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Mechanical Engineering Department

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Module-1: Introduction

Fluid Mechanics-I: ME181403

Introduction: Fluid mechanics is a branch of engineering/science which deals with the study of moving and stationary fluids. We are surrounded by fluids like air, water and blood, they move inside our body without their flow we cannot survive for a moment. A few examples of applications of fluid mechanics are in the field of transportation, power generation and conversion, materials processing and manufacturing, food production, and civil infrastructure.

Definition of fluid: A fluid is a matter/substance that deforms continuously under an applied shear stress. A fluid can be either a liquid or a gas. Any shear stress applied to a fluid, no matter how small, will result in motion of that fluid. That is why fluids cannot have a preferred/definite shape. On the other hand, a solid does not deform continuously under an applied shear stress, and does have a preferred shape to which it returns when the applied forces on it are withdrawn.

Let us consider a rectangular element of a solid ABCD as shown in Figure 1(a). Under the action of a shear force *F* the element takes the shape ABC$^{/}$D$^{/}$. If the solid is perfectly elastic, it returns to its preferred shape ABCD when the shear force *F* is removed.

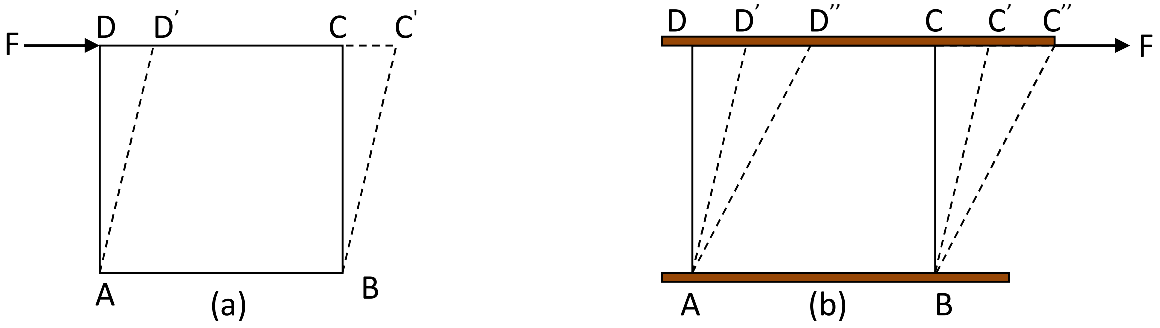


Figure 1: Deformation of solid and fluid elements under a constant externally applied shear force.

In contrast, a fluid deforms continuously under the action of a shear force, however small. Thus, the element of the fluid ABCD confined between the parallel plates (see Figure 1(b)) successively deforms to shapes such as ABC$^{/}$D$^{/}$ and ABC$^{//}$D$^{//}$, and keep deforming as long as the force *F* is maintained on the upper plate.

Dimension and Units: For mechanical systems, the units of all physical variables can be expressed in terms of the units of four basic variables, namely, mass, length, time and temperature. The units for other variables can be derived from these basic units. The most commonly used unit is the international system of units and referred to as SI (or MKS) units. The basic units of this system are *meter* for length, *kilogram* for mass, *second* for time. Some of the common variables used in fluid mechanics, and their SI units are listed in Table 1.

Table 1: SI units

Quantity	Name of unit	Symbol	Equivalent
Length	Meter	m	
Mass	Kilogram	kg	
Time	Second	s	
Temperature	Kelvin	K	
Frequency	Hertz	Hz	s^{-1}
Force	Newton	N	$kg\ m\ s^{-2}$
Pressure	Pascal	Pa	$N\ m^{-2}$
Energy	Joule	J	$N\ m$
Power	Watt	W	$J\ s^{-1}$

Concept of Continuum: A fluid is composed of a large number of molecules in constant motion undergoing collisions with each other, and is therefore discontinuous or discrete at the most microscopic scales. In principle, it possible to study the mechanics of a fluid by studying the motion of the molecules themselves, as is done in kinetic theory or statistical mechanics. However, we are generally interested in the average manifestation of the molecular motion. For example, forces are exerted on the boundaries of a fluid's container due to the constant bombardment of the fluid molecules. The statistical average of these collision forces per unit area is called pressure and is a macroscopic property.

When the molecular density of the fluid and the size of the region of interest are large enough, such average properties are sufficient for the explanation of macroscopic phenomena and the discrete molecular structure of matter may be ignored and replaced with a continuous distribution, is known as *continuum*.

The continuum approximation is valid when the Knudsen number, $KN = l/L$, where l is the mean free path of the molecules and L is the length scale of interest (a body length, pipe diameter through which a fluid flows, etc.) is much less than unity ($l/L << 1$).

No-Slip Condition of Viscous Liquids: A liquid in direct contact with a solid surface sticks to the surface due to the viscous effects, and there is no slip of the liquid on the solid surface. This condition is known as the *no-slip condition*.

Classification of Fluids: Fluids may be classified broadly into the following categories:

1. *Ideal Fluid*: A fluid which is incompressible and having no viscosity is known as an ideal fluid. In practice, all fluids are compressible to certain extent and viscous, therefore ideal fluid is only an imaginary fluid.

2. *Real Fluid*: A fluid which possesses viscosity is known as a real fluid. In practice, all the fluids are real.

3. *Incompressible Fluid*: A fluid in which the density does not change with change in external force or pressure and time is known as an incompressible fluid. All liquids are considered in this category.

4. *Compressible Fluid:* A fluid in which the density changes with change in external force or pressure and time is known as a compressible fluid. All gases are considered in this category.

5. *Newtonian Fluid*: A real fluid in which shear stress is directly proportional to the rate of shear strain or velocity gradient is known as a Newtonian fluid. Examples are air, water, gasoline etc.

6. *Non-Newtonian Fluid*: A real fluid in which shear stress is not directly proportional to the rate of shear strain or velocity gradient is known as a non-Newtonian fluid. Example is blood.

Properties of Fluids: The following are the properties of fluids:

1. *Mass Density (ρ)*: It is the mass of the fluid per unit volume. If m and V denote the mass and volume of the fluid,

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

2. *Specific Volume*: It defined as volume per unit mass. This means, it is the reciprocal of mass density or simply density.

3. *Specific Weight*: It is defined as the weight per unit volume of a fluid. The specific weight of a fluid is generally denoted by γ (lowercase Greek letter gamma). Just as mass has a weight $W = mg$, density and specific weight are simply related by gravity as follows:

$$\gamma = \rho g$$

4. *Specific Gravity (SG)*: It is defined as the ratio of the density of a fluid to the density of some standard fluid at a given/specified temperature (usually water for liquids at 4°C, for which the density of water $\rho_w = 1000\ kg/m^3$, and for gas, it is air). That is specific gravity for liquid SG_l,

$$SG_l = \frac{\rho}{\rho_w}$$

And, specific gravity for gas SG_g,

$$SG_g = \frac{\rho}{\rho_a}$$

Note that the specific gravity of a fluid is a dimensionless quantity. It is also known as relative density.

5. *Viscosity*: It is a property of a fluid that represents the internal resistance of a fluid to motion. The force with which a flowing fluid exerts on a body surface due to the viscosity in the flow direction is known as the drag force, and the magnitude of this force depends on the viscosity of the fluid.

To obtain relation for viscosity with shear stress and rate of shear strain, let us consider a fluid layer between two parallel plates immersed in a large body of static fluid. Let, the two plates are separated by a distance L as shown in the Figure 2. Now, we assume that a constant force F is applied along the upper plate while the lower plate is held fixed. After initial transients, let us consider that the upper plate moves continuously with a constant velocity U under the influence of F. The fluid in contact with the upper plate sticks to the plate surface and moves along with it at the same velocity U, and the shear stress τ acting on this fluid layer is given by

$$\tau = \frac{F}{A} \tag{1}$$

where, *A* denotes the contact area between the plate and the fluid layer. Note that the fluid layer deforms continuously under the influence of the shear stress.

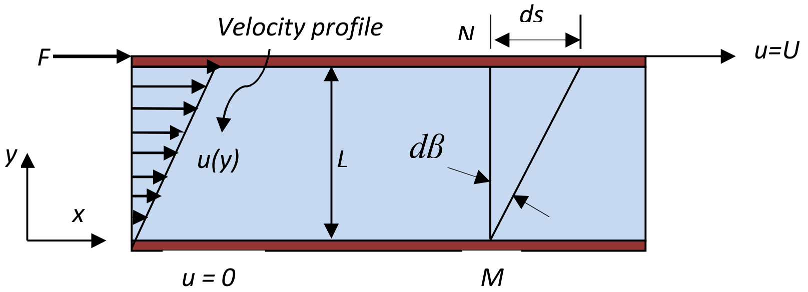


Figure 2: The behaviour of a fluid in laminar flow between two parallel plates when the upper plate moves with a constant velocity.

The fluid in contact with the lower plate which is fixed assumes the velocity of that plate, i.e., $u = 0$ (because of the no-slip condition). In steady laminar flow, the fluid velocity between the plates varies linearly with the vertical distance from the lower plate, between the value 0 and *U*. Thus, the velocity profile is

$$u(y) = \frac{y}{L}\mathrm{U} \tag{2}$$

Taking derivative of the above equation with respect to *y*, we obtain the velocity gradient as

$$\frac{du}{dy} = \frac{U}{L} \tag{3}$$

Let, during a differential time interval *dt*, the sides of fluid particles along a vertical line *MN* rotate through a differential angle *dβ* while the upper plate moves a differential distance $ds = U\,dt$. From the above figure, we get

$$\tan d\beta = \frac{ds}{L} = \frac{U dt}{L} = \frac{du}{dy}dt \qquad \text{[Using eq.(2)]} \tag{4}$$

For small value of *dβ*, we know $\tan d\beta = d\beta$. Thus, the angular displacement or deformation (or shear strain) is given by

$$d\beta = \frac{du}{dy}dt \tag{5}$$

Rearranging the above equation, we can obtain the rate of deformation under the influence of shear stress as follows:

$$\frac{d\beta}{dt} = \frac{du}{dy} \tag{6}$$

Thus, we conclude that the rate of deformation of a fluid element is equivalent to the velocity gradient. Furthermore, it has been verified experimentally that for most fluids the rate of deformation (and thus the velocity gradient) is directly proportional to the shear stress τ,

$$\tau \propto \frac{d\beta}{dt} \quad \text{or} \quad \tau \propto \frac{du}{dy} \tag{7}$$

The fluids that follow the above relationship are known as Newtonian fluids which are expressed first by the great scientist Sir Isaac Newton in 1687. Most common fluids such as water, air, gasoline and oils are Newtonian fluids. Blood and liquid plastics are examples of non-Newtonian fluids where the relationship between the shear stress and rate of deformation is not linear.

In one-dimensional shear flow of Newtonian fluids, shear stress can be expressed by the following equation:

$$\tau = \mu \frac{du}{dy} \tag{8}$$

where, the constant of proportionality μ is called the *coefficient of viscosity* or *dynamic* (or *absolute*) *viscosity* of the fluid. It has two common units that are *kg/m* s or *Pa s* (Pascal second) and *poise* (1 poise = 0.1 *Pa s*). In fluid mechanics and heat transfer, the ratio of dynamic viscosity to density appears frequently is given the name *kinematic viscosity,* $v = \mu/\rho$**.** Two common units of kinematic viscosity are m/s^2 and *stoke* (1 stoke = 1 cm^2/s = 0.0001 m/s^2).

A plot of shear stress versus the rate of shear strain or deformation (velocity gradient) for a Newtonian fluid is a straight line whose slope gives the viscosity of the fluid (see Figure 3).

The shear force F acting on a Newtonian fluid layer (or, by Newton's third law, the force acting on the plate) is

$$F = A\tau = A\mu \frac{du}{dy} \tag{9}$$

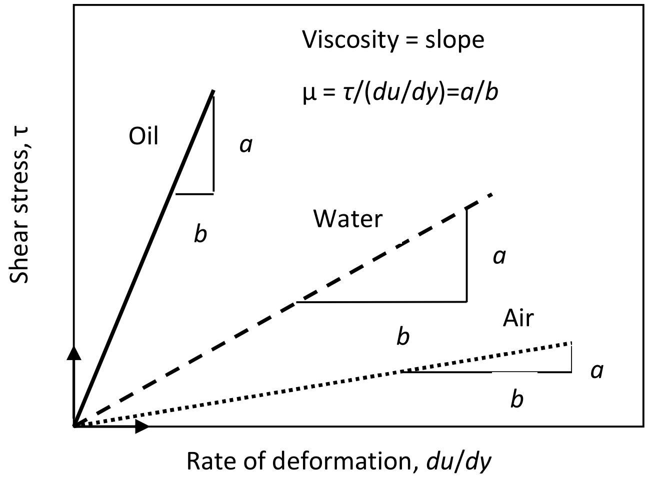


Figure 3: The rate of shear strain or deformation (velocity gradient) of a Newtonian fluid is directly proportional to shear stress, and the constant of proportionality is the viscosity.

Therefore, the force F required moving the upper plate at a constant velocity U while the lower plate remains stationary is

$$F = A\mu\frac{U}{L} \tag{10}$$

In general, the viscosity of a fluid depends on both temperature and pressure; however the dependence on the pressure is rather weak. For liquids, both the dynamic and kinematic viscosities are practically independent of pressure. For gases, this is also the case for dynamic viscosity, but not for kinematic viscosity since the density of a gas is proportional to its pressure.

Viscosity which is the measure of it resistance to deformation arises because of the cohesive forces between the molecules in liquids and by the molecular collisions in gases. Viscosity of fluids greatly varies with temperature. For liquids, it decreases with rise in temperature while it increases with increase in temperature.

6. *Compressibility*: It is the property of a fluid that represents the variation of density with pressure at constant temperature. Compressibility of a fluid is measured in terms of the coefficient of compressibility (κ). It is a common observation that a fluid contracts when more pressure is applied on it and expands when the pressure acting on it is reduced.

Mathematically, coefficient of compressibility (also called bulk modulus of compressibility or bulk modulus of elasticity) at constant temperature (*T*) is represented as,

$$\kappa = -V\left(\frac{\partial p}{\partial V}\right)_T = \rho\left(\frac{\partial p}{\partial \rho}\right)_T$$

It can also be expressed approximately in terms of finite changes as,

$$\kappa \cong -\left(\frac{\Delta p}{\Delta V/V}\right)_T \cong \left(\frac{\Delta p}{\Delta \rho/\rho}\right)_T$$

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

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

In terms of finite changes, it is approximated as,

$$\beta \cong \frac{1}{V}\left(\frac{\Delta V}{\Delta T}\right)_p \cong -\frac{1}{\rho}\left(\frac{\Delta \rho}{\Delta T}\right)_p$$

7. *Surface Tension (σ)*: It is a property of a fluid, which is defined as force per unit length (normal to it) on the fluid interface (liquid-liquid or liquid-gas) between two fluids. Herein, the force (pulling) on a liquid surface or droplets arises because of the attractive forces among the molecules of the same fluid. Surface tension is usually expressed in the unit *N/m*.

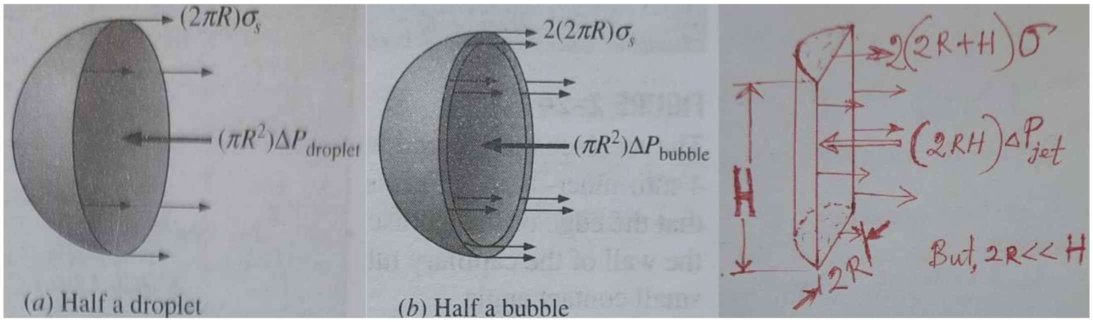
The excess pressure *ΔP* inside a spherical droplet, bubble and liquid jet (see Figure 4) are given by

$$\Delta P_{droplet} = P_i - P_o = \frac{2\sigma}{R}$$

$$\Delta P_{bubble} = P_i - P_o = \frac{4\sigma}{R}$$

$$\Delta P_{jet} = P_i - P_o = \frac{\sigma}{R}$$

where, P_i and P_o denote the pressures inside and outside the droplet or bubble or liquid jet. R denotes the radius of the droplet or bubble or liquid jet.



(a) Half a droplet

(b) Half a bubble

Figure 4: Free body diagram of half droplet, half bubble and half liquid jet.

The rise or fall of a liquid level in a tube with small diameter inserted into the liquid due to surface tension is called the *capillary effect*. The capillary rise or fall in a tube of radius R is given by

$$h = \frac{2\sigma}{\rho g R}\cos\theta$$

where θ is the contact angle which is the angle between the tube wall and the tangent to the fluid film or surface in contact with the wall. A liquid is said to wet the surface when $\theta < 90^{\circ}$ and not wet the surface when $\theta > 90^{\circ}$. It is cleared from the above equation that the capillary rise is inversely proportional to the radius of the tube and is negligible for tubes whose diameter is larger than about $1cm$.

8. *Vapour pressure*: It is defined as the pressure exerted by its vapour in phase equilibrium with its liquid at a given temperature. In a fluid motion, if the pressure at some location is lower than the vapour pressure, then bubbles start forming. This phenomenon is called as *cavitation* because they form cavities in the liquid.

Classification of Fluid Flows: Fluid flows may be classified into following general categories:

1. *Viscous and inviscid flow*: The fluid flow in which frictional /viscous effects become significant are treated as viscous flow. Boundary layer flows are the

example of viscous flow. The flow becomes inviscid when we neglect the effect of viscosity.

2. *Internal and external flow*: The flow of an unbounded fluid over a surface is treated as external flow and if the fluid flow is completely bounded/ confined by surface, and then it is treated as internal flow. For example, flow over a flat plate is considered as external flow while flow through pipe/ duct is considered as internal flow. However, in special cases, when the duct is partially filled and there is free surface in the flow, 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 and outside the boundary layers the flow becomes inviscid for external flows.

3. *Compressible and incompressible flow*: The flow is treated as incompressible if the density of the fluid remains nearly constant throughout the flow. On the other hand, the flow is treated as compressible when the variation of density is more than 5%. High speed gas flows are generally associated with compressible flows like gas flow over rockets, spacecraft and missiles. In such cases, the flow speed is often expressed in terms of the dimensionless, Mach number (*Ma*) defined as

$$Ma = \frac{Speed\ of\ flow}{Speed\ of\ sound} = \frac{v}{c}$$

The speed of sound is $c = 346$ *m/s* in air at room temperature at sea level. Depending on the value *Ma*, flow is categorised as follows:

(a) $Ma < 0.3$, Incompressible flow

(b) $0.3 \leq Ma < 1$, Subsonic flow

(c) $Ma = 1$, Sonic flow

(d) $Ma > 1$, Supersonic flow

(e) $Ma \gg 1$, Hypersonic flow

4. *Laminar and turbulent flow*: A fluid flow is treated as laminar when the motion of the fluid is highly ordered and is characterised by smooth layers of fluid. Examples are the flow of highly viscous fluids at low velocities. A fluid flow is treated as turbulent flow when the fluid motion occurs at high velocities which characterised by velocity fluctuations. The flow that alternated between being laminar and turbulent is called transitional flow. The dimensionless

number, Reynolds number is the key parameter that determines whether the flow is laminar or turbulent and is defined as

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

where ρ is the density of fluid, U is the velocity of the fluid, L is the reference length, and μ and ν denote the dynamic and kinematic viscosities respectively. Reynolds number is a dimensionless number which physically means the ratio of inertia force to viscous force of the fluid. For example, a fluid flow is generally in a pipe when the Re is less than about 2000, and is turbulent when Re is greater than about 4000, and transitional flow occurs between the above range of Re.

5. *Steady and unsteady flow*: When there is no change in fluid property at any point in the flow with time, the fluid flow is treated as steady. On the other hand, the fluid flow is treated as unsteady when the fluid property at a point in the flow varies with time. A fluid flow is referred to as periodic when the unsteady flow oscillates about a steady mean like the blood flow in arteries and veins.

6. *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 natural flow, the 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.

7. *One, two and three dimensional flow*: A flow field is best characterised by the velocity distribution, and thus can be treated as one, two and three dimensional flows if velocity varies in the respective directions.