Topic I: Introduction to Fluid Mechanics

Fluid mechanics fluid; shear stress; continuum hypothesis; general flow classification; units and dimensions; density; specific weight; specific gravity; specific volume; mass and force; temperature; compressibility; surface tension; vapor pressure and cavitation; dynamic viscosity; kinematic viscosity; density/viscosity measurement devices.

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Basic definitions:

Fluid Mechanics: science of fluids either at rest (fluid static) or in motion (fluid dynamic) and their effects on solid boundaries such as solid walls or interfaces between different phases.

Fluid: substance that deforms continuously when subject to shear stress.

Shear stress* (τ) *: force required to slide one unit area layer of substance over another; [=] N/m^2, lbf/ft^2.

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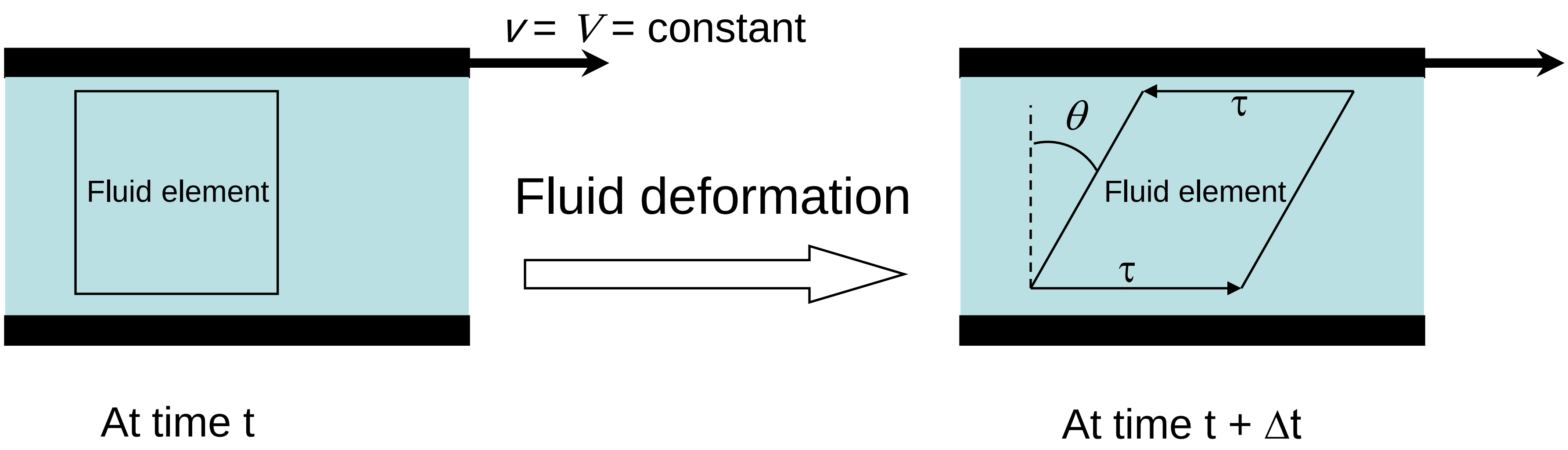
Example: Fluid between two parallel plates subject to a shear stress due to the motion of upper plate (**Couette flow**)



Fluid deforms i.e., it undergoes strain θ due to shear stress τ

⇒ Such behavior is different from solid substances which resist shear stresses by static deformation

• Fluid element in contact with the boundary takes the velocity of that boundary. Example is the no slip condition (Fluid in contact with stagnant (stationary) wall has zero velocity.

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- Both liquids and gases behaves as fluids.

$\rightarrow$ Liquids: - Closely spaced molecules with large intermolecular forces.

- Retain volume and take shape container.

$\rightarrow$ Gases: - Widely spaced molecules with small intermolecular forces.

- Takes volume and shape of container.

- The following general descriptions of liquids and gases that we will use in our text book:

- Gases are readily compressible.
- Liquids are only slightly compressible.

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• **Continuum Hypothesis:** Fluid behaves as continuum, i.e., the number of molecules within the smallest region of interest is sufficient to consider all fluid properties as continuous functions.

- Here, limiting volume V* is defined; below which molecular variations may be important.
- At atmospheric pressure; $V^*=10^{-9}$ mm^3 for all liquids and gases.

Example: How many molecules in a volume of 10^{-9} mm^3 air at standard conditions STP(T=0 ^oC, P=1 atm)

Answer: 30 million molecules. **Verify that!** (**Hint**: assume ideal gas and remember that 1 mole = 6.02×10^{23} molecules

Avogadro's number=6.02×10^{23}

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- **Flow classifications:**

  - Hydrodynamics: flow of fluid of constant density (ρ = constant).

  Examples: hydraulic (flow of liquids in pipes or open channels); low speed gas pipe systems,…etc.

  - Gas dynamic: flow of fluid of variable density ($\rho \neq$ constant).

  Examples: gas turbine, high-speed aerodynamics; high speed gas pipe system,…etc.

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- **Fluid properties:**

  - Properties and parameters involved in this course can be dimensional (density, pressure,…etc) or dimensionless (friction factor, Reynolds number, specific gravity,...etc).

  - Physical properties involved in this course are: **density**, **specific weight, specific gravity**, **surface tension**, **vapor pressure** and **viscosity**.

Remember that it is important to know how to deal with different systems of units

Refer to Chemical Engineering Principles (1) Course.

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- **Three common systems of units:**

1- The International System of Units (SI):

- The SI units for the **basic** quantities are:

$$\text{length} = \text{meter (m)}$$
$$\text{time} = \text{second (s)}$$
$$\text{mass} = \text{kilogram (kg) or } N \cdot s^2/m$$
$$\text{force} = \text{newton (N) or } kg \cdot m/s^2$$

- An equivalent unit for force indicated above is **derived** from the relationship between force and mass,

$$F = ma$$

where ***a*** is the acceleration expressed in m/s^2

- Therefore, the derived unit for force is

$$F = ma = \text{kg}\cdot\text{m/s}^2 = \text{N}$$

SI Unit Prefixes

Prefix	SI symbol	Factor
giga	G	$10^9 = 1\,000\,000\,000$
mega	M	$10^6 = 1\,000\,000$
kilo	k	$10^3 = 1\,000$
milli	m	$10^{-3} = 0.001$
micro	μ	$10^{-6} = 0.000\,001$
nano	n	$10^{-9} = 0.000\,000\,001$

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- Results of calculations should normally be adjusted so that the number is expressed in terms of these prefixes.

- **Some examples follow**:

Computed Result	Reported Result
0.004 23 m	4.23×10^{-3} m, or 4.23 mm (millimeters)
15 700 kg	15.7×10^{3} kg, or 15.7 Mg (megagrams)
86 330 N	86.33×10^{3} N, or 86.33 kN (kilonewtons)

2.The US Customary (or BG ; British Gravitational) System

- U.S. Customary System defines the basic quantities as follows:

$$\begin{aligned} \text{length} &= \text{foot (ft)} \\ \text{time} &= \text{second (s)} \\ \text{force} &= \text{pound (lb)} \\ \text{mass} &= \text{slug or lb-s}^2/\text{ft} \end{aligned}$$

- It may help to note the relationship between force and mass,

$$F = ma$$

$$m = \frac{F}{a} = \frac{\text{lb}}{\text{ft/s}^2} = \frac{\text{lb-s}^2}{\text{ft}} = \text{slug}$$

3. CGS (centimeter, gram, second) System

$$F = ma = \frac{g.cm}{s^2} = dyne$$

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Mass expressed as lbm….

- In the analysis of fluid systems, some professionals use the unit lbm (pounds-mass) for the unit of mass instead of the unit of slugs.
- When one tries to relate force and mass units using Newton's law, one obtains

$$F = ma = \text{lbm}(\text{ft/s}^2) = \text{lbm-ft/s}^2$$

- **This is *not* the same as the lbf.**
- In summary, because of the cumbersome nature of the relationship between lbm and lbf, **it is better to avoid the use of lbm.**
- Mass will be expressed in the unit of slugs when problems are in the U.S. Customary System of units.

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Temperature

- Temperature is most often indicated in (degrees Celsius) or (degrees Fahrenheit).
- The following values at sea level on Earth is as follow:

Water freezes at 0°C and boils at 100°C.

Water freezes at 32°F and boils at 212°F.

- Given the temperature in °F the temperature in °C is

$$T_C = (T_F - 32)/1.8$$

- Given the temperature in °C the temperature in °F is

$$T_F = 1.8T_C + 32$$

Absolute Temperature

- The absolute temperature is defined so the zero point corresponds to the condition where **all molecular motion stops.**
- This is called ***absolute zero***.
- In the **SI unit system**, the standard unit of temperature is the ***Kelvin***, for which the standard symbol is K and the reference (zero) point is absolute zero.
- In the **US unit system**, the standard unit of temperature is the ***Rankine***, for which the standard symbol is ^oR and the reference (zero) point is absolute zero
- We can then make the conversion by using

$$T_K = T_C + 273.15$$

$$T(^oR) = T(^oF) + 459.67 = 1.8\, T(K)$$

Consistent Units in an Equation

- A simple straightforward procedure called ***unit cancellation*** will ensure proper units in any kind of calculation, not only in fluid mechanics, but also in virtually all your technical work.

- **SI units** for common quantities used in fluid mechanics:

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	$N \cdot s^2/m^4$

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- **U.S. customary** units for common quantities used in fluid mechanics:

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	$slugs/ft^3$	

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- **UNIT-CANCELLATION PROCEDURE**

1) Solve the equation algebraically for the desired term.
2) Decide on the proper units for the result.
3) Substitute known values, including units.
4) Cancel units that appear in both the numerator and the denominator of any term.
5) Use conversion factors to eliminate unwanted units and obtain the proper units as decided in Step 2.
6) Perform the calculation.

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Example. Imagine you are traveling in a car at a constant speed of 80 kilometers per hour (km/h). How many seconds (s) would it take to travel 1.5 km?

For the solution, use the equation $s = vt$

solve for the desired term, t

$$t = \frac{s}{v} = \frac{1.5\ \text{km}}{80\ \text{km/h}}$$

$$t = \frac{1.5\ \text{km}\cdot\text{h}}{80\ \text{km}}$$

$$t = \frac{1.5\ \cancel{\text{km}}\cdot\cancel{\text{h}}}{80\ \cancel{\text{km}}} \times \frac{3600\ \text{s}}{1\ \cancel{\text{h}}}$$

t = 67.5 s

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Physical properties involved in this course:

1- Density, specific volume, Specific Weight and Specific Gravity:

- **Density** (ρ) : Mass per unit volume

$$\rho = \frac{m}{V} \qquad \text{Units} \rightarrow \text{SI: } [=]\frac{kg}{m^3} \quad \text{US: } [=]\frac{slug}{ft^3}$$

- Specific volume (v): Volume per unit mass

$$v = \frac{V}{m} = \frac{1}{\rho} \qquad \text{Units} \rightarrow \text{SI: } [=]\frac{m^3}{kg} \quad \text{US: } [=]\frac{ft^3}{slug}$$

- **Specific weight** (γ): *gravitational force (weight) per unit volume*

$$\gamma = \frac{w}{V} = \frac{mg}{V} = \rho g \qquad \text{Units} \rightarrow \text{SI: } [=]\frac{N}{m^3} \quad \text{US: } [=]\frac{lbf}{ft^3}$$

- **Specific gravity** 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.

These definitions for specific gravity (sg) can be shown mathematically as

$$\mathbf{sg} = \frac{\gamma_s}{\gamma_w \,@\, 4°\mathrm{C}} = \frac{\rho_s}{\rho_w \,@\, 4°\mathrm{C}}$$

$\mathbf{sg}[=]$ dimensionless

where the subscript ***s*** refers to the substance whose specific gravity is being determined and the subscript ***w*** refers to water.

Specific Gravity in Degrees Baume or Degree API

- The reference temperature for specific gravity measurements on the Baumé or American Petroleum Institute (API) scale is 60°F rather than 4°C as defined before.

- To emphasize this difference, the API or Baumé specific gravity is often reported as

$$\text{Specific gravity}\ \frac{60^\circ}{60^\circ}\text{F}$$

- **For liquids heavier than water,**

$$\mathbf{sg} = \frac{145}{145 - \mathbf{deg\ \ Baume}}$$

$$\mathbf{deg\ \ Baume} = 145 - \frac{145}{\mathbf{sg}}$$

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- For liquids lighter than water,

$$\mathbf{sg} = \frac{140}{130 + \mathbf{deg\ \ Baume}}$$

$$\mathbf{deg\ \ Baume} = \frac{140}{\mathbf{sg}} - 130$$

- The API has developed a scale that is slightly different from the **Baumé scale for liquids lighter than water**.
- The formulas are

$$\mathbf{sg} = \frac{141.5}{131.5 + \mathbf{deg\ \ API}}$$

$$\mathbf{deg\ \ API} = \frac{141.5}{\mathbf{sg}} - 131.5$$

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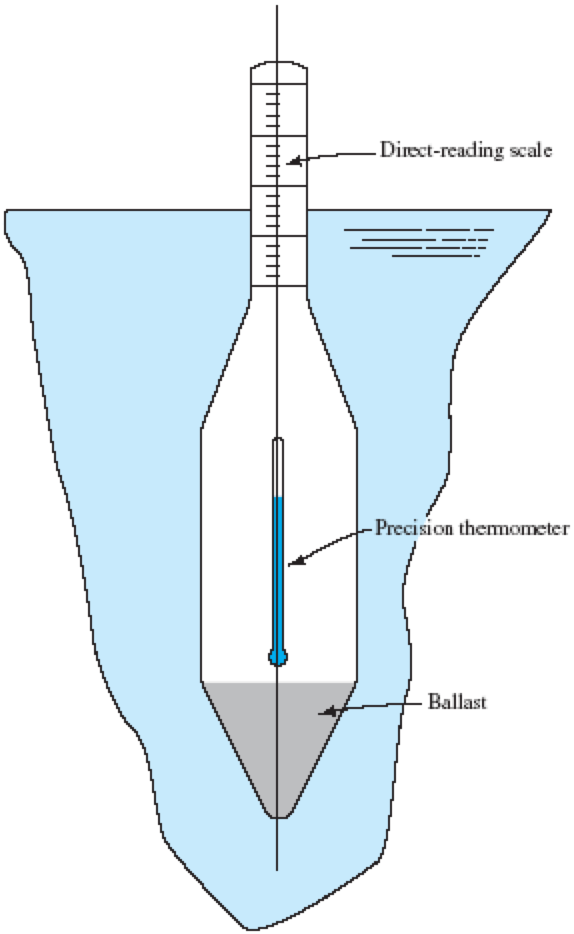
- **Hydrometer** is a common device used to measure density, sg, or deg API, deg Baume.



"Hydrometer with built-in thermometer (thermo-hydrometer)."

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- **Effect of temperature and pressure on fluid density**:

-Gases: $\rho = \rho(gas, T, P)$

→ Ideal gases: $\rho = \frac{P}{R'T}$ $\qquad R' = \frac{R}{Mwt}$

For air: $R'_{air} = \frac{R}{Mwt} = 287.05$ N.m/(kg.K)

→ Real gases: $\rho = \frac{P}{ZR'T}$

Where Z is the compressibility factor
Refer to Thermodynamic I course
Or use Equation of State (EOS) for real gases

-Liquids: $\rho \approx \rho(liquid, T)$

- As T ↑: ρ ↓ $\qquad$ - As P ↑: ρ ↑

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- ***Compressibility*** refers to the change in volume (*V*) of a substance that is subjected to a change in pressure on it.
- The usual quantity used to measure this phenomenon is the ***bulk modulus*** *of elasticity* or, simply, ***bulk modulus, E***:

$$E = \frac{-\Delta p}{(\Delta V)/V}$$

Values for bulk modulus for selected liquids at atmospheric pressure and 68°F (20°C).

Liquid	Bulk Modulus (psi)	Bulk Modulus (MPa)
Ethyl alcohol	130 000	896
Benzene	154 000	1 062
Machine oil	189 000	1 303
Water	316 000	2 179
Glycerine	654 000	4 509
Mercury	3 590 000	24 750

Example. Compute the change in pressure that must be applied to water to change its volume by 1.0 percent.

The 1.0-percent volume change indicates that $\Delta V/V = -0.01$. Then, the required change in pressure is

$$\Delta p = -E[(\Delta V)/V] = [-2179 \text{ MPa}][-0.01] = 21.79 \text{ MPa}$$

In general: - liquids are incompressible ($\rho \sim$ constant with pressure variations).

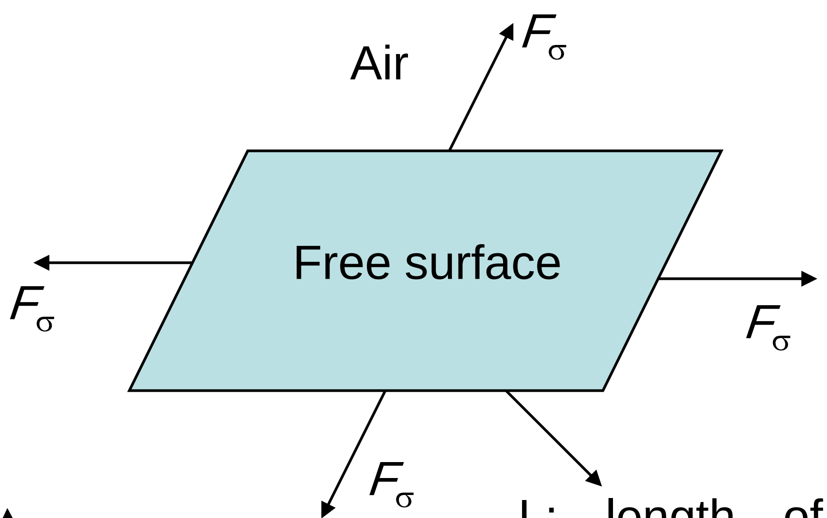
- Gases are compressible ($\rho \neq$ constant with pressure variations).

2- Surface tension (σ):

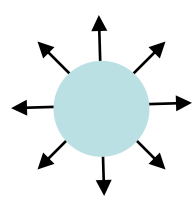
- When surface tension?

It occurs when the system has free surface (Air-Water) or interfaces between different phases.

Near interface, surface tension force, F_σ, appear to compensate the force imbalance.



L: length of cut along the contact line between solid and liquid.



Away from free surface, intermolecular forces are equal in all directions

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Surface tension can be defined as work that must be done to bring enough molecules from the inside of the liquid to form one unit area of interface.

$$\sigma [=] \frac{J}{m^2} [=] \frac{N.m}{m^2} [=] \frac{N}{m}$$

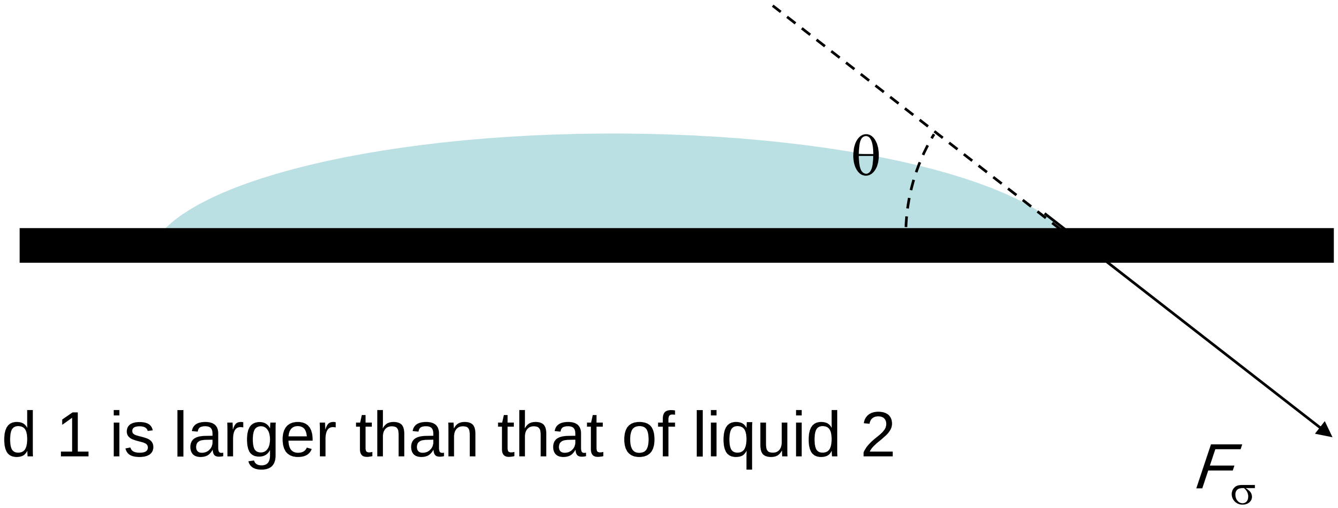
$$\therefore \sigma = \frac{F_\sigma}{L} \Rightarrow F_\sigma = \sigma L$$

L: length of cut along the contact line between solid and liquid.

F_σ: surface tension force

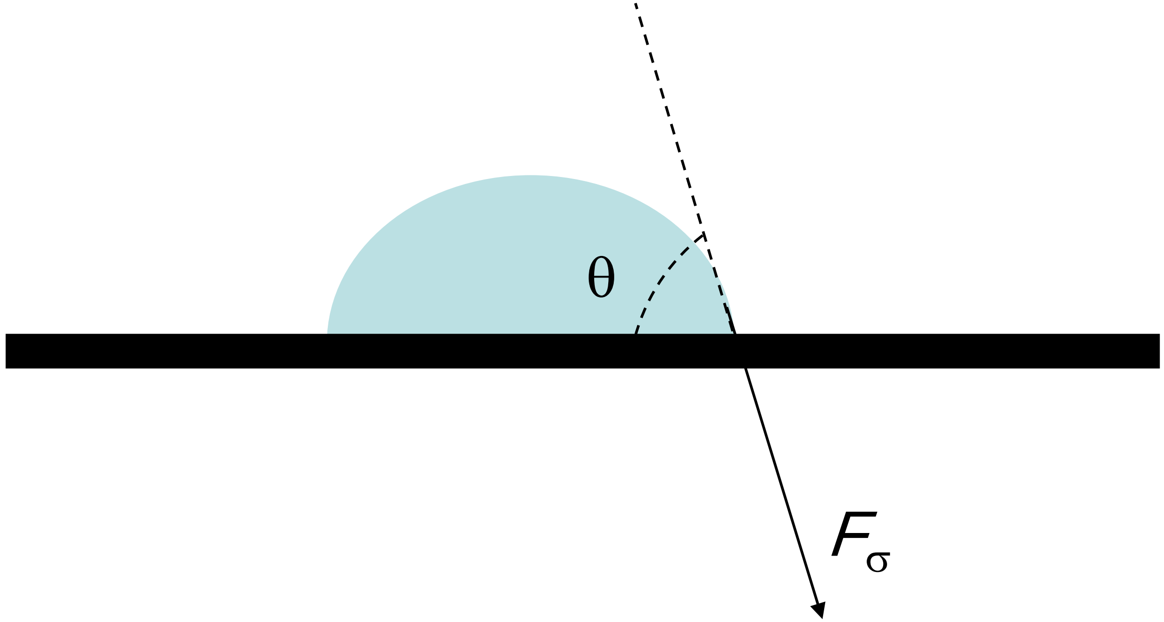
Effect of surface tension on wetting phenomena:

a) Liquid 1



Wetting for liquid 1 is larger than that of liquid 2

b) Liquid 2



$L = \pi D$

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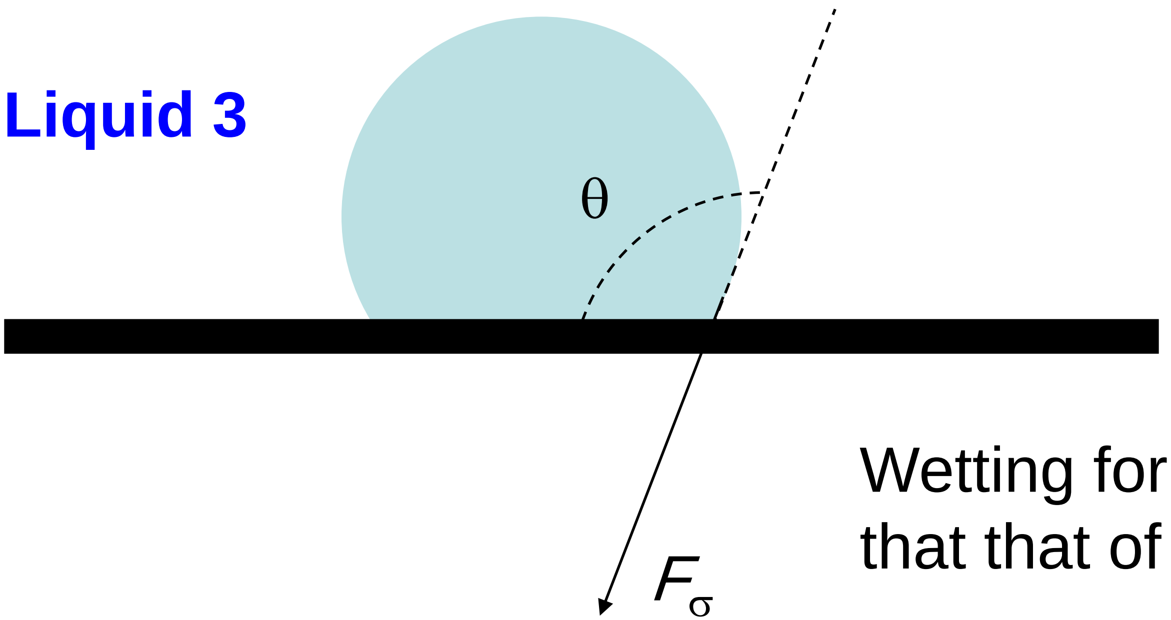
b) Liquid 3



Wetting for liquid 3 is smaller that that of liquid 2

θ: Contact angle between the solid surface and the line tangent to the liquid edge as shown in the above figures; measured from the inside of the liquid.

-It is clear from the figures above that as wetting increases the corresponding contact angle decreases.

- As surface tension increases wetting decreases (θ increases).

Ex: $\theta_{water} \approx 0^o$; $\theta_{Hg} \approx 140^o$

Surface tension of water

Temperature (°F)	Surface Tension (mlb/ft)	Temperature (°C)	Surface Tension (mN/m)
32	5.18	0	75.6
40	5.13	5	74.9
50	5.09	10	74.2
60	5.03	20	72.8
70	4.97	30	71.2
80	4.91	40	69.6
90	4.86	50	67.9
100	4.79	60	66.2
120	4.67	70	64.5
140	4.53	80	62.7
160	4.40	90	60.8
180	4.26	100	58.9
200	4.12		
212	4.04		

Surface tension of mercury at 25 ^{o}C is $\boldsymbol{\sigma_{Hg}}$ = 485 N/m

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- Some physical phenomena that occur due to surface tension effects:

- Capillary rise or depression in tubes of small diameter (d ≤ 10 mm).
- Transformation of liquid jet into droplets.
- rain falls as spherical droplets
-…etc.

Example. To what height above the reservoir level will water at 20 ^{o}C rise in a glass tube of an insider diameter of 1.6 mm.

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System: water rises in capillary above the reservoir level

Applying force balance on the system:

$$\sum F_z = 0$$

$$F_\sigma \cos\theta - W = 0$$

$$F_\sigma = \sigma L = \sigma \pi d$$

$$W = mg = \rho V g = \gamma V$$

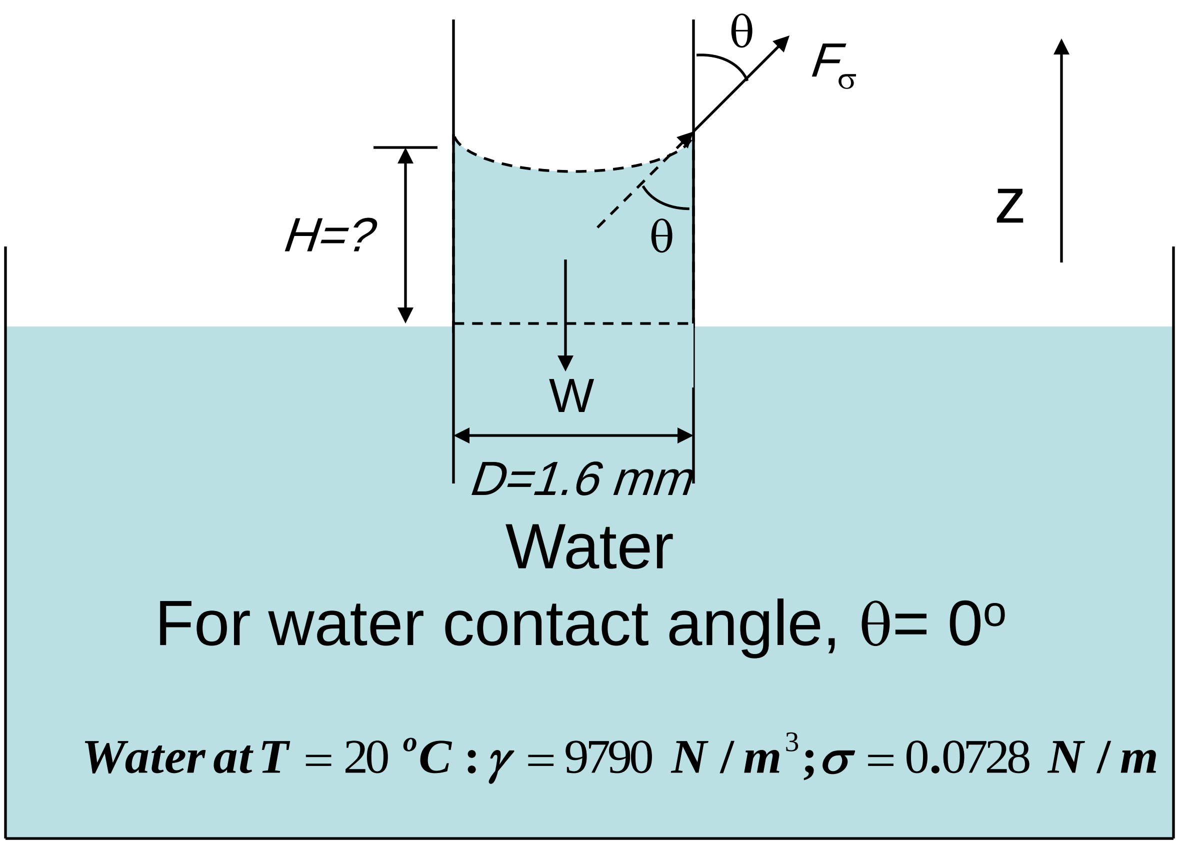
$$V = \frac{\pi d^2}{4} H$$

$$W = \gamma \frac{\pi d^2}{4} H$$

$$\sigma \pi d \cos\theta - \gamma \frac{\pi d^2}{4} H = 0$$

$$\therefore\ H = \frac{4\sigma\cos\theta}{\gamma d} = 0.0186\,m$$

$$= 18.6\,mm$$



-Repeat this example for Mercury?

-How H is affected by surface tension?

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3- Vapor pressure (P^v or P^{sat}):

- It is absolute pressure.
- As temperature increases, vapor pressure of liquid increases.

- Boiling occurs when $P = P^v(T)$.

- When boiling occurs by pressure decrease due to velocity increase, the phenomenon is called **Cavitation**.

Here **Cavitation number** is defined as:

$$\text{Cavitation number} = \frac{P - P^v}{0.5\rho\overline{U}^2} \leq 0$$

- When Cavitation number ≤ 0; Cavitation will occur which causes damage of pump.

4- Dynamic viscosity of fluid (μ):

-Viscosity is a measure of resistance of fluid to flow.

- For examples, water has relatively low viscosity and it pours easily while honey has high viscosity and it pours very slowly.
- Here, we define **Newtonian fluid**: fluid in which the shear stress is directly proportional to the rate of strain:

$$\Rightarrow \qquad \tau \,\alpha\, \frac{d\theta}{dt}$$

$$\tau = \mu \frac{d\theta}{dt}$$

Where μ is the constant of proportionality which is called viscosity or dynamic viscosity.

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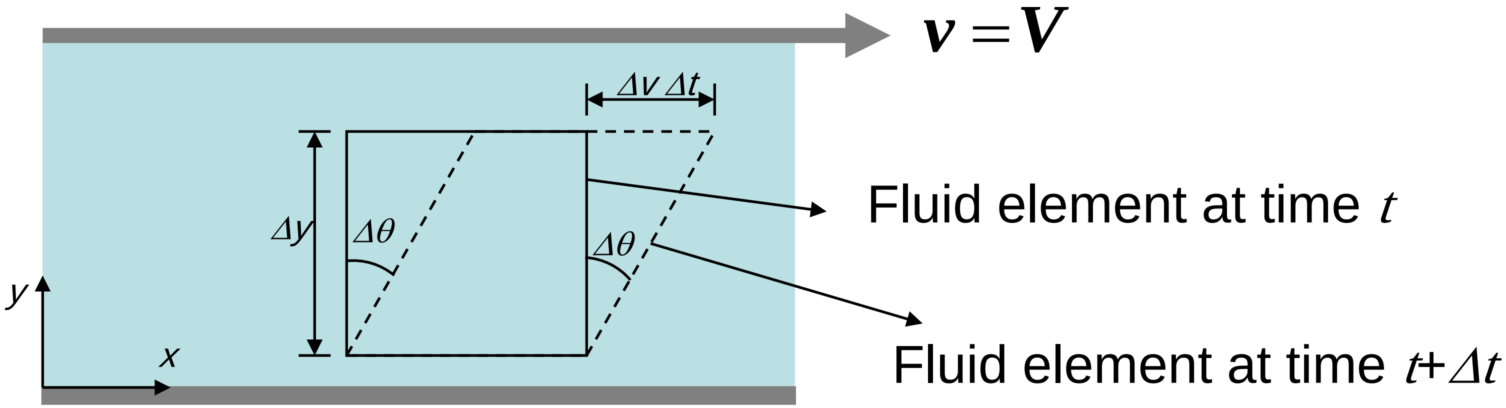
-You know from previous courses that viscosity has the a unit of **kg/(m.s).** From where this unit did basically come?

→ To answer that and to understand another important concept in fluid mechanics , recall **Couette flow**:



$$\tan(\Delta\theta) = \frac{\Delta v \Delta t}{\Delta y}$$

Since the fluid element is very small, $\Delta\theta$ is small angle, and for small angles: $\tan(\Delta\theta) = \Delta\theta$

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Thus, $$\Delta\theta = \frac{\Delta v \Delta t}{\Delta y}$$

And $$\frac{\Delta\theta}{\Delta t} = \frac{\Delta v}{\Delta y}$$

Take the limit $$\lim_{\Delta t \to 0}\left(\frac{\Delta\theta}{\Delta t}\right) = \lim_{\Delta y \to 0}\left(\frac{\Delta v}{\Delta y}\right)$$

gives: $$\frac{d\theta}{dt} = \frac{dv}{dy}$$

$\frac{dv}{dy}$ is called velocity gradient; 1/s, which equals the rate of strain.

Thus, $$\tau = \mu \frac{d\theta}{dt} = \mu \frac{dv}{dy}$$

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

"Newton's law of viscosity"

Units for viscosity: $$\mu = \frac{\tau}{dv/dy}$$

SI Units: $$\mu \,[=]\, \frac{N/m^2}{(m/s)/m} = \frac{N.m.s}{m^3} = \frac{N.s}{m^2} = kg\frac{m}{s^2}\frac{s}{m^2} = \frac{kg}{m.s} = Pa.s$$

US Units: $$\mu \,[=] = \frac{lbf.s}{ft^2} = \frac{slug}{ft.s}$$

CGS Units: $$\mu \,[=] = \frac{dyne.s}{cm^2} = \frac{g}{cm.s} = poise$$

$$1\frac{g}{cm.s} = 1\ poise = 0.1\,Pa.s \qquad 1\,centpoise = 0.01\,Pa.s$$

Velocity profile for Couette flow:

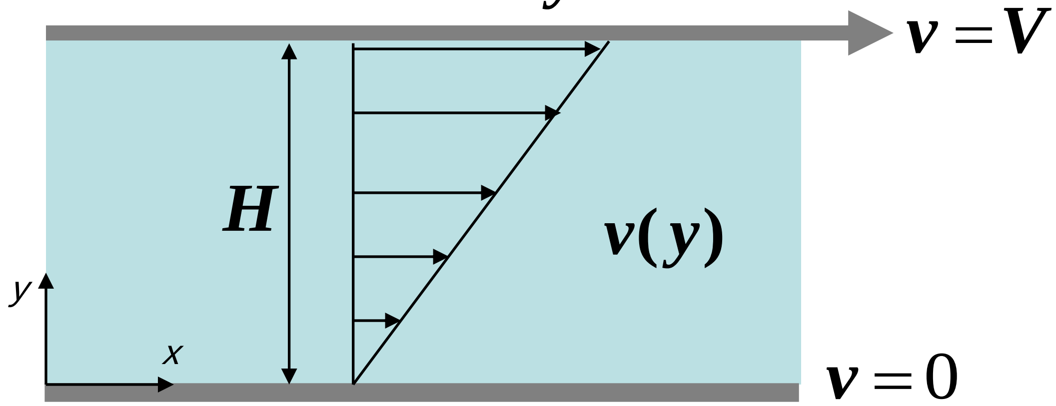
- It is linear velocity profile: $\boldsymbol{v(y) = a + by}$

Where **a** and **b** are constants found by applying the following the boundary conditions: $\boldsymbol{v(0) = 0 = a + b(0) \Rightarrow a = 0}$

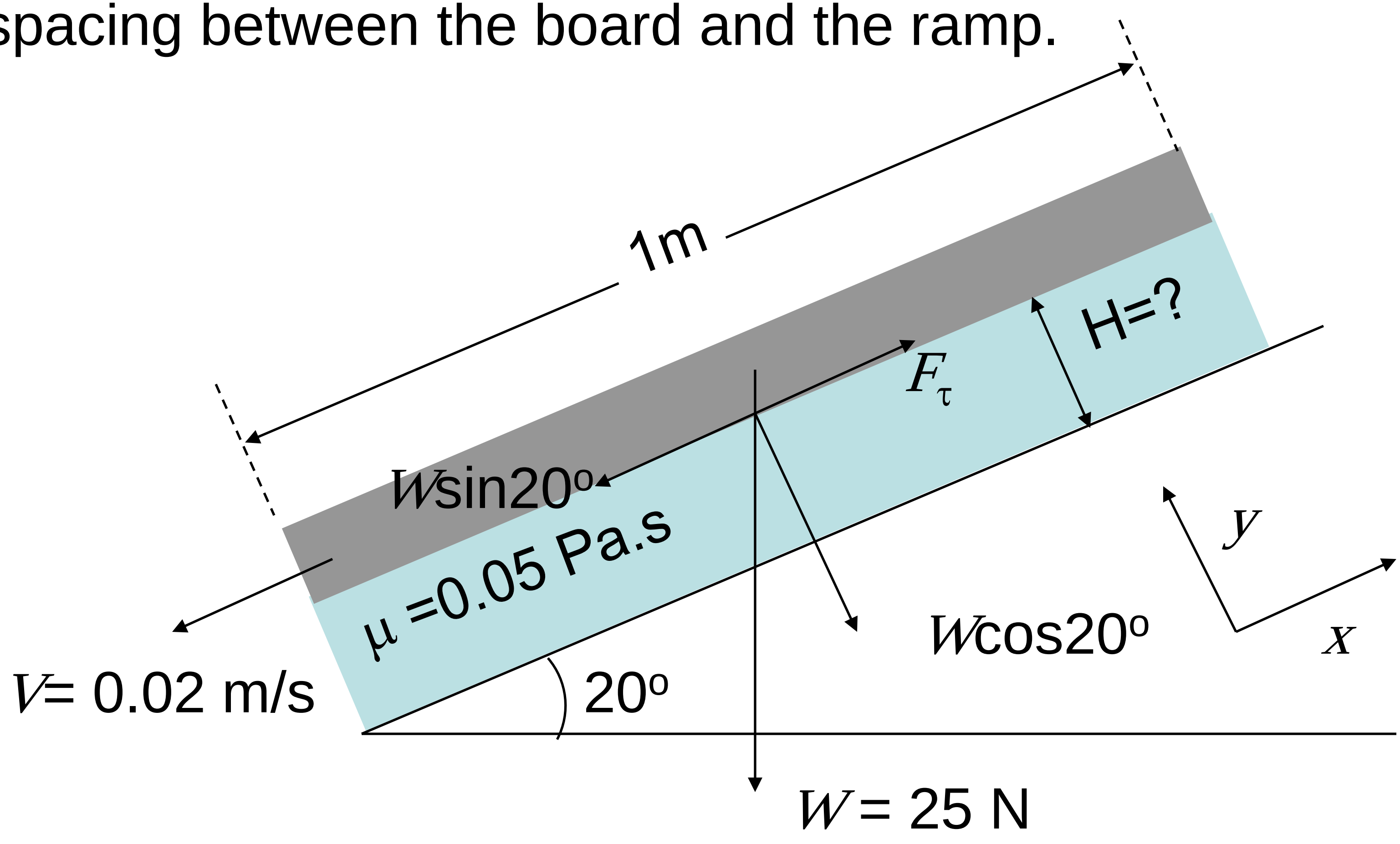
$$\boldsymbol{v(H) = V = 0 + bH \Rightarrow b = \frac{V}{H}}$$

$$\boldsymbol{\therefore v(y) = \frac{V}{H} y}$$

Now the shear stress is: $\boldsymbol{\tau = \mu \frac{dv}{dy} = \mu \frac{V}{H}}$



Example. A board 1 m by 1 m that weighs 25 N slides down on an inclined ramp(slope= 20^{o}) with a velocity of 2 cm/s. The board is separated from the ramp by a thin film of oil with a viscosity of 0.05 Pa.s. Neglecting the edge effects, calculate the spacing between the board and the ramp.



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System: The board.

Forces affects on the system: Shear Stress forces (F_τ) and Weight; W

Applying Force balance in x-direction :

$$\sum \boldsymbol{F}_x = 0 \Rightarrow \boldsymbol{F}_\tau - \boldsymbol{W}\,\mathbf{sin}\,20^o = 0$$

$$\boldsymbol{F}_\tau = \boldsymbol{\tau A}$$

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

For Couette flow:

$$\boldsymbol{\tau} = \boldsymbol{\mu}\frac{\mathbf{V}}{\boldsymbol{H}}$$

Thus: $$\boldsymbol{H} = \frac{\boldsymbol{\mu VA}}{\boldsymbol{W}\,\mathbf{sin}\,20^o}$$

$$H = \frac{(0.05)(0.02)(1)(1)}{25\sin 20^o} = 1.17\times 10^{-4}\,m$$

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- **Kinematic viscosity (ν):** ratio of viscosity to the density of fluid:

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

Units for Kinematic viscosity:

SI Units: $\nu\ [=]\ \frac{kg/(m.s)}{kg/m^3} = \frac{m^2}{s}$

US Units: $\nu\ [=] = \frac{ft^2}{s}$

CGS Units $\nu\ [=] = \frac{cm^2}{s} = stoke$

$$1\ stoke = 1\times10^{-4}\ \frac{m^2}{s} \qquad 1\ centistoke = 0.01 stoke$$

- **Effect of temperature and pressure on viscosity:**

$$\mu = \mu(\text{fluid}, T, P)$$

-As pressure increases, viscosity increases since molecules of fluid become more closed to each other which lead to more molecular collisions and thus friction.

- But effect of P on μ is not as large as T, it can be neglected for moderate P changes.

- As temperature increases:

$\rightarrow$ Viscosity of liquid decreases since cohesive forces between molecules becomes weaker.

$\rightarrow$ Viscosity of gas increases due to the increase of molecular activities and thus more molecular collisions and friction.

Topic I: Introduction to Fluid Mechanics

- **Newtonian fluid**: any fluid that behaves in accordance with Newton's law of viscosity($\tau = \mu \frac{dv}{dy}$).

- Most common fluids such as air, water, oil, gasoline, alcohols are classified as Newtonian fluids.

- **Non-Newtonian fluid**: any fluid that does NOT behave in accordance with Newton's law of viscosity.

- The study of the deformation of fluids is called ***Rheology***, which is the field from which we learn about the viscosity of fluids.

Topic I: Introduction to Fluid Mechanics

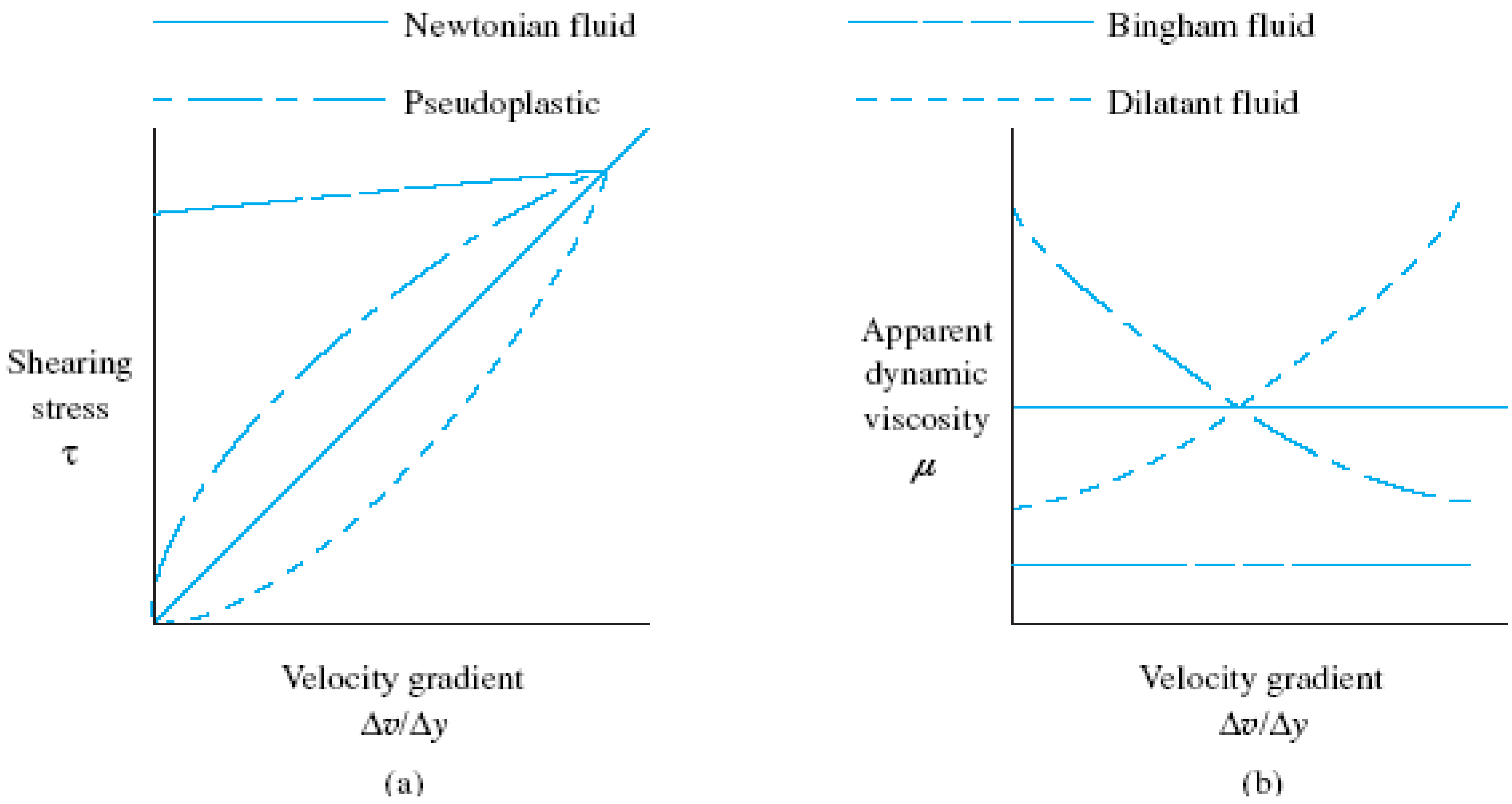
- Two major classifications of non-Newtonian fluids are *time-independent* and *time-dependent* fluids.
- As their name implies, time-independent fluids have a viscosity at any given shear stress that does not vary with time.
- The viscosity of time-dependent fluids, however, changes with time.

- **Three types of time-independent fluids can be defined**:

1. ***Pseudoplastic*** *or Thixotropic Fluids:* blood plasma, water suspensions of clay,…etc.
2. ***Bingham*** *Fluids :* Chocolate, mayonnaise, paints, asphalt,…etc.
3. ***Dilatant*** *Fluids (*Sometimes called *plug-flow fluids):* Concentrated sugar solutions, starch in water, Ethyl glycol,…etc.

Topic I: Introduction to Fluid Mechanics

- Plotting of shear stress versus velocity gradient indicates the difference between Newtonian and non-Newtonian fluid.



- As shown in the previous figure, the apparent viscosity of non-Newtonian fluid is affected by the velocity gradient in addition to the operating conditions (particularly temperature and pressure).

Fluid	Temperature (°C)	Dynamic Viscosity ($N\cdot s/m^2$ or $Pa\cdot s$)
Water	20	1.0×10^{-3}
Gasoline	20	3.1×10^{-4}
SAE 30 oil	20	3.5×10^{-1}
SAE 30 oil	80	1.9×10^{-2}

"viscosity for different fluids"

SAE: The Society of Automobile Engineers

Viscosity Measurement Devices

- Rotating-drum viscometer:

$$\tau = -\mu \frac{dV}{dr} = -\mu \frac{\Delta V}{\Delta r} = -\mu \frac{(0 - V_1)}{\Delta r} = \mu \frac{V_1}{\Delta r}$$

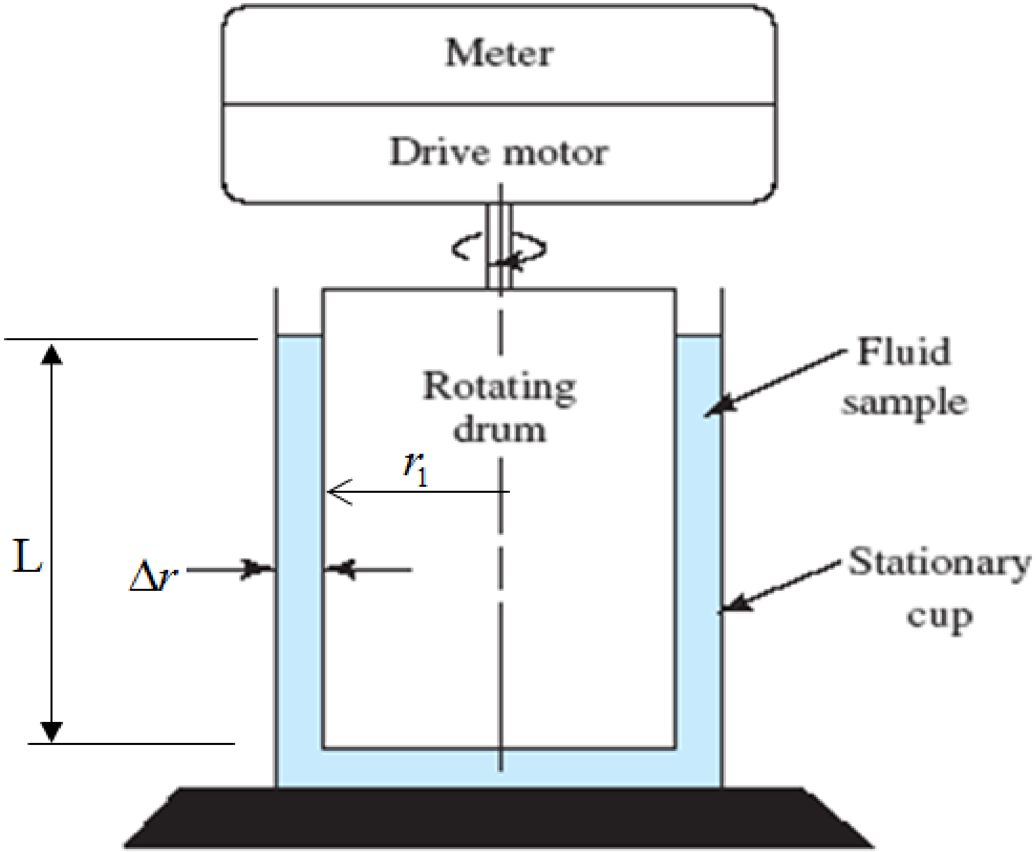
$$\Rightarrow \mu = \frac{\tau \, \Delta r}{V_1}$$

$$V_1 = 2\pi \, r_1 \, rpm$$

$$\tau = \frac{F}{A} = \frac{F}{2\pi \, r_1 \, L}$$

$$\Gamma = F \, r_1 \qquad ;\Gamma : \text{Torque}$$

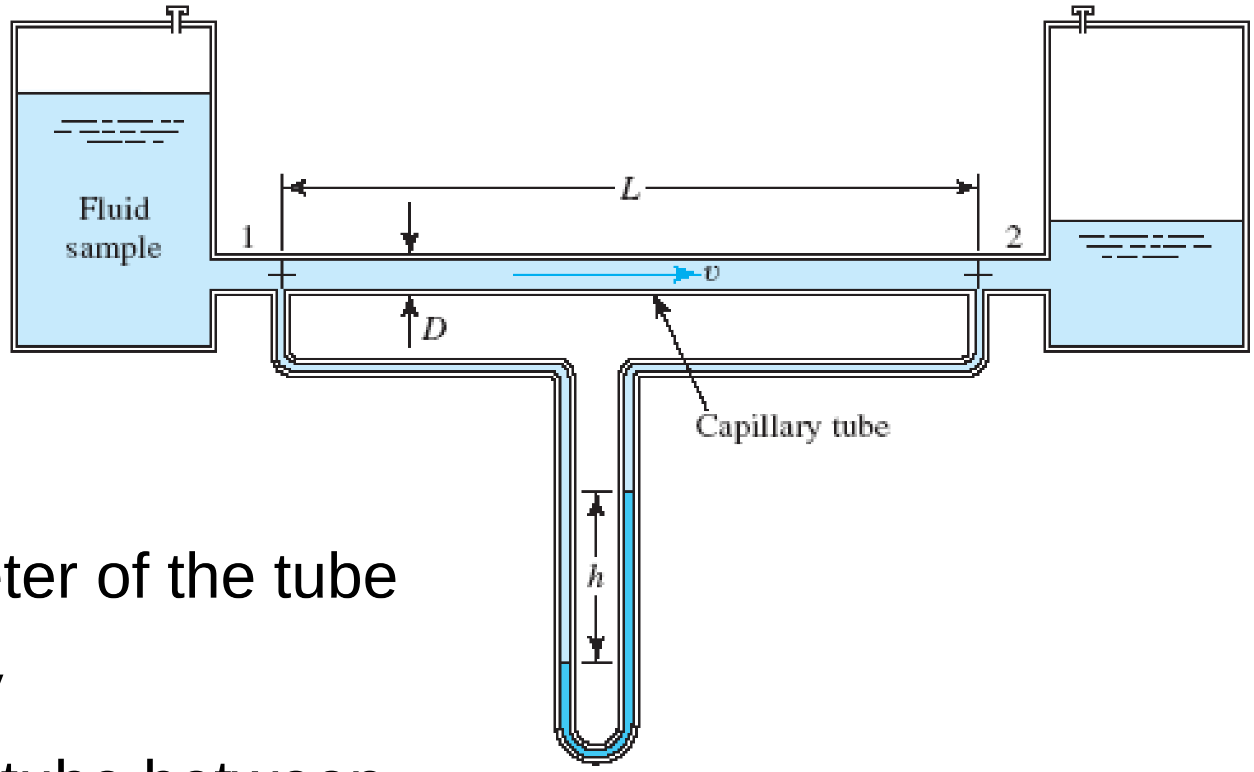
$$\text{motor power} = \Gamma \, 2\pi \; rpm$$



Viscosity Measurement Devices

- Capillary-tube viscometer:

$$\mu = \frac{(p_1 - p_2)D^2}{32vL}$$



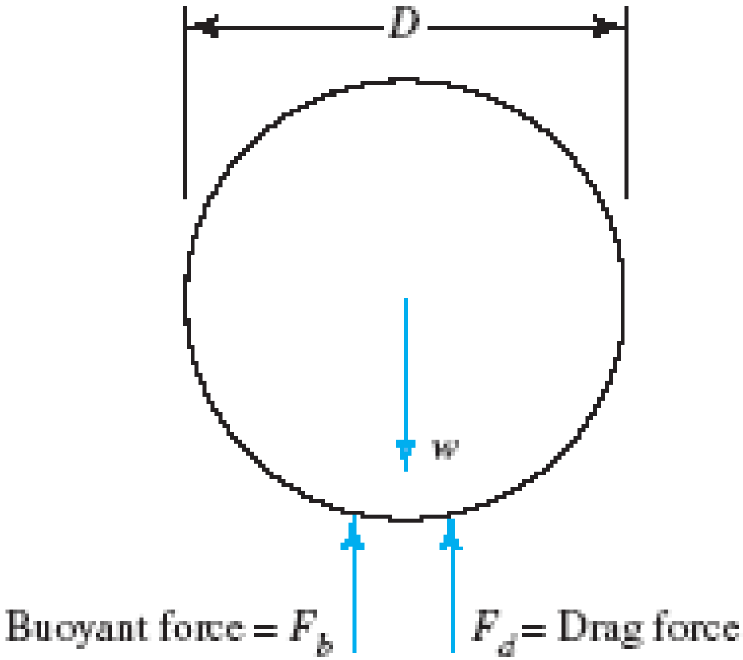
D: the inside diameter of the tube

V : the fluid velocity

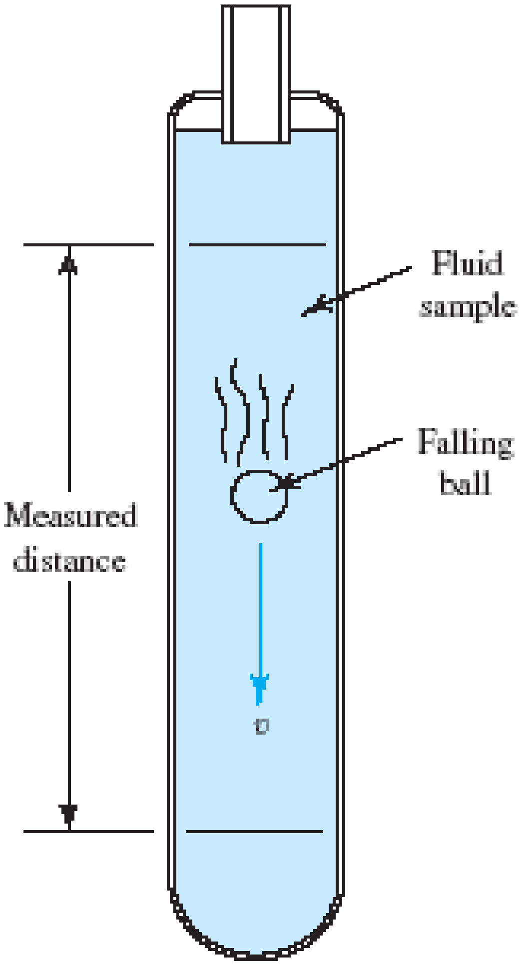
L :the length of the tube between points 1 and 2 where the pressure is measured.

Viscosity Measurement Devices

- Falling-Ball Viscometer:



“Forces on falling-ball”



Viscosity Measurement Devices

Applying the vertical direction force balance on the ball:

$$w - F_b - F_d = 0.$$

where w is the weight of the ball, F_b, is the buoyant force, and F_d is the viscous drag force on the ball.

If γ_s is the specific weight of the sphere, γ_f is the specific weight of the fluid, V is the volume of the sphere, and D is the diameter of the sphere, we have:

$$w = \gamma_s V = \gamma_s \pi D^3/6$$

$$F_b = \gamma_f V = \gamma_f \pi D^3/6$$

Viscosity Measurement Devices

For very viscous fluids and small velocity, the drag force on the sphere is:

$$F_d = 3\pi\mu v D$$

Where v is the *terminal velocity (*$v = s/t$*)*. Where s is distance in which the ball will travel during time t.

Then the equation for calculating viscosity becomes:

$$\mu = \frac{(\gamma_s - \gamma_f)D^2}{18v}$$

Viscosity Measurement Devices

Example. In a falling ball viscometer, a steel ball with a diameter of 2.5 mm is allowed to fall freely in a heavily fuel oil having a specific gravity of 0.9. Steel weighs 77 kN/m^3. If the ball is observed to fall 30 mm in 10 seconds, calculate the dynamic viscosity of the oil in Pa.s.

$$\text{sg} = 0.90$$
$$D = 2.5 \text{ mm} = 0.0025 \text{ m}$$
$$\gamma_s = 77 \text{ kN/m}^3$$
$$s = 30 \text{ mm} = 0.03 \text{ m}$$
$$t = 10 \text{ s}$$

$$\mu = \frac{(\gamma_s - \gamma_f)D^2}{18\upsilon}$$

$$\upsilon = s/t = 0.03 \text{ m}/10 \text{ s} = 0.003 \text{ m/s}$$

$$\mu = \frac{[77 \text{ kN/m}^3 - 0.9(9.81 \text{ kN/m}^3)](0.0025 \text{ m})^2}{18(0.003)}$$

$$= \frac{(68.171 \text{ kN/m}^3)(0.0025 \text{ m})^2}{18(0.003)}$$

$$= \mathbf{7.89 \ Pa \cdot s}$$

Viscosity Measurement Devices

- Saybolt Universal Viscometer :