CHAPTER-1
BASIC CONCEPTS AND PROPERTIES OF FLUIDS

BASIC CONCEPTS

- *Mechanics* is the oldest physical science that deals with both stationery and moving boundaries under the influence of forces. The branch of the mechanics that deals with bodies at rest is called *statics* while the branch that deals with bodies in motion is called *dynamics*.
- *Fluid Mechanics* is the science that deals with behavior of fluids at rest (fluid statics) or in motion (fluid dynamics) and the interaction of fluids with solids or other fluids at the boundaries.
- A substance in liquid / gas phase is referred as ‘fluid’. Distinction between a solid & a fluid is made on the basis of substance’s ability to resist an applied shear (tangential) stress that tends to change its shape. A solid can resist an applied shear by deforming its shape whereas a fluid deforms continuously under the influence of shear stress, no matter how small is its shape. In solids, stress is proportional to strain, but in fluids, stress is proportional to ‘strain rate.’

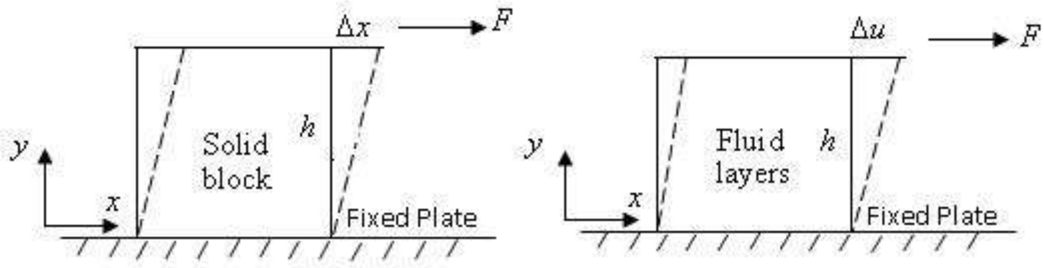

Fig. 1.1.1: Illustration of solid and fluid deformation.

Referring to Fig. 1.1.1, the shear modulus of solid (S) and coefficient of viscosity $(\propto)$ for fluid can defined in the following manner;

$$S = \frac{\text{Shear stress}}{\text{Shear strain}} = \frac{(F/A)}{(\Delta x/h)} \;;\quad \propto = \frac{\text{Shear stress}}{\text{Shearstrain rate}} = \frac{(F/A)}{(\Delta u/h)} \qquad (1.1.1)$$

Here, the shear force(F) is acting on the certain cross-sectional area (A), h is the height of the solid block / height between two adjacent layer of the fluid element, Δx is the elongation of the solid block and Δu is the velocity gradient between two adjacent layers of the fluid.

- Although liquids and gases share some common characteristics, they have many distinctive characteristics on their own. It is easy to compress a gas whereas liquids are incompressible. A given mass of the liquid occupies a fixed volume, irrespective of the size and shape of the container. A gas has no fixed volume and will expand continuously unless restrained by the containing vessel. For liquids a free surface is formed in the volume of the container is greater than that of the liquid. A gas will completely fill any vessel in which it is placed and therefore, does not have a free surface.

Dimension and Unit

A *dimension* is the measure by which a physical variable is expressed quantitatively and the *unit* is a particular way of attaching a number to the quantities of dimension. All the properties of fluid are assigned with certain unit and dimension. Some basic dimensions such as mass (M), length (L), time (T) and temperature (θ) are selected as *Primary/Fundamental* dimensions/unit. While others such as velocity, volume is expressed in terms of primary dimensions and is called as *secondary/derived* dimensions/unit. In this particular course, SI (Standard International) system of units and dimension will be followed to express the properties of fluid.

Fluid as Continuum

Fluids are aggregations of molecules; widely spaced for a gas and closely spaced for liquids. Distance between the molecules is very large compared to the molecular diameter. The number of molecules involved is immense and the separation between them is normally negligible. Under these conditions, fluid can be treated as *continuum* and *the properties at any point can be treated as bulk behavior of the fluids*.

For the continuum model to be valid, the smallest sample of matter of practical interest must contain a large number of molecules so that meaningful averages can be calculated. In the case of air at sea-level conditions, a volume of 10^{-9} mm^3 contains 3×10^7 molecules. In engineering sense, this volume is quite small, so the continuum hypothesis is valid.

In certain cases, such as, very-high-altitude flight, the molecular spacing becomes so large that a small volume contains only few molecules and the continuum model fails. For all situations in these lectures, the continuum model will be valid.

Properties of Fluid

Any characteristic of a system is called *property*. It may either be *intensive* (mass independent) or *extensive* (that depends on size of system). The state of a system is described by its properties. The number of properties required to fix the state of the system is given by *state postulates*. Most common properties of the fluid are:

1. Pressure (p) : It is the normal force exerted by a fluid per unit area. More details will be available in the subsequent section (Lecture 02). In SI system the unit and dimension of pressure can be written as, N/m^2 and $M\ L^{-1}\ T^{-2}$, respectively.

2. Density: The density of a substance is the quantity of matter contained in unit volume of the substance. It is expressed in three different ways; mass density $\rho = \dfrac{\text{mass}}{\text{volume}}$, specific weight (ρg) and relative density/specific gravity $SG = \dfrac{\rho}{\rho_{water}}$. The units and dimensions are given as,

For mass density;	Dimension: $M\ L^{-3}$	Unit: kg/m^3
For specific weight;	Dimension: $M\ L^{-2}\ T^{-2}$	Unit: N/m^3

The standard values for density of water and air are given as $1000 kg/m^3$ and $1.2\ kg/m^3$, respectively. Many a times the reciprocal of mass density is called as specific volume (ν) .

3**. Temperature** (T): It is the measure of hotness and coldness of a system. In thermodynamic sense, it is the measure of internal energy of a system. Many a times, the temperature is expressed in centigrade scale (°C) where the freezing and boiling point of water is taken as 0°C and 100°C, respectively. In SI system, the temperature is expressed in terms of absolute value in Kelvin scale (K = °C+ 273).

4. Viscosity : When two solid bodies in contact, move relative to each other, a

friction force develops at the contact surface in the direction opposite to motion. The situation is similar when a fluid moves relative to a solid or when two fluids move relative to each other. The property that represents the internal resistance of a fluid to motion (i.e. *fluidity*) is called as *viscosity*. The fluids for which the rate of deformation is proportional to the shear stress are called Newtonian fluids and the linear relationship for a one-dimensional system is shown in Fig. 1.1.2. The shear stress (τ) is then expressed as,

$$\tau = \propto \frac{du}{dy} \tag{1.1.2}$$

where, $\frac{du}{dy}$ is the shear strain rate and $\propto$ is the dynamic (or absolute) viscosity of the fluid.

The dynamic viscosity has the dimension M $L^{-1}T^{-1}$ and the unit of kg/m.s (or, N.s/m^2 or Pa.s) . A common unit of dynamic viscosity is *poise* which is equivalent to 0.1 Pa.s. Many a times, the ratio of dynamic viscosity to density appears frequently and this ratio is given by the name kinematic viscosity $\nu = \frac{\propto}{\rho}$. It has got the dimension of L^2 T^{-1} and unit of *stoke* (1 stoke = 0.0001 m^2/s). Typical values of kinematic viscosity of air and water at atmospheric temperature are 1.46 x 10^{-5} m^2/s and 1.14 x 10^{-6} m^2/s, respectively.

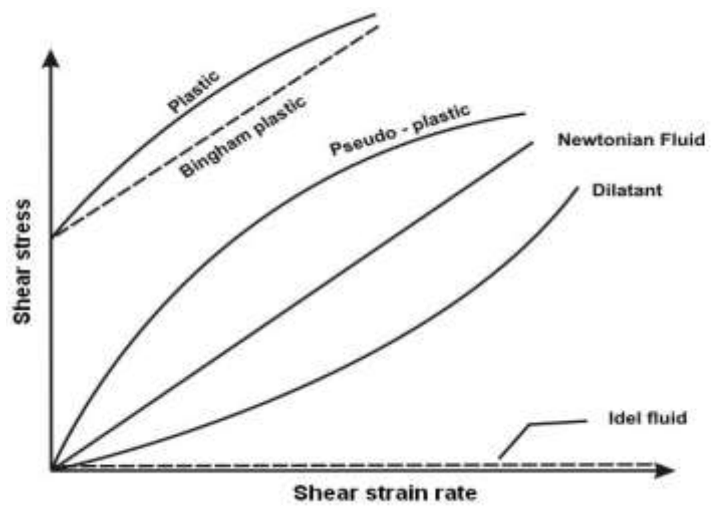

Fig. 1.1.2: Variation of shear stress with rate of deformation.

In general, the viscosity of a fluid mainly depends on temperature. For liquids, the viscosity decreases with temperature and for gases, it increases with temperature. Sutherland's correlation is used to determine viscosity of gases as a function of temperature.

$$\frac{\propto}{\propto_0} = \left(\frac{T}{T_0}\right)^{\frac{3}{2}} \frac{T_0 + S}{T + S} \tag{1.1.3}$$

For air, the reference value of viscosity $\propto_0 = 1.789 \cdot 10^{-5}$ kg/m.s at $T_0 = 288$ K and $S = 110$ K . In the case of liquids, the viscosity is approximated as below;

$$\ln\frac{\propto}{\propto_0} = a + b\frac{T_0}{T} + c\left(\frac{T_0}{T}\right)^2 \tag{1.1.4}$$

For water at $T_0 = 273$ K, $\propto_0 = 0.001792$ kg/m.s, $a = -1.94, b = -4.8, c = 6.74$.

5. Thermal Conductivity (k) : It relates the rate of heat flow per unit area (q) to the temperature gradient $\frac{dT}{dx}$ and is governed by Fourier Law of heat conduction i.e.

$$q = -k\frac{dT}{dx} \tag{1.1.5}$$

In SI system the unit and dimension of pressure can be written as, W/m.K and M LT$^{-3}\theta^{-1}$, respectively. Thermal conductivity varies with temperature for liquids as well as gases in the same manner as that of viscosity. The reference value of thermal conductivity (k_0) for water and air at reference temperature is taken as, 0.6 W/m.K and 0.025 W/m.K, respectively.

6. Coefficient of compressibility/Bulk modulus (E_v) : It is the property of that fluid that represents the variation of density with pressure at constant temperature. Mathematically, it is represented as,

$$E_v = -v\left(\frac{\partial p}{\partial v}\right)_T = \rho\left(\frac{\partial \rho}{\partial T}\right)_T \tag{1.1.6}$$

In terms of finite changes, it is approximated as,

$$E_v = \frac{(\Delta v / v)}{\Delta T} = -\frac{(\Delta \rho / \rho)}{\Delta T} \tag{1.1.7}$$

It can be shown easily that E_v for an ideal gas at a temperature p is equal to its absolute pressure (N/m^{-2}).

7. Coefficient of volume expansion (β) : It is the property of that fluid that represents the variation of density with temperature at constant pressure. Mathematically, it is represented as,

$$\beta = \frac{1}{v}\left(\frac{\partial v}{\partial T}\right)_p = -\frac{1}{\rho}\left(\frac{\partial \rho}{\partial T}\right)_p \tag{1.1.8}$$

In terms of finite changes, it is approximated as,

$$\beta = \frac{(\Delta v / v)}{\Delta T} = -\frac{(\Delta \rho / \rho)}{\Delta T} \tag{1.1.9}$$

It can be shown easily that E_v for an ideal gas at a temperature T is equivalent to inverse of the absolute temperature.

8. Specific heats: It is the amount of energy required for a unit mass of a fluid for unit rise in temperature. Since the pressure, temperature and density of a gas are interrelated, the amount of heat required to raise the temperature from T_1 to T_2 depends on whether the gas is allowed to expand during the process so that the energy supplied is used in doing the work instead of raising the temperature. For a given gas, two specific heats are defined corresponding to the two extreme conditions of constant volume and constant pressure.

(a) Specific heat at constant volume (c_v)

(b) Specific heat at constant pressure (c_p)

The following relation holds good for the specific heat at constant volume and constant pressure. For air ; c_p = 1.005 KJ/kg.K c_v = 0.718 KJ/kg. K

$$c_p - c_v = R; \quad c_p = \frac{\gamma R}{\gamma - 1}; \; c_v = \frac{R}{\gamma - 1} \tag{1.1.10}$$

9. Speed of sound (c): An important consequence of compressibility of the fluid is that the disturbances introduced at some point in the fluid propagate at finite velocity. The velocity at which these disturbances propagate is known as "acoustic velocity/speed of sound". Mathematically, it is represented as below;

$$c = \sqrt{\frac{dp}{d\rho}} = \sqrt{\frac{E_v}{\rho}} \tag{1.1.11}$$

In an isothermal process,

$$E_v = p \quad \Rightarrow c = \sqrt{\frac{p}{\rho}} \tag{1.1.12}$$

$c = \sqrt{RT}$ (for an ideal gas medium)

In isentropic process,

$$E_v = \gamma p \;\Rightarrow c = \sqrt{\frac{\gamma p}{\rho}} \tag{1.1.13}$$

$c = \sqrt{\gamma RT}$ (for an ideal gas medium)

10. Vapour pressure (p_v) : It is defined as the pressure exerted by its vapour in phase equilibrium with its liquid at a given temperature. For a pure substance, it is same as the saturation pressure. In a fluid motion, if the pressure at some location is lower than the vapour pressure, bubbles start forming. This phenomenon is called as cavitation because they form cavities in the liquid.

11. Surface Tension (σ) : When a liquid and gas or two immiscible liquids are in contact, an unbalanced force is developed at the interface stretched over the entire fluid mass. The intensity of molecular attraction per unit length along any line in the surface is called as surface tension. For example, in a spherical liquid droplet of radius

(r), the pressure difference (Δp) between the inside and outside surface of the droplet is given by,

$$\Delta p = \frac{2\sigma}{r} \tag{1.1.14}$$

In SI system the unit and dimension of pressure can be written as, N/m and MT^{-2} , respectively.

State Relations for Gases and Liquids

All gases at high temperatures and low pressures are in good agreements with 'perfect gas law' given by,

$$p = \rho RT = \rho \frac{\bar{R}}{M} T \tag{1.1.15}$$

where, R is the characteristic gas constant, $\bar{R}$ is the universal gas constant and M is the molecular weight.

Liquids are nearly incompressible and have a single reasonable constant specific heat. Density of a liquid decreases slightly with temperature and increases moderately with pressure. Neglecting the temperature effect, an empirical pressure- density relation is expressed as,

$$\frac{p}{p_a} = (B+1)\left(\frac{\rho}{\rho_a}\right)^n - B \tag{1.1.16}$$

Here, B and n are the non-dimensional parameters that depend on the fluid type and vary slightly with the temperature. For water at 1 atm, the density is 1000 kg/m^3 and the constants are taken as, B = 3000 and n = 7

Classifications of Fluid Flows

Some of the general categories of fluid flow problems are as follows;

1. Viscous and Inviscid flow: The fluid flow in which frictional effects become signification, are treated as viscous flow. When two fluid layers move relatively to each other, frictional force develops between them which is quantified by the fluid property ‘viscosity’. Boundary layer flows are the example viscous flow. Neglecting the viscous terms in the governing equation, the flow can be treated as inviscid flow.

2. Internal and External flow: The flow of an unbounded fluid over a surface is treated as ‘external flow’ and if the fluid is completely bounded by the surface, then it is called as ‘internal flow’. For example, flow over a flat plate is considered as external flow and flow through a pipe/duct is internal flow. However, in special cases, if the duct is partially filled and there is free surface, then it is called as open channel flow. Internal flows are dominated by viscosity whereas the viscous effects are limited to boundary layers in the solid surface for external flows.

3. Compressible and Incompressible flow: The flow is said to be ‘incompressible’ if the density remains nearly constant throughout. When the density variation during a flow is more than 5% then it is treated as ‘compressible’. This corresponds to a flow Mach number of 0.3 at room temperature.

4. Laminar and Turbulent flow: The highly ordered fluid motion characterized by smooth layers of fluid is called ‘Laminar Flow’, e.g. flow of highly viscous fluids at low velocities. The fluid motion that typically occurs at high velocities is characterized by velocity fluctuations are called as ‘turbulent.’ The flow that alternates between being laminar & turbulent is called ‘transitional’. The dimensionless number i.e. Reynolds number is the key parameter that determines whether the flow is laminar or turbulent.

5. Steady and Unsteady flow: When there is no change in fluid property at point with time, then it implies as steady flow. However, the fluid property at a point can also vary with time which means the flow is unsteady/transient. The term ‘periodic’ refers to the kind of unsteady flows in which the flow oscillates about a steady mean.

5. Natural and Forced flow: In a forced flow, the fluid is forced to flow over a surface by external means such as a pump or a fan. In other case (natural flow), density

difference is the driving factor of the fluid flow. Here, the buoyancy plays an important role. For example, a warmer fluid rises in a container due to density difference.

6. One/Two/Three dimensional flow: A flow field is best characterized by the velocity distribution, and thus can be treated as one/two/three dimensional flow if velocity varies in the respective directions.