FLUID MECHANICS

SETG2343 | SETN1123 | SETK2233

Course Outline

1: Physics of fluid
2: Fluid statics
3: Fluid dynamics
4: Friction flow in pipes
5: Flow metering
6: Pump
7: Dimensional analysis

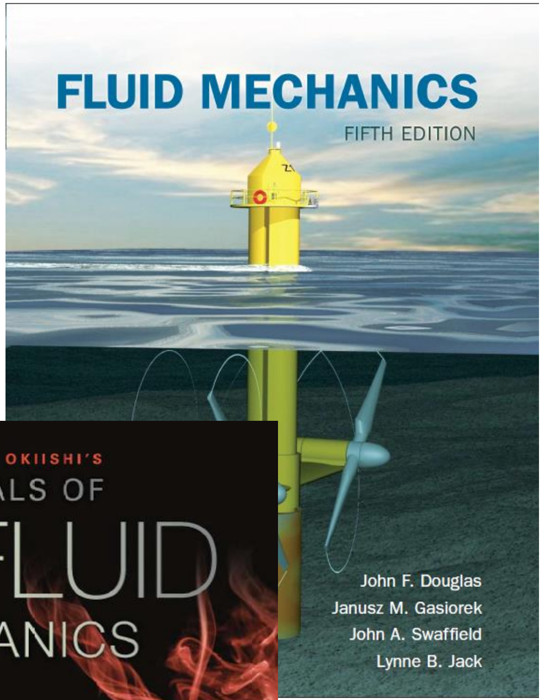
References

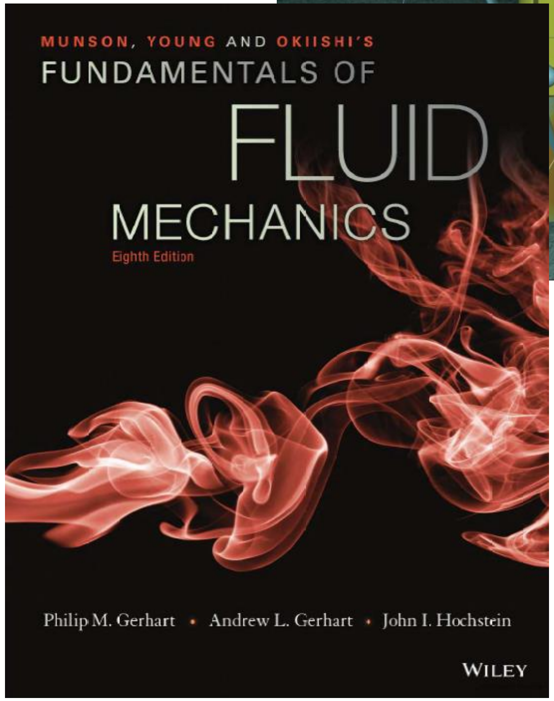
Main references

1) Douglas, John F., Janusz M. Gasiorek, John A. Swaffield, and Lynne B. Jack. *Fluid mechanics*. Pearson education, 2005.
2) Munson, B.R., D.F. Young, and T.H. Okiishi. *Fundamentals of Fluid Mechanics.* 8th Edition. London: John Wiley and Sons, 2018.

Others:

1) Dougherty, R.L., J.B. Franzini, and E.J. Finnemore (1986). *Fluid Mechanics with Engineering Applications*. London: McGraw Hill.





THE PHYSICS OF FLUID

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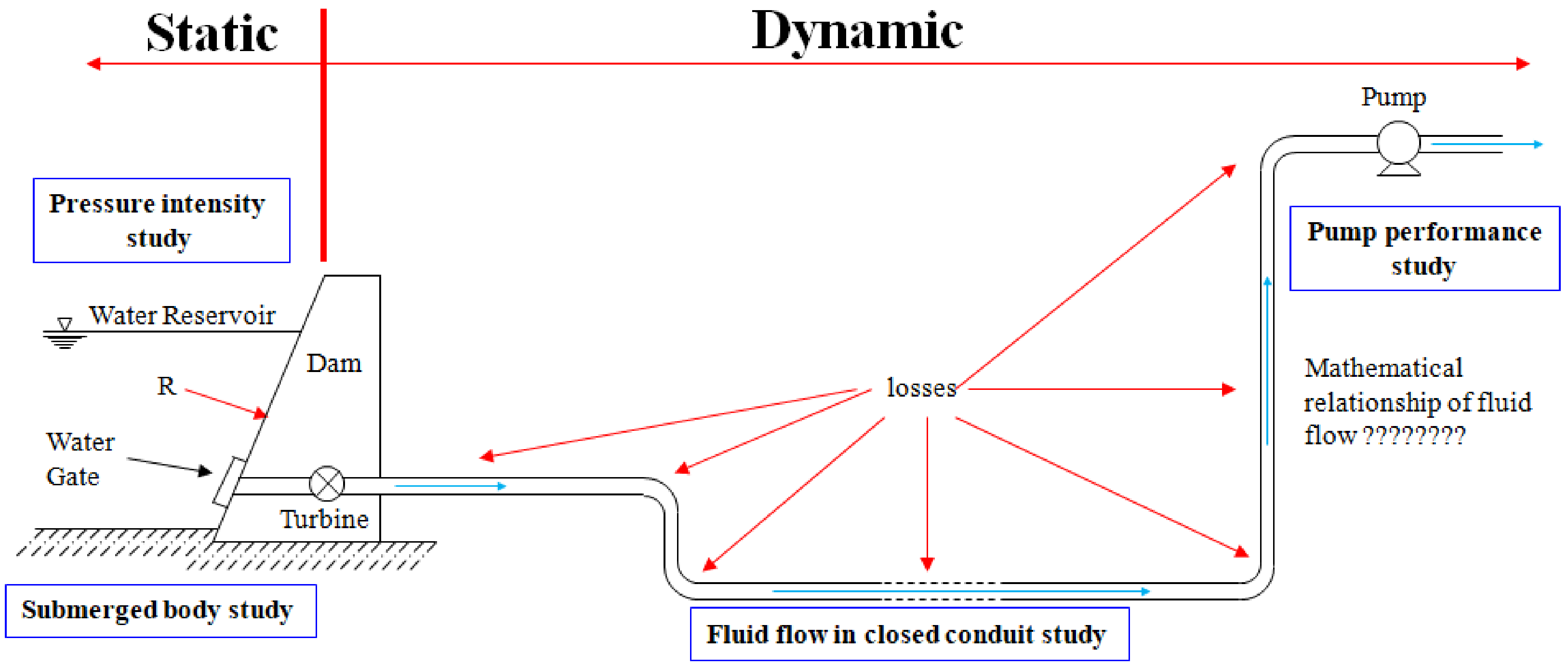
Objectives of the Topic

- Identify the key fluid properties used in the analysis of fluid behaviour.
- List the dimensions and units of physical quantities.
- Explain effects of fluid compressibility.
- Understand the types of flow used in fluids terminology.

Contents

Introduction

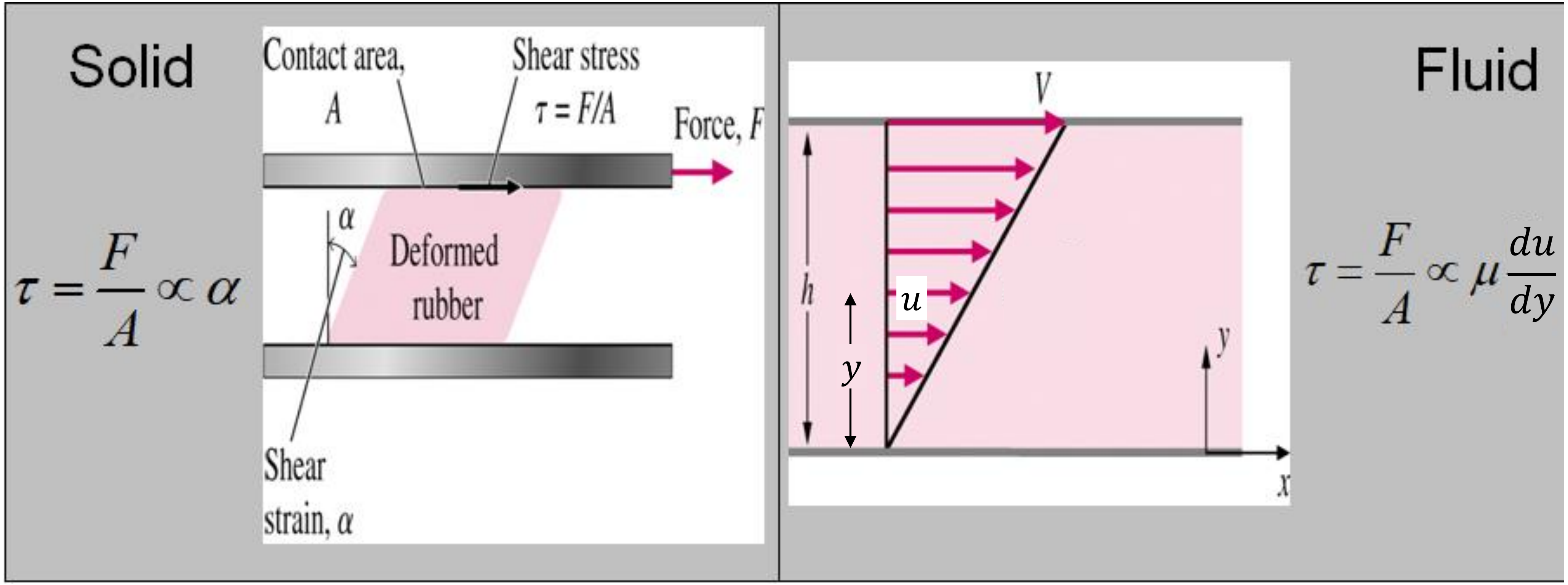
- Branches of applied mechanics
- Study of fluid behavior at rest (static) or/and in motion (dynamic), and the effect of fluid to the boundary either to a solid surface or to another fluid



What if Fluids?

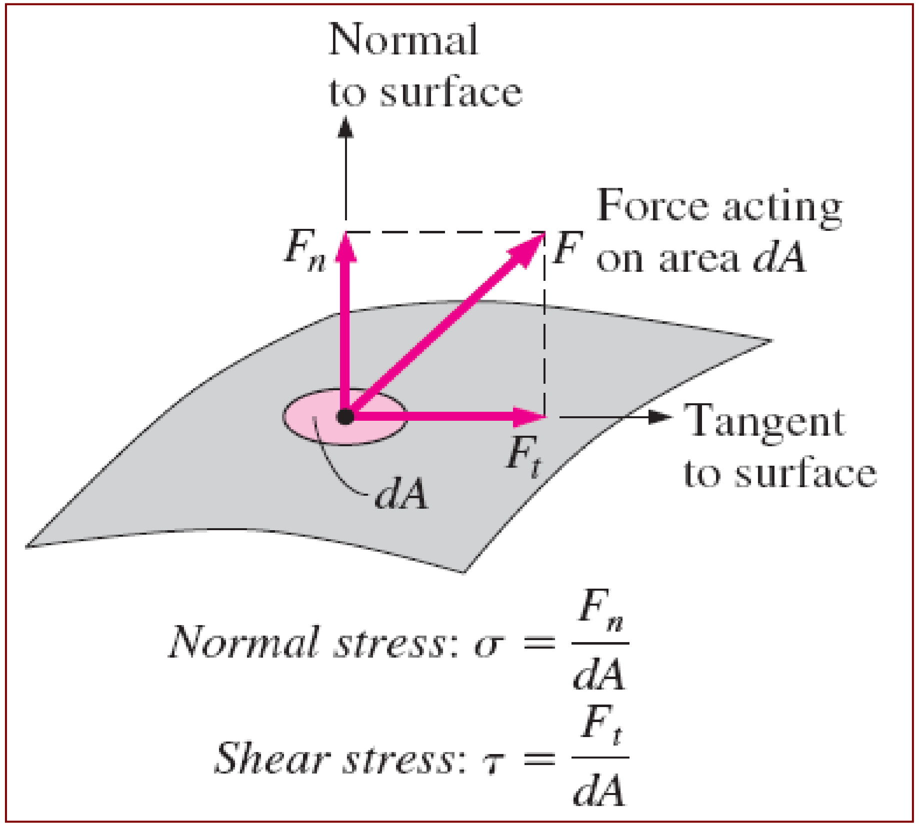
- A **fluid** **deforms continuously** under the influence of a **shear stress**, no matter how small.
- Fluid: A substance in the **liquid** or **gas** phase.
- In solids, stress is **proportional** to **strain** , but in fluids, stress is proportional to **strain rate**.
- **When a constant shear force 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**.

Definition of Fluids



Definition of Fluids

- Stress: Force per unit area
- Normal stress: The normal component of a force acting on a surface per unit area
- Shear stress: The tangential component of a force acting on a surface per unit area



The normal stress and shear stress at the surface of a fluid element

Fluids at rest: shear stress = 0
and **pressure is the only normal stress**

Fluid Category

- **Liquid:**

  Groups of molecules can move relative to each other, but the volume remains relatively constant because of the strong cohesive forces between the molecules

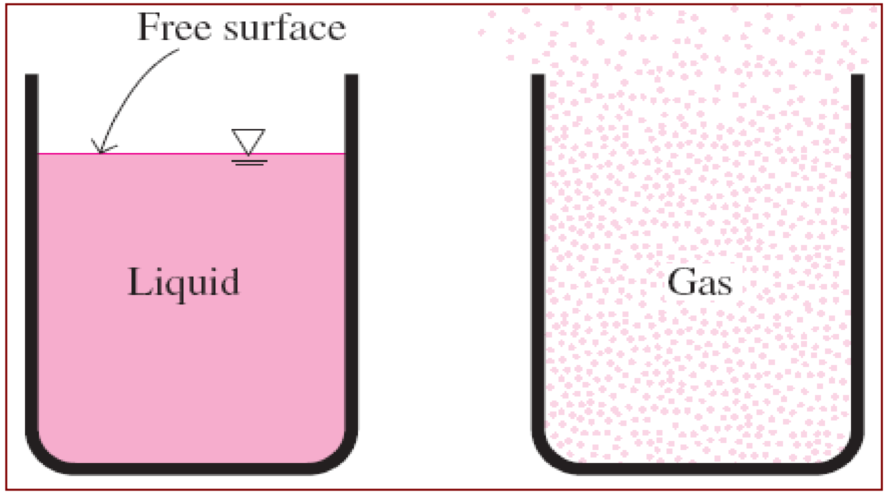
  As a result, a liquid takes the shape of the container it is in, and it forms a free surface in a larger container in a gravitational field

- **Gas:**

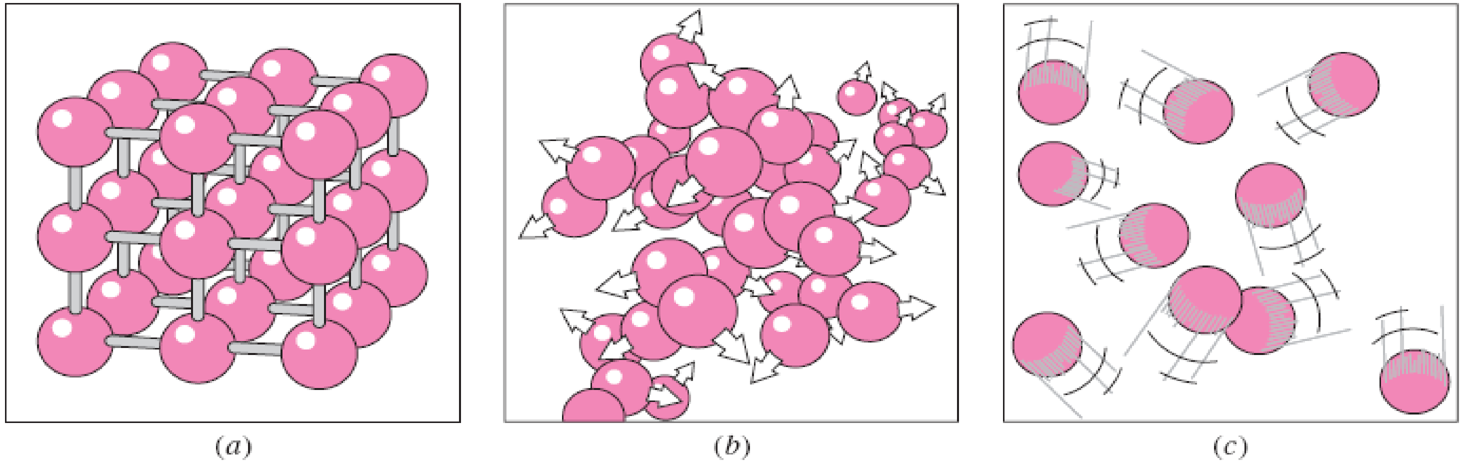
  Expands until it encounters the walls of the container and fills the entire available space. This is because the gas molecules are widely spaced, and the cohesive forces between them are very small

  Unlike liquids, a gas in an open container cannot form a free surface

Fluid Category



Unlike a liquid, a gas does not form a free surface, and it expands to fill the entire available space.



The arrangement of atoms in different phases: (*a*) molecules are at relatively fixed positions in a solid, (*b*) groups of molecules move about each other in the liquid phase, and (*c*) individual molecules move about at random in the gas phase

Fluid Category

- Liquid:

  Difficult to compress and, regarded ➡ **incompressible**

  A given mass of liquid occupies a fixed **V**, irrespective of the size or shape of its container & a free surface is formed if the volume of the container is greater than that of the liquid

- Gas:

  Easy to compress. Changes of **V** with **P** are large, cannot normally be neglected and are related to changes of temperature.

  A given mass of a gas has no fixed **V** and will expand continuously unless restrained by containing vessel. It will completely fill any vessel in which it is place and, therefore, does not form a free surface

Application of Fluid Mechanics

Natural flows and weather
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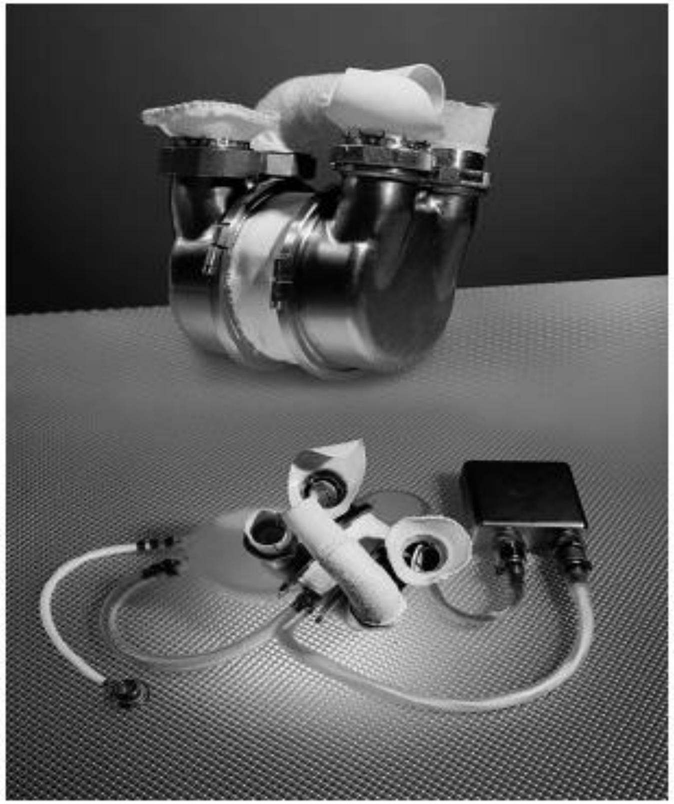

Fluid dynamics is used extensively in the design of artificial hearts. Shown here is the Penn State Electric Total Artificial Heart

Power plants

Application of Fluid Mechanics

Boats
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Aircraft and spacecraft
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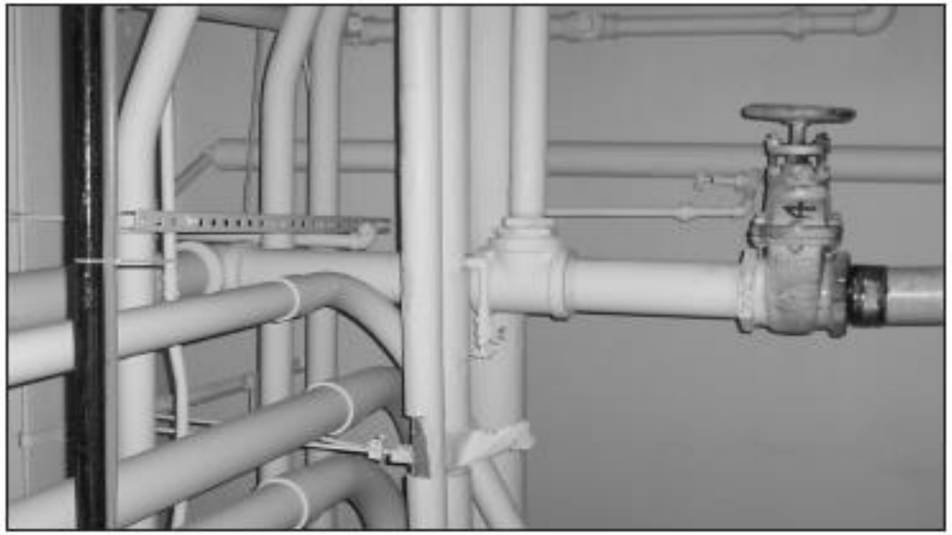
Human body

Cars

Industrial applications

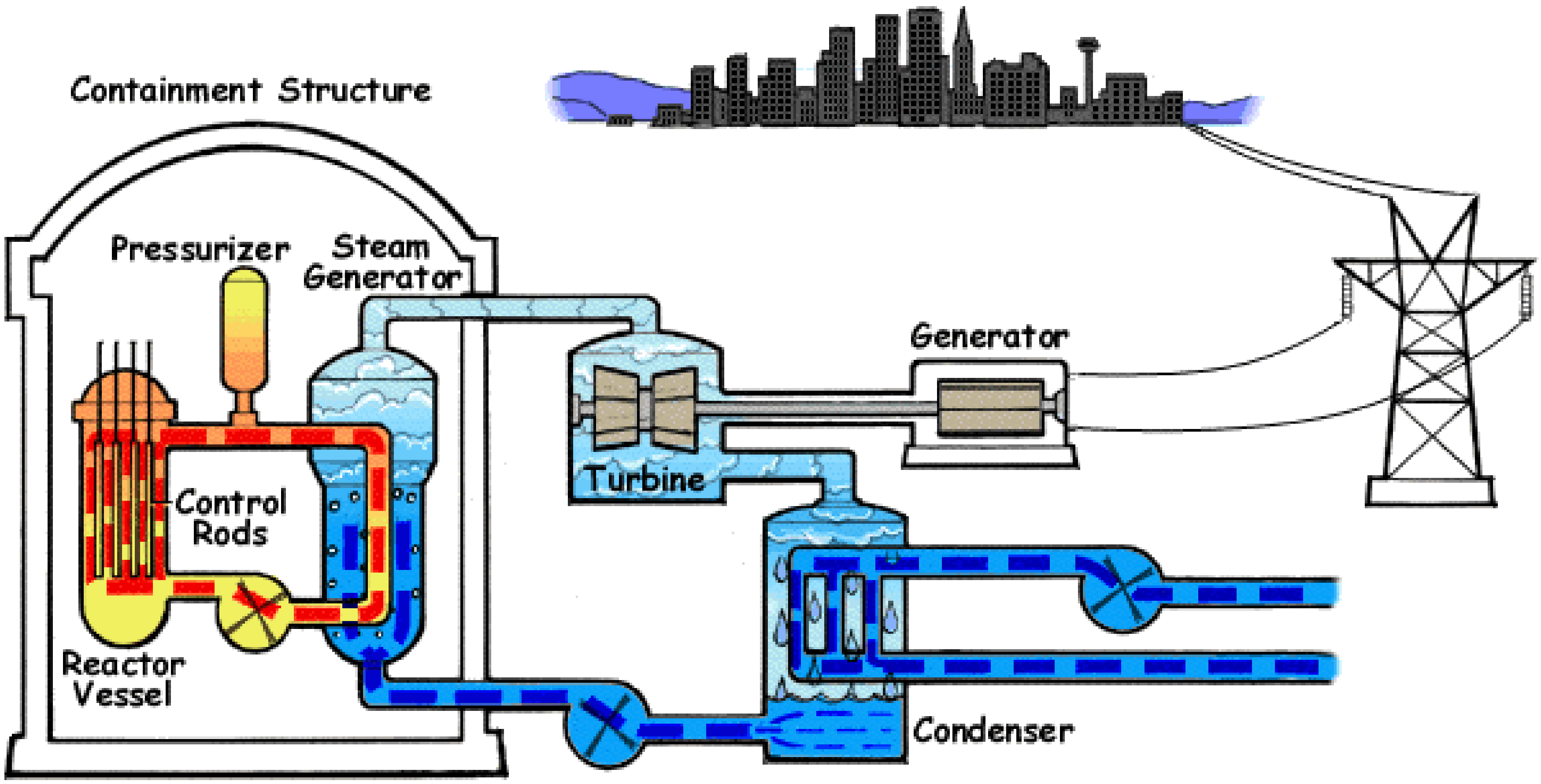
Application of Fluid Mechanics

Wind turbines



Piping and plumbing systems

Application of Fluid Mechanics



System of Unit

- Any phenomenon can be characterized by physical quantity
- The magnitudes assigned to the physical quantities are called units
- Some basic physical quantities such as mass *m*, length *L*, time *t*, and temperature *T* are selected as primary or fundamental quantities, while others such as velocity *V*, energy *E*, and volume *V* are called secondary or derived quantities
- Two system of unit available:

  Metric SI Units (Systéme International d’Unités)

  British Units / Imperial Units / British Commonwealth Units / US Customary / FPS /etc

Notes

1) In solving any engineering issues, it is advisable to use only one system of unit
2) If the system of unit is mixed, change to a singular unit
3) In the examination/test, follow the instruction given

System of Unit

- Introduced by the French ➡ becomes international standard unit
- Widely used in the field of sciences and engineering

Fundamental Dimension	Unit	Notes
length	meter (m)	All other units can be derived from these fundamental units **Example**: Volume = m^3 Acceleration = $m.s^{-2}$ Density = $kg.m^{-3}$
mass	kilogram (kg)	
time	second (s)	
temperature	degree Celsius (^oC) or Kelvin (K) – absolute	

System of Unit

- SI Unit (Systéme International d'Unités)

The SI unit of force, the Newton (N), is derived via Newton's second law:

$$\text{force in N} = M\,(\text{mass in kg}) \text{ X } a\ (\text{acceleration in m/s}^2)$$

$$\therefore \quad 1\text{ N} = 1\text{ kg.m/s}^2$$

Along with the Newton are derived the joule (J) of work

$$\text{where} \quad \rightarrow \quad 1\text{ J} = 1\text{ N.m}$$

$$\text{pressure or stress, pascal (Pa)} \ \rightarrow \ 1\text{ Pa} = 1\text{ N/m}^2$$

System of Unit

- **British Units/ Imperial/ British Commonwealth / US Customary / FPS / etc**

One of the earliest unit used in engineering field particularly in British Commonwealth & USA

Widely used in Petroleum Engineering field

Fundamental Dimension	Unit	Notes
length	foot (ft)	All other units can be derived from these fundamental units **<u>Example</u>**: Volume = ft^3 Acceleration = $ft.sec^{-2}$ Work = lb.ft Pressure = $lb.ft^{-2}$
force	pound of force (lb)	
time	second (s)	
temperature	degree Fahrenheit (^oF) or Rankine (R) – absolute	

[In Petroleum Engineering, the unit of pressure is always stated as psi (lb/in^2)]

System of Unit

- **British Units / Imperial / British Commonwealth / US Customary / FPS / etc**

The unit for mass in this system is ***slug***

Unit Derivation : For a freely falling body in a vacuum at gravity acceleration (**g = 32.2 ft/sec^2** at sea level), and the only force acting is its weight. From Newton's 2nd law

$$\text{force in } \textit{pounds} = \text{mass in } \textit{slug} \text{ X acceleration in ft/sec}^2$$

$$\text{weight in } \textit{pounds} = \text{mass in } \textit{slug} \text{ X g (32.2 ft/sec}^2\text{)}$$

$$\text{mass } M \text{ in } \textit{slug} = \frac{\text{weight W in pounds}}{\text{g(32.2 ft/sec}^2\text{)}}$$

$$\text{From the relation above, } \textit{slug} = \text{lb.sec}^2/\text{ft}$$

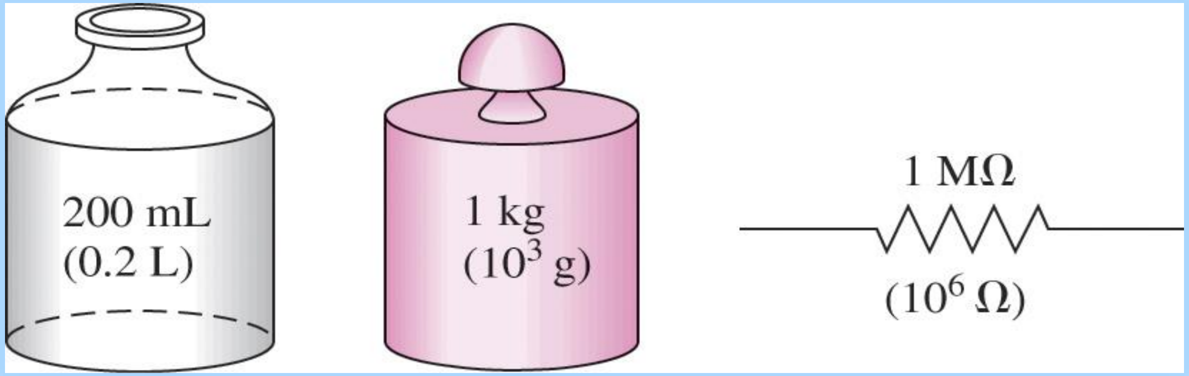
System of Unit

$$1 \text{ lbm} = 0.45359 \text{ kg}$$
$$1 \text{ ft} = 0.3048 \text{ m}$$

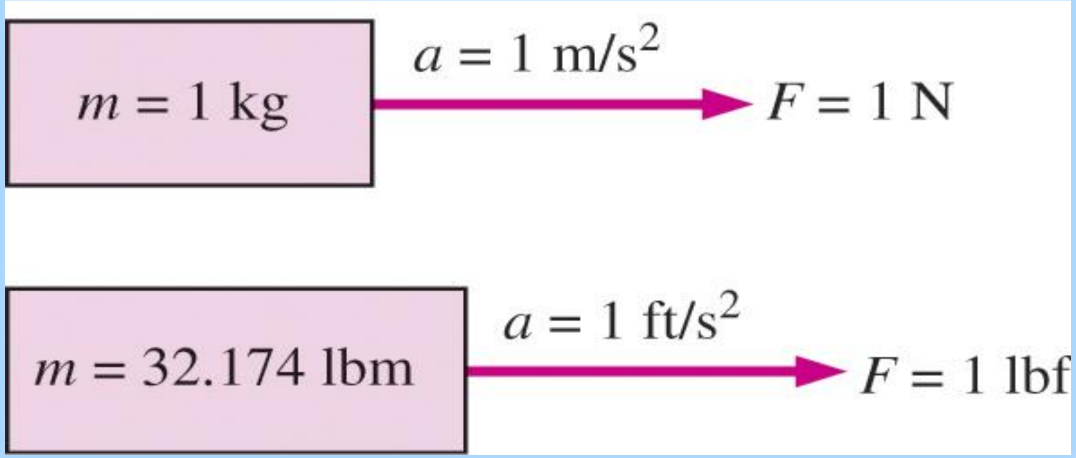
Work = Force × Distance
1 J = 1 N·m
1 cal = 4.1868 J
1 Btu = 1.0551 kJ

$$\text{Force} = (\text{Mass})(\text{Acceleration})$$
$$F = ma$$

$$1 \text{ N} = 1 \text{ kg} \cdot \text{m/s}^2$$
$$1 \text{ lbf} = 32.174 \text{ lbm} \cdot \text{ft/s}^2$$



The SI unit prefixes are used in all branches of engineering



The definition of the force units

Prefixes

Factor	Name	Symbol	Factor	Name	Symbol
10^{24}	yotta	Y	10^{-1}	deci	d
10^{21}	zetta	Z	10^{-2}	centi	c
10^{18}	exa	E	10^{-3}	milli	m
10^{15}	peta	P	10^{-6}	micro	μ
10^{12}	tera	T	10^{-9}	nano	n
10^{9}	giga	G	10^{-12}	pico	p
10^{6}	mega	M	10^{-15}	femto	f
10^{3}	kilo	k	10^{-18}	atto	a
10^{2}	hecto	h	10^{-21}	zepto	z
10^{1}	deka	da	10^{-24}	yocto	y

Properties of Fluids

- Some important properties of fluids are:
    - Mass density
    - Specific weight
    - Specific gravity/relative density
    - Viscosity
    - Compressibility
    - Surface tension
    - Capillary

Properties of Fluids

Density

$$\rho = \frac{m}{V} \qquad (\mathrm{kg/m^3})$$

Specific weight: The weight of a unit volume of a substance

$$\gamma_s = \rho g \qquad (\mathrm{N/m^3})$$

$V = 12\ \mathrm{m^3}$
$m = 3\ \mathrm{kg}$

↓

$\rho = 0.25\ \mathrm{kg/m^3}$
$v = \frac{1}{\rho} = 4\ \mathrm{m^3/kg}$

Density is mass per unit volume.
Specific volume is volume per unit mass

Specific gravity, SG: The ratio of the density of a substance to the density of some standard substance at a specified temperature (usually water at 4 °C)

$$\mathrm{SG} = \frac{\rho}{\rho_{H_2O}}$$

The specific gravity of some substances at 20°C and 1 atm unless stated otherwise

Substance	SG
Water	1.0
Blood (at 37°C)	1.06
Seawater	1.025
Gasoline	0.68
Ethyl alcohol	0.790
Mercury	13.6
Balsa wood	0.17
Dense oak wood	0.93
Gold	19.3
Bones	1.7–2.0
Ice (at 0° C)	0.916
Air	0.001204

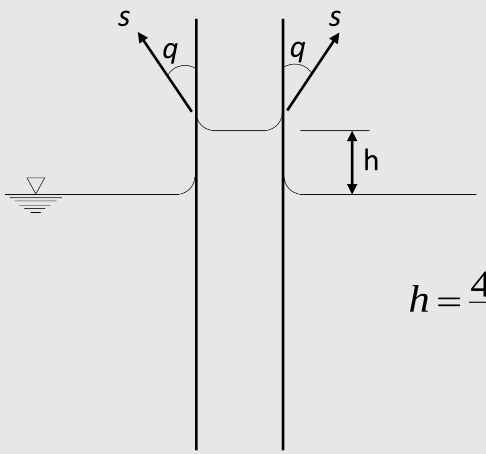
Properties	Description	Unit	
		SI	British
Mass density (*rho* → *ρ*)	Mass per unit volume $\rho = \frac{M}{V}$	kg/m^3	lb-mass/ft^3 (slug/ft^3)
Specific weight (*gamma* → *γ* or *w*)	Weight per unit volume γ or $w = \rho\, g$	N/m^3	lb-weight/ft^3
Specific gravity / relative density (*SG*)	The ratio of the weight of a substance to the weight of an equal volume of water at 4 °C $SG = \frac{w \text{ for substance}}{w \text{ for water @ } 4^{o}C} = \frac{\rho \text{ for substance}}{\rho \text{ for water @ } 4^{o}C}$	Ratio	Ratio
Viscosity	The ability of fluid to resist shearing forces. There are 2 types of viscosity: ○ Dynamic viscosity or absolute viscosity (*mu* → *μ*): Shear force per unit area required to drag one layer of fluid with unit velocity past another layer unit distance away from it in the fluid. $\mu = \frac{\text{shear stress}}{\text{rate of shear strain}}$ ○ Kinematics viscosity (*nu* → *υ*): the ratio of dynamic viscosity to mass density. $\nu = \frac{\mu}{\rho}$	Ns/m^2 (kg/ms) m^2/s	lb.sec/ft^2 ft^2/s

Properties	Description	Unit	
		SI	British
Compressibility (*E*) (*bulk modulus – E*)	○ The ratio of the change in unit pressure to the corresponding volume change per unit volume. ○ For liquids $E = \frac{dp}{-dv/v}$ ○ For isothermal conditions (fixed temperature), the ideal gas law is used. $p_1 v_1 = p_2 v_2 \quad \text{dan} \quad \frac{\gamma_1}{\gamma_2} = \frac{p_1}{p_2} = \text{constant}$ $\text{bulk modulus } E = p$ ○ For adiabatic or isentropic conditions (no heat is exchanged between the fluids and its container), the following equations are used. $p_1 v_1^k = p_2 v_2^k, \left(\frac{\gamma_1}{\gamma_2}\right)^k = \frac{p_1}{p_2} = \text{constant, and } \frac{T_1}{T_2} = \left(\frac{p_2}{p_1}\right)^{(k-1)/k}$ $E = kp$ (k is the ratio of the specific heat at constant pressure to the specific heat at constant volume)	Pa	lb/ft^2

Properties	Description	Unit	
		SI	British
Surface tension (*sigma* → σ)	▪ Within the body of a liquid, a molecule is attracted equally in all directions by other molecules surrounding it. ▪ But at the surface between liquid and air, the upward and downward attractions are unbalanced. The liquid surface behaves as if it were an elastic membrane under tension. ▪ This surface tension is the same at every point on the surface and acts in the plane of the surface normal to any line in the surface. ▪ Surface tension is not affected by the curvature of the surface, and it is constant at a given temperature for the surface of separation of two particular substances. ▪ Increase of temperature causes a decrease of surface tension. ▪ Mathematically $\sigma = \frac{\Delta F}{\Delta L}$	N/m	lb/ft

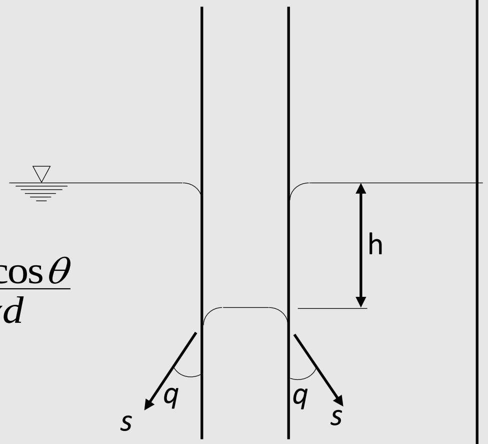
<table>
<tr><th rowspan="2">Properties</th><th rowspan="2">Description</th><th colspan="2">Unit</th></tr>
<tr><th>SI</th><th>British</th></tr>
<tr><td>Capillarity</td><td>

- Rise or fall of liquid in capillary tube (or in porous media) is caused by surface tension and depends on the relative magnitudes of cohesion of the liquid and adhesion of the liquid to the walls of the containing vessel.
- Liquids rise in tubes they wet (adhesion > cohesion) and fall in tubes they do not wet (cohesion > adhesion).



Water

$$h = \frac{4\sigma\cos\theta}{\gamma d}$$



Mercury

- Capillarity is important when using tubes smaller than about 10 mm in diameter.
- This factor is negligible when the capillary tube diameter is larger 12 mm.

</td><td>mm</td><td>in</td></tr>
</table>

Pressure

- Pressure is defined as the amount of force exerted on a unit area of a substance or on a surface

$$\mathbf{P} = \frac{\mathbf{Force}}{\mathbf{Area}} = \frac{\mathbf{F}}{\mathbf{A}}$$

where: P = pressure, Pa ($N.m^{-2}$), $lb.ft^{-2}$, psi ($lb.in^{-2}$), atm
(1 atm = 101,300 Pa = 2,116 $lb.ft^{-2}$), bar (1 bar = 10^5 Pa)

- Differences or gradients in pressure often drive a fluid flow, especially in ducts
- Gauge pressure, P_{gauge}, P_g (pressure which is taken directly from pressure gauge)
- Absolute pressure, $P_{absolute}$, P_a

$$P_a = P_g + P_{atm}$$

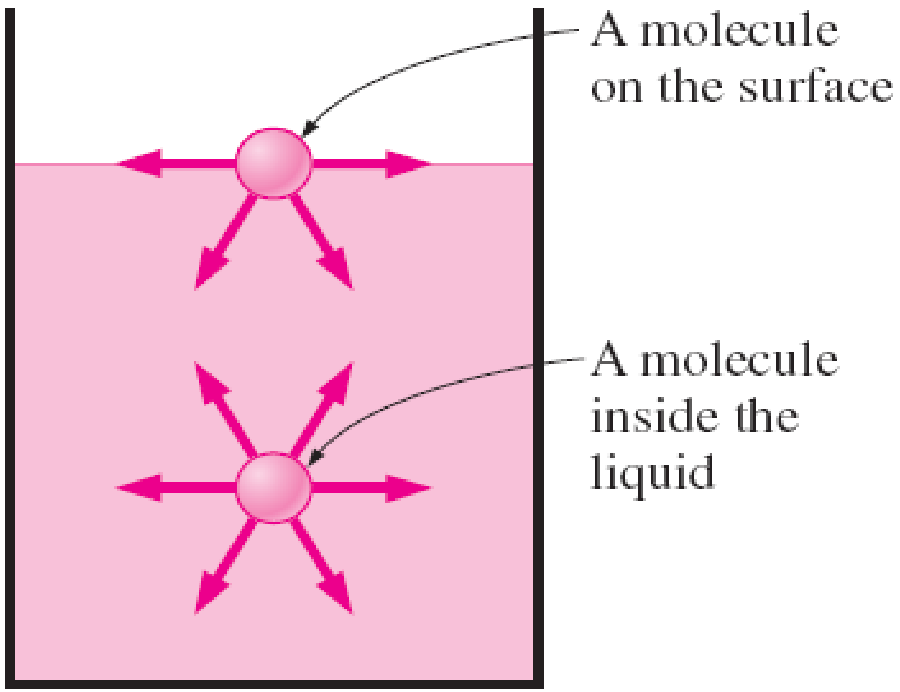
$$(P_{atm} = 14.7 \text{ psi} = 101.325 \text{ kPa})$$

Viscosity

- Define as **a quantity measure of a fluid's resistance to flow** or **a property that represents the internal resistance of a fluid to motion**
- It determines the fluid strain rate that is generated by a given applied shear stress
- Viscosity is due to the internal frictional force that develops between different layers of fluids as they are forced to move relative to each other

Surface Tension

- This effect is also called ***surface energy*** [per unit area] and is expressed in the equivalent unit of $N \cdot m/m^2$
- Within the body of a liquid, a molecule is attracted equally in all directions by other molecules surrounding it
- But at the surface between liquid and air, the upward and downward attractions are unbalanced. The liquid surface behaves as if it were an elastic membrane under tension



Attractive forces acting on a liquid molecule at the surface and deep inside the liquid

Surface Tension

Surface Tension

Fluids Terminology

Some important terminology of fluids are:

- Ideal Fluid
- Real Fluid
- Compressible and Incompressible Flow
- Subsonic and Supersonic Flow
- Pressure
- Work
- Friction

Fluids Terminology

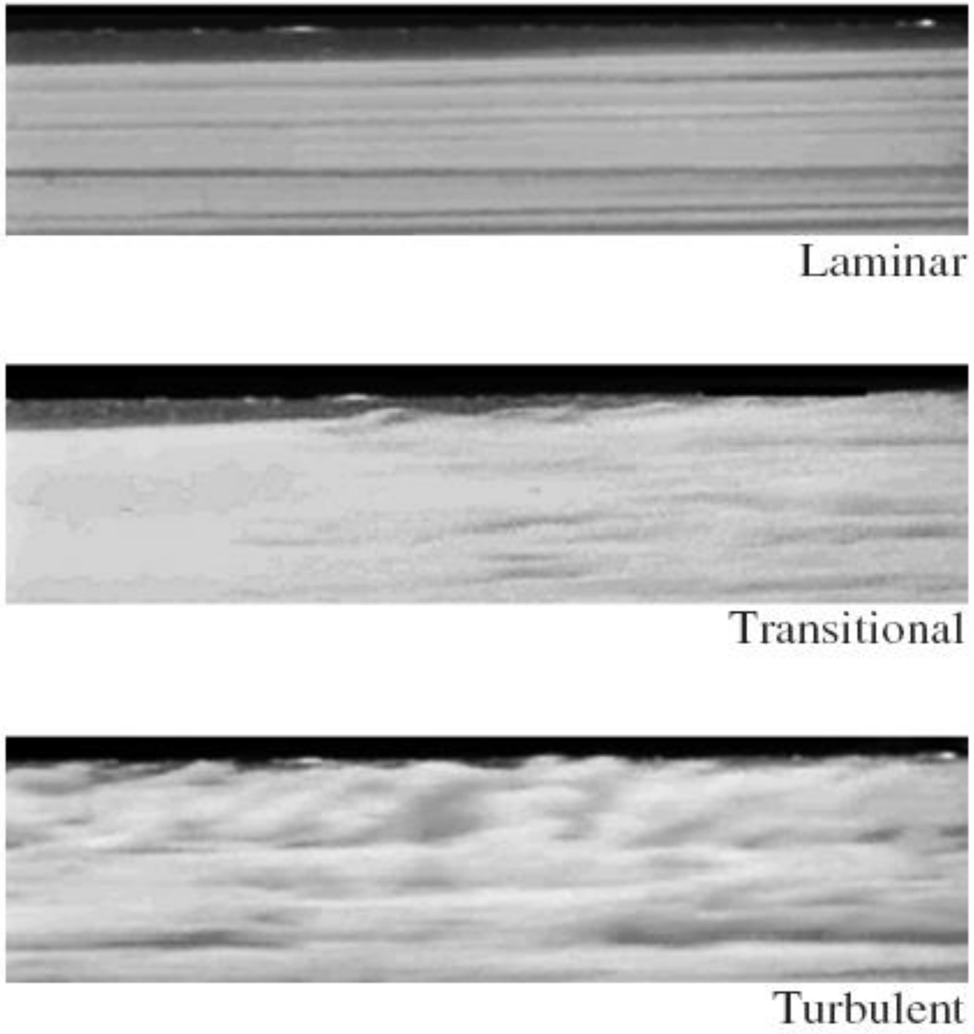
Types	Description
Ideal Fluid	▪ A fluid which is assumed to have no viscosity, no surface tension and no density. ▪ This fluid does not exists, merely an assumption to simplify mathematical analysis.
Real Fluid	▪ A fluid which has viscosity, surface tension and density. ▪ This fluid is really exists.
Compressible & Incompressible Flow	▪ All fluids are compressible → so the ρ will change with p. ▪ But under steady flow conditions and provided that the changes of ρ are small, it is often possible to simplify the analysis of a problem by assuming that the fluid is incompressible and of constant density. ▪ Liquids are relatively difficult to compress, it is usual to treat them as if they were incompressible for all cases of steady flow. ▪ However, in unsteady flow conditions, high Δp can develop and the compressibility of liquids must be taken into account ▪ Gases are easily compressed (except when Δp & $\Delta \rho$ are very small), the effects of compressibility and changes of internal energy must be taken into account.
Subsonic & Supersonic Flow	▪ The elastic forces in fluid is one of important factor to consider in analysing fluid in unsteady state flow. ▪ Elastic forces is measured in Mach number (Ma). ▪ Mach number (Ma) is a ratio of the free stream velocity and the velocity of propagation of pressure waves. $Ma = \frac{Uo}{c}$, $Ma < 1$ subsonic flow, $Ma > 1$ supersonic flow

Properties	Description	Unit	
		SI	British
Pressure (p)	• Force per unit area $p = \frac{\text{Force}}{\text{Area}} = \frac{F}{A}$ • Types of Pressure 1. Gauge pressure, p_{gauge} , p_g (pressure which is taken directly from pressure gauge) 2. Absolute pressure , $p_{absolute}$, p_a $p_a = p_g + p_{atm}$ $(p_{atm} = 14.7 \text{ psi} = 101.325 \text{ kPa})$	N/m (Pa) N/m (Pa)	lb/ft^2 (psi/psig) lb/ft^2 (psi/psia)
Work	• (Exerted Force) X Distance N.m = Joule or Hp (horsepower)	Joule	Hp
Friction (f)	• All fluids have their own viscosity and it will create shear stress under flow conditions. • Shear stress will create friction force which will change pressure and kinetic energy to heat energy. • This action will generate pressure losses and it will change the flow rate in one system. • Therefore, energy losses due to friction demand more energy to transfer the fluid from one point to one point because the energy has been change to heat energy.	Dimensi- onless	Dimensi- onless

Laminar and Turbulent Flow

- Laminar flow: The highly ordered fluid motion characterized by smooth layers of fluid. The flow of high-viscosity fluids such as oils at low velocities is typically laminar.
- Turbulent flow: The highly disordered fluid motion that typically occurs at high velocities and is characterized by velocity fluctuations. The flow of low-viscosity fluids such as air at high velocities is typically turbulent.
- Transitional flow: A flow that alternates between being laminar and turbulent.
- The determination of the types of flow (laminar or turbulent) is based on **Reynold No. , Re**.

Laminar and Turbulent Flow

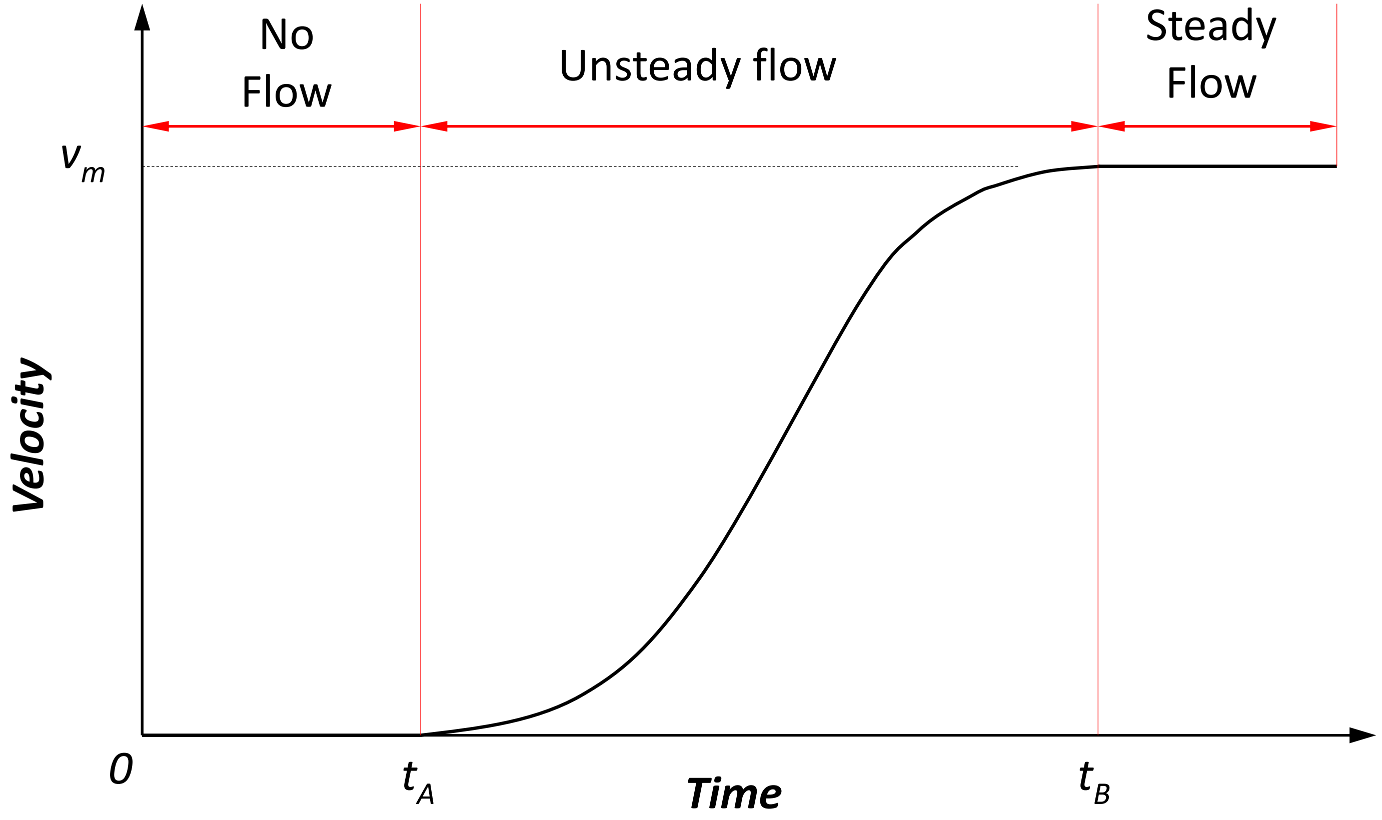


Laminar, transitional, and turbulent flows

Types of Flow

- Flow is described ***uniform*** if the *v* at a given *t* is the same in magnitude and direction at every point in the fluid.
- If, at the given instant, the *v* changes from point to point, the flow is described as ***non-uniform***.
- In practice, when a fluid flows past a solid boundary, there will be variations of velocity in the region close to the boundary. However, if the size and shape of the cross-section of the stream of fluid is constant, the flow is considered to be uniform.

Types of Flow



- A steady flow is one in which the *v*, *p* & *A* of the stream may vary from point to point but do not change with *t.*
- If, at a given point, conditions do change with *t*, the flow is described as unsteady

Types of Flow

In practice, there will always be slight variations of *v* & *p*, but, if the average values are constant, the flow is considered to be steady. There are, therefore, 4 possible types of flow:

1. **Steady uniform flow**
   Conditions do not change with position (*x*) or time (*t*). The velocity (*v*) & cross-sectional area (*A*) of the stream of fluid are the same at each cross-section. (e.g. flow of liquid through a pipe of uniform diameter (*D*) running completely full at constant velocity (*v*)).

D = constant

$$\frac{dv}{dt} = 0, \frac{dv}{dx} = 0$$

2. **Steady non-uniform flow**
   Conditions change from point to point but not with *t*. The *v* & *A* of the stream may vary from cross-section to cross-section, but, for each cross-section, they will not vary with *t*. (e.g. flow of a liquid at a constant rate through a tapering pipe running completely full.

$D \neq \text{constant}$

$$\frac{dv}{dt} = 0, \frac{dv}{dx} \neq 0$$

Types of Flow

3. **Unsteady uniform flow**
   At a given instant of *t*, the *v* at every point is the same, but this *v* will change with *t* . (e.g. accelerating flow of a liquid through a pipe of uniform *D* running full (such as would occur when a pump is started up)).

$$\frac{dv}{dx} = 0, \frac{dv}{dt} \neq 0$$

4. **Unsteady non-uniform flow**
   The *A* & *v* vary from point to point and also change with *t*. (e.g. a bubble traveling along a channel of liquid).

$$\frac{dv}{dx} \neq 0, \frac{dv}{dt} \neq 0$$

THANK YOU

Stay safe!