is measured by Capillary tube viscometer**

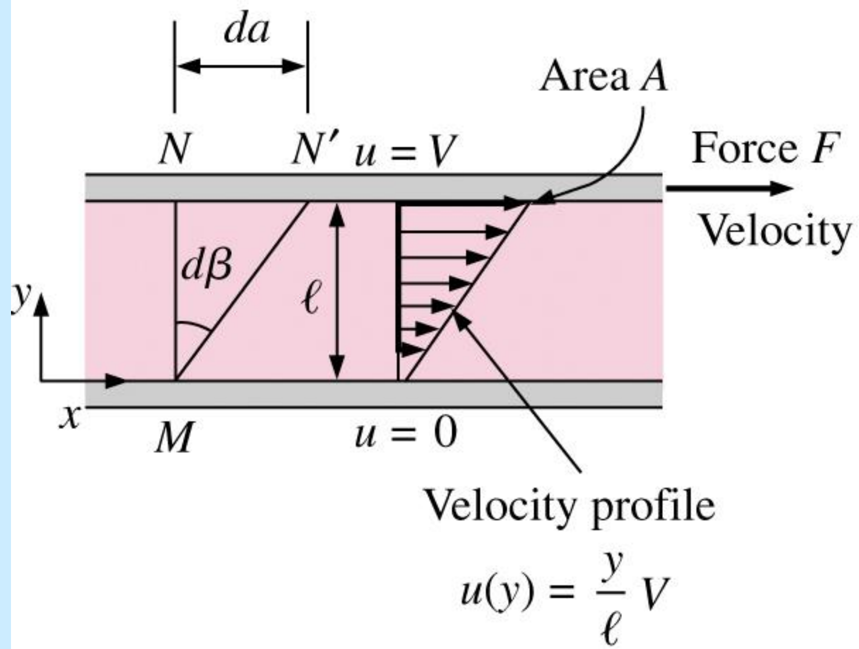
Example of the effect of viscosity

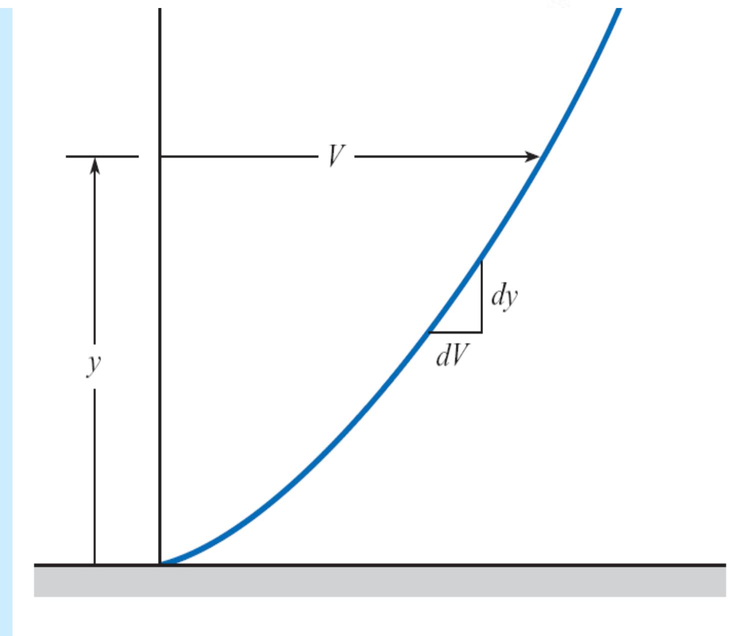
- Think: resistance to flow.
- *V :* fluid velocity
- *y :* distance from solid surface
- Rate of strain, dV/dy
- μ : dynamic viscosity [N.s/m^2]

τ: shear stress

Shear stress: An applied force per unit area needed to produce deformation in a fluid

$$\tau = \mu \, dV/dy$$





Velocity distribution next to a boundary

VISCOSITY μ

$$\tau = \mu \, dV/dy$$

- Would it be easier to walk through a 1-m pool of water or oil?

  – *Water*

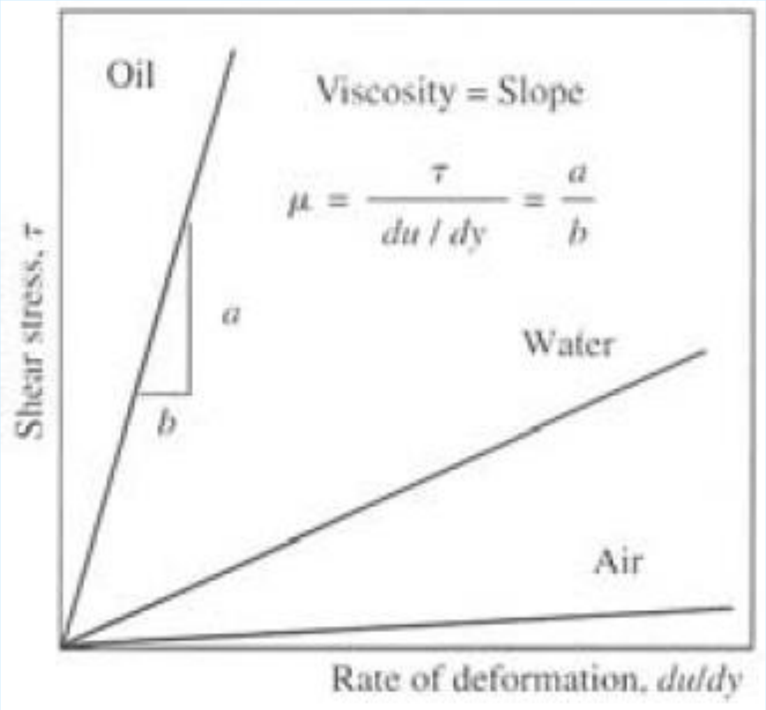
  Why?

 – *Less friction in the water*

- *Rate of deformation*

– Water moves out of your way at a quick rate when you apply a shear stress (*i.e.,* walk through it)

– Oil moves out of your way more slowly when you apply the same shear stress



Viscosity = slope of the line shown above
• the ratio between shear stress applied and rate of deformation

Kinematic Viscosity

- Many fluid mechanics equations contain the variables of

  - Viscosity, μ

  - Density, ρ

So, to simplify these equations sometimes use ***kinematic viscosity (ν)***

$$\nu = \frac{\mu}{\rho} = \frac{N.s/m^2}{kg/m^3} = m^2/s$$

Terminology

Viscosity, μ

Absolute viscosity, μ

Dynamic viscosity, μ

Kinematic Viscosity, ν

Kinematic viscosity, ν

Definition: is the ratio of the viscosity to the density;

$$\nu = \mu / \rho$$

- will be found to be important in cases in which significant viscous and gravitational forces exist.

  Units: m^2/s

  Typical values:
  Water = 1.14x10-6 m^2/s;   Air = 1.46x10-5 m^2/s;

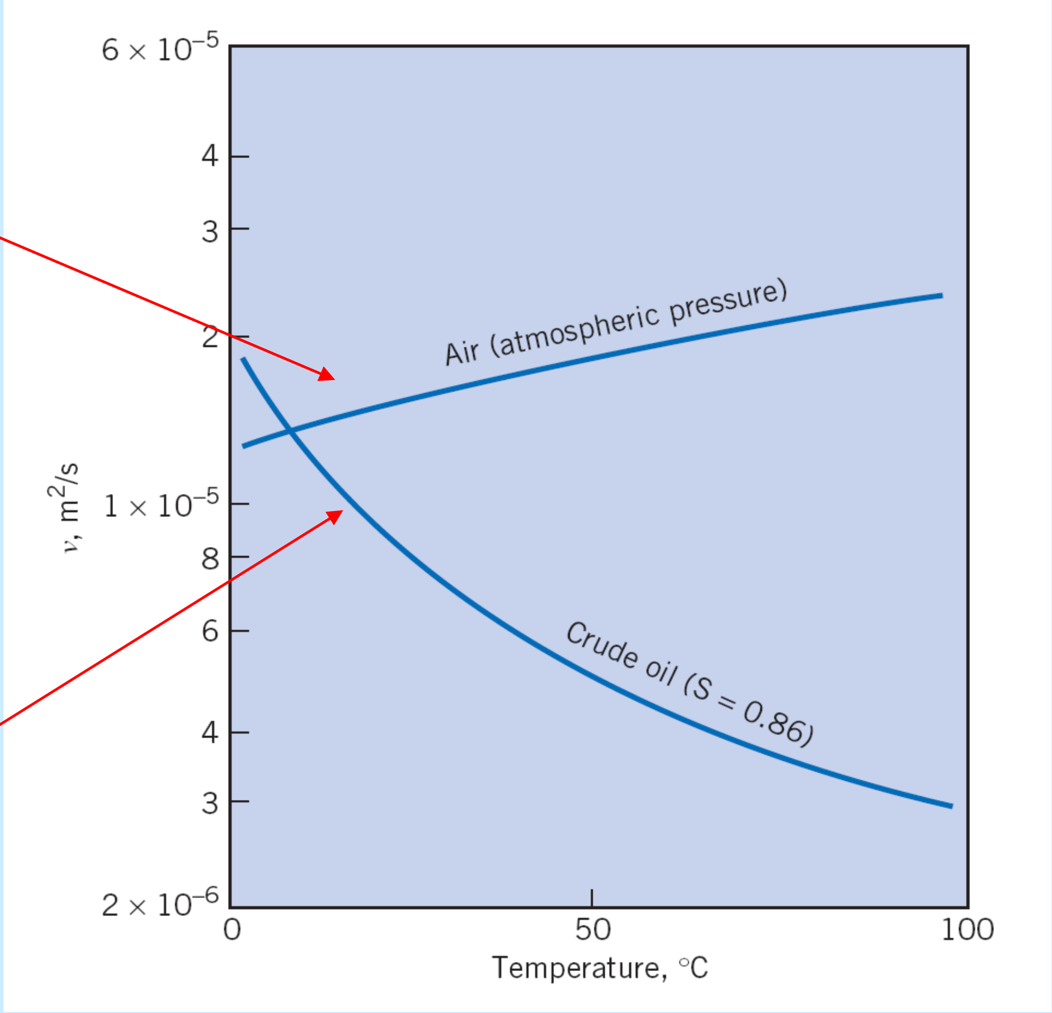
In general,
viscosity of liquids $\downarrow$ with $\uparrow$ temperature, whereas

viscosity of gases $\uparrow$ with $\uparrow$ in temperature.

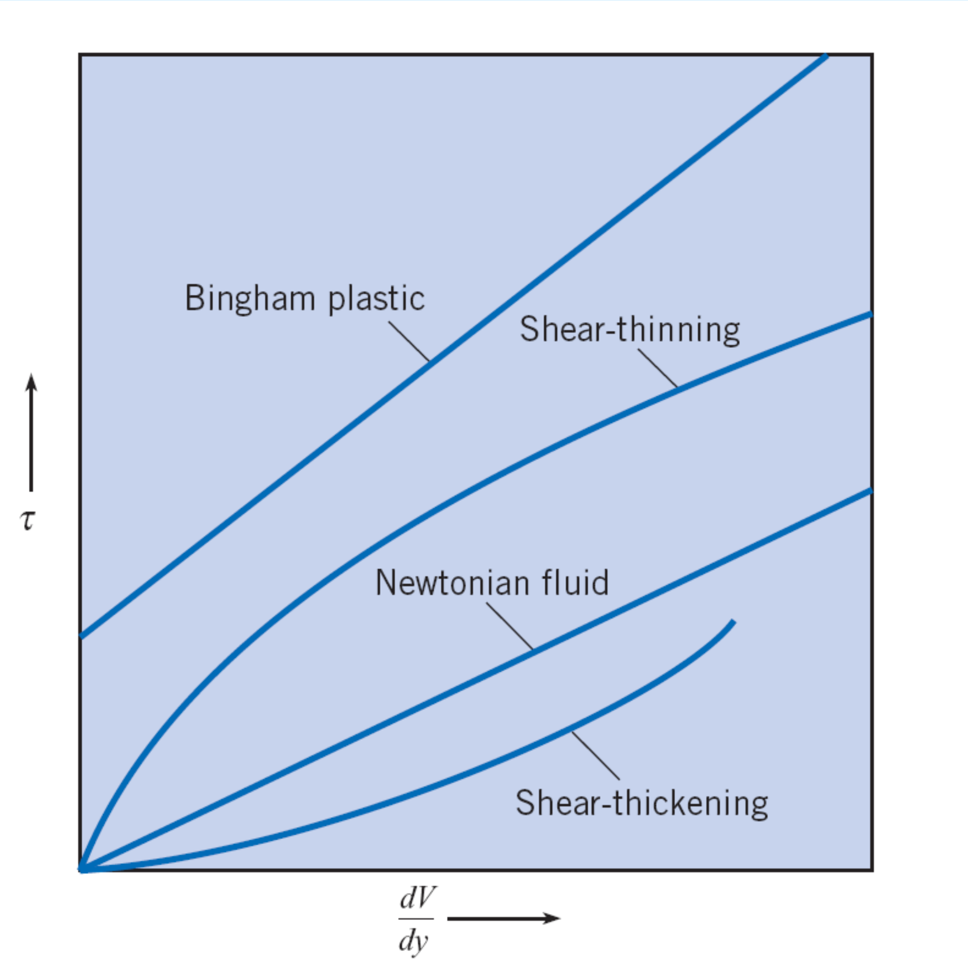
Kinematic viscosity for air & crude oil

Increasing temp → increasing viscosity

Increasing temp → decreasing viscosity

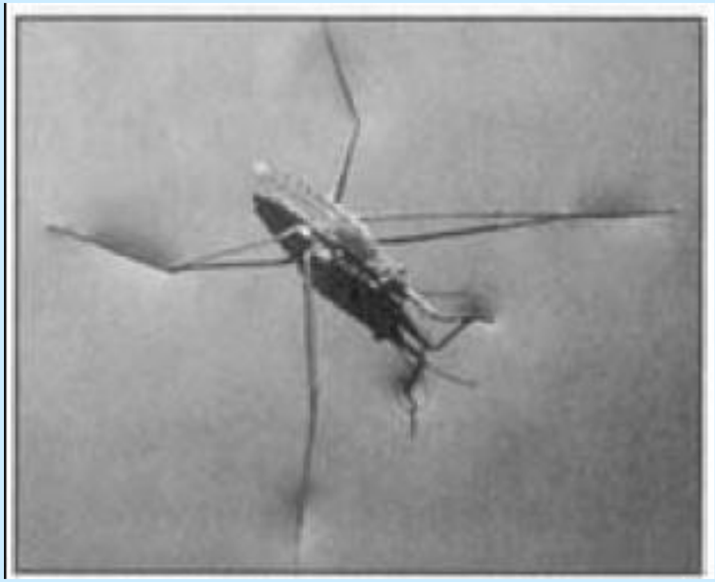


Newtonian vs. Non-Newtonian Fluids



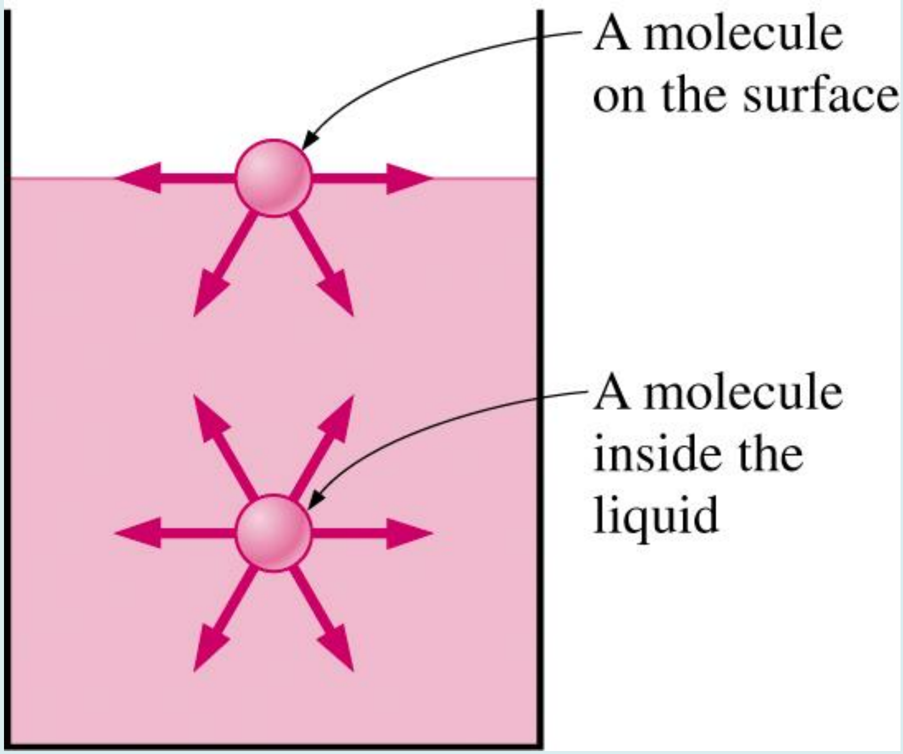
- *Newtonian fluid*: shear stress is proportional to shear strain
  - – Slope of line is dynamic viscosity
- ***Shear thinning***: ratio of shear stress to shear strain (**viscosity**) decreases as shear strain increases (toothpaste, paint, etc.)
- ***Shear thickening***: ratio of shear stress to shear strain (**viscosity**) increases with shear rate (glass particles in water, gypsum-water mixtures).

Surface tension



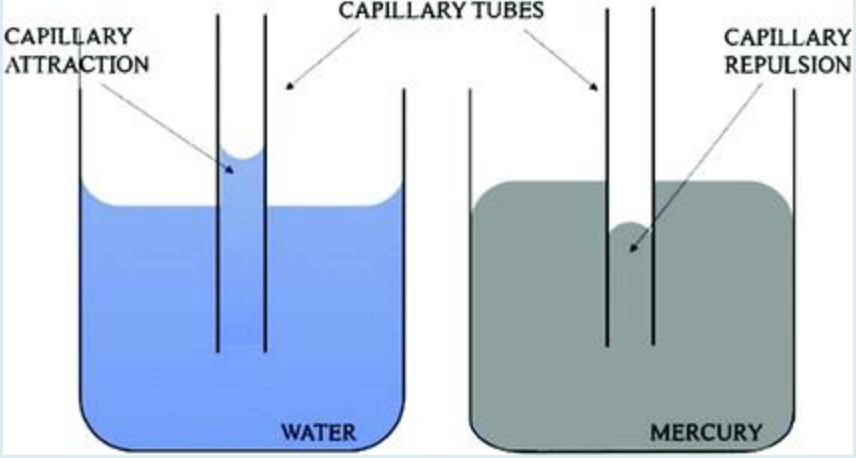
- What's happening here?
  - *Bug is walking on water*
- Why is this possible?
  - It doesn't weigh much
  - It's spreading its weight out
  - The downward forces are less than the effects of surface tension

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_s.
- Attractive force on surface molecule is not symmetric.
- Repulsive forces from interior molecules causes the liquid to minimize its surface area and attain a spherical shape.

Capillarity



- The surface tension leads to the phenomenon known as capillarity
- where a column of liquid in a tube is supported in the absence of an externally applied pressure.
- Rise or fall of a liquid in a capillary tube is caused by surface tension and depends on the relative magnitude of cohesion of the liquid and the adhesion of the liquid to the walls of the containing vessels.
- Liquid rise in tubes if they wet a surface (adhesion > cohesion), such as water.
- Liquid fall in tubes that do not wet (cohesion > adhesion), such as mercury.
- Capillarity is important when using tubes smaller than 10 mm (3/8 in.).
- For tube larger than 12 mm (1/2 in.) capillarity effects are negligible.

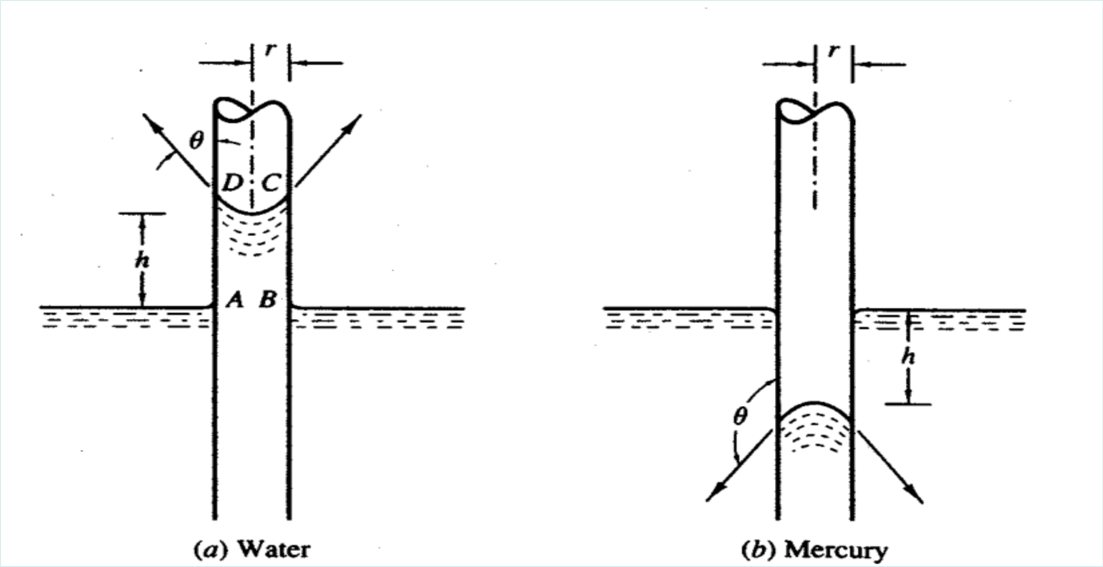


Figure 1.3
Capillary actions

$$h = \frac{2\sigma\cos\theta}{\gamma r} \qquad (1.8)$$

where h = height of capillary rise (or depression)

σ = surface tension

θ = wetting (contact) angle

γ = specific weight of liquid

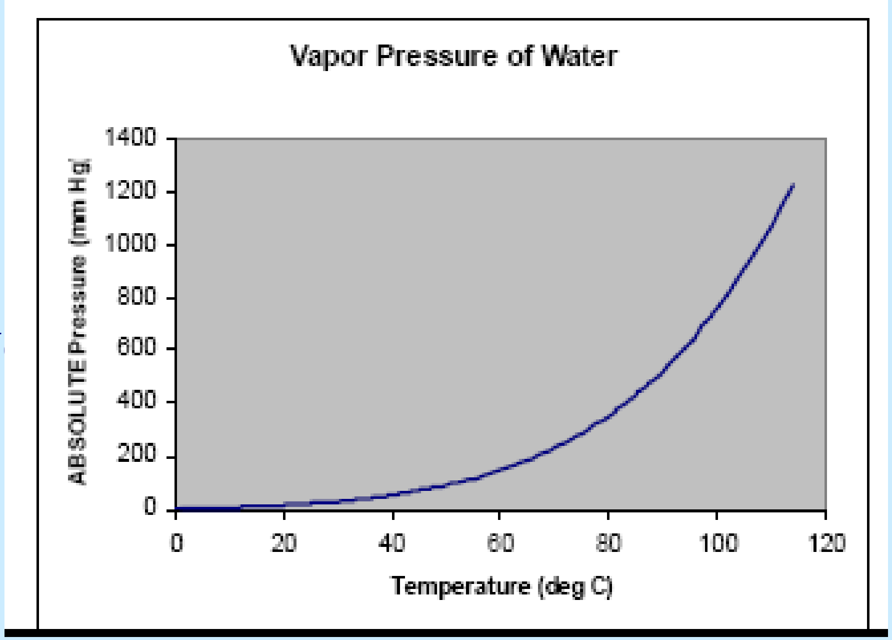
r = radius of tube

Vapor Pressure

Vapor pressure: the **pressure at which a liquid will boil.**

- **Vapor pressure ↑ when temperature increases**
- **At atmospheric pressure, water at 100 °C will boil**
- **Water can boil at lower temperatures if the liquid's actual pressure is low than the vapor pressure.**

Temp. (°C)	Pressure (mm Hg)
-10	2.1
0	4.6
20	17.5
40	55.3
60	149.4
80	355.1
100	760
110	1075



Example

- By making the dimension of the first term equal to the second term:

$$[m] \bullet \frac{[u]}{[t]} = [k] \bullet [x]$$

Hence,

$$[k] = \frac{[m] \bullet [u]}{[t] \bullet [x]} = \frac{M \bullet LT^{-1}}{LT}$$

$$= \underline{MT^{-2}}$$

Example

Given $m = 80$ kg and $a=10\ m/s^2$. Find the force

Solution

- $F = ma$
- $F = 80\ kg \times 10\ m/s^2 = 800\ kg.m/s^2$
- **F= 800N**

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:

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

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

$$\text{SG}_{\text{oil}} = \frac{\rho_{\text{oil}}}{\rho_{\text{w@4°C}}} = \frac{900}{1000} = 0.9$$

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;

$$h = \frac{2\sigma\cos\theta}{\gamma r}$$

$$\therefore \quad \cos\theta = \frac{\gamma r h}{2\sigma} = \frac{9810\text{x}0.0015\text{x}0.006}{2\text{x}0.4}$$

$$\theta = 83.7^\circ$$

Summary

This chapter has summarized on the aspect below:

- Understanding of a fluid
- Engineering unit of SI unit were discussed
- Fluid properties of density, specific weight, specific gravity, and viscosity were outlined and taken up
- Newtonian and non-Newtonian fluid were identified
- Discussion on the vapor pressure of the liquid
- Surface tension
- Capillarity phenomena