Lecture NO (2)

Fluids Mechanics and Fluid Properties

Objectives of this section

- **Define the nature of a fluid.**
- **Show where fluid mechanics concepts are common with those of solid mechanics and indicate some fundamental areas of difference.**
- **Introduce viscosity and show what Newtonian and non-Newtonian fluids are.**
- **Define the appropriate physical properties and show how these allow differentiation between solids and fluids as well as between liquids and gases.**

2.1 Introduction

Chemical engineering has to do with industrial processes in which raw materials are changed or separated into useful products.

The chemical engineer must develop, design, and engineer both the complete process and the equipment used; choose the proper raw materials; operate the plants efficiently, safely, and economically; and see to it that products meet the requirement set by the customers.

Fluid Mechanic: **As its name suggests it is the branch of applied mechanics concerned with the statics and dynamics of fluids - both liquids and gases. The analysis of the behavior of fluids is based on the fundamental laws of mechanics which relate continuity of mass and energy with force and momentum together with the familiar solid mechanics properties.**

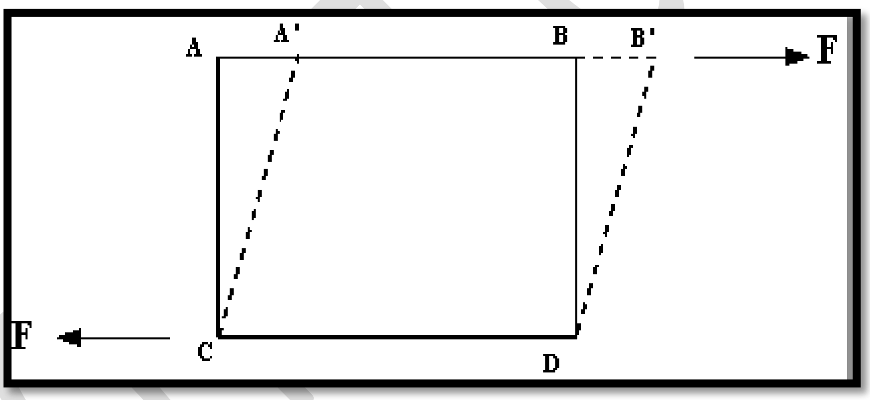
2.2 Fluids

There are two aspects of fluid mechanics which make it different to solid mechanics:

1. The nature of a fluid is much different to that of a solid

2. In fluids we usually deal with *continuous* streams of fluid without a beginning or end. In solids we only consider individual elements.

We normally recognize three states of matter: solid; liquid and gas. However, liquid and gas are both fluids: in contrast to solids they lack the ability to resist deformation. Because a fluid cannot resist the deformation force, it moves, it *flows* under the action of the force. Its shape will change continuously as long as the force is applied. A solid can resist a deformation force while at rest, this force may cause some displacement but the solid does not continue to move indefinitely. The deformation is caused by *shearing* forces which act tangentially to a surface. Referring to the figure below, we see the force F acting tangentially on a rectangular (solid lined) element ABDC. This is a shearing force and produces the (dashed lined) rhombus element A'B'DC.



Shearing force, F, acting on a fluid element.

We can then say:

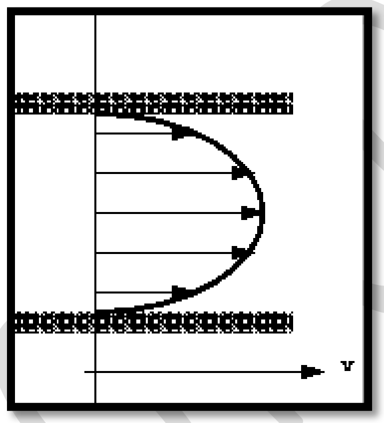
A Fluid is a substance which deforms continuously, or flows, when subjected to shearing forces.

And conversely this definition implies the very important point that:

If a fluid is at rest there are no shearing forces acting.
All forces must be perpendicular to the planes which they are acting.

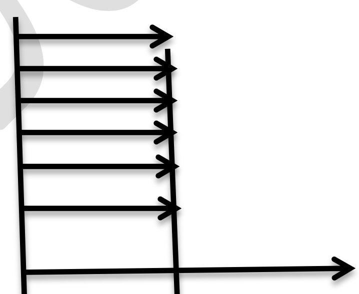
When a fluid is in motion shear stresses are developed if the particles of the fluid move relative to one another. When this happens adjacent particles have different velocities. If fluid velocity is the same at every point then there is no shear stress produced: the particles have zero relative velocity.

Consider the flow in a pipe in which water is flowing. At the pipe wall the velocity of the water will be zero. The velocity will increase as we move toward the center of the pipe. This change in velocity across the direction of flow is known as velocity profile and shown graphically in the figure below:



Velocity Profile in a Pipe.

Because particles of fluid next to each other are moving with different velocities there are shear forces in the moving fluid i.e. shear forces are normally present in a moving fluid. On the other hand, if a fluid is a long way from the boundary and all the particles are travelling with the same velocity, the velocity profile would look something like this:

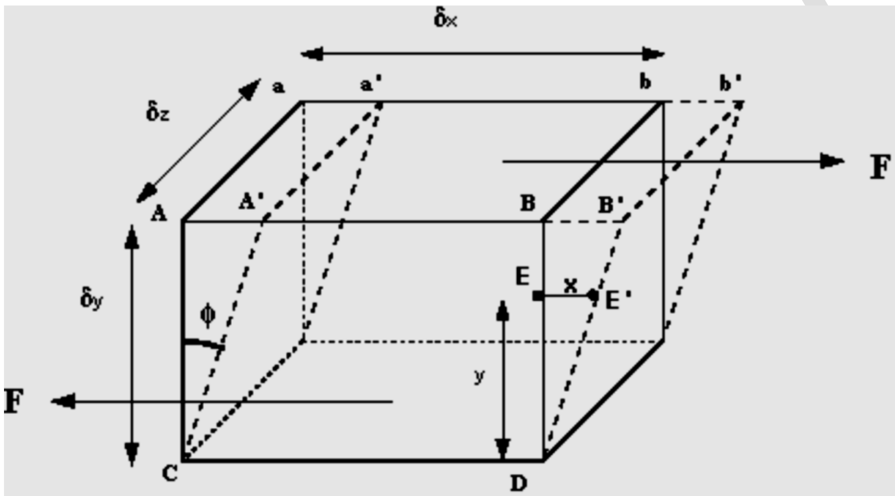


Velocity profile in uniform flow

And there will be no shear forces present as all particles have zero relative velocity. In practice we are concerned with flow past solid boundaries; aero planes, cars, pipe walls, river channels etc. and shear forces will be present.

Newton's Law of Viscosity

How can we make use of these observations? We can start by considering a 3d rectangular element of fluid, like that in the figure below.



The shearing force F acts on the area on the top of the element. This area is given by $A = \delta s \times \delta x$ We can thus calculate the shear stress which is equal to force per unit area i.e. ϕ

$$\text{shear stress}, \tau = \frac{F}{A}$$

The deformation which this shear stress causes is measured by the size of the angle ϕ and is known as shear strain.

In a solid shear strain, ϕ, is constant for a fixed shear stress τ. In a fluid ϕ increases for as long as τ is applied - the fluid flows.

It has been found experimentally that the *rate of shear stress* (shear stress per unit time ,/time) is directly proportional to the shear stress.

If the particle at point E (in the above figure) moves under the shear stress to point E' and it takes time *t* to get there, it has moved the distance *x*. For small deformations we can write

$$\text{shear strain } \Phi = \frac{x}{y}$$

$$\text{rate of shear strain } = \frac{\Phi}{t}$$

$$= \frac{x}{yt} = \frac{x}{t}\frac{1}{y} = \frac{u}{y}$$

Where $\frac{x}{t} = u$ is the velocity of the particle at E.

Using the experimental result that shear stress is proportional to rate of shear strain then

$$\tau = constant \times \frac{u}{y}$$

The term $\frac{u}{y}$ is the change in velocity with y, or the velocity gradient, and may be written in the differential form $\frac{du}{dy}$ The constant of proportionality is known as the dynamic viscosity, μ, of the fluid, giving

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

This is known as Newton's law of viscosity.

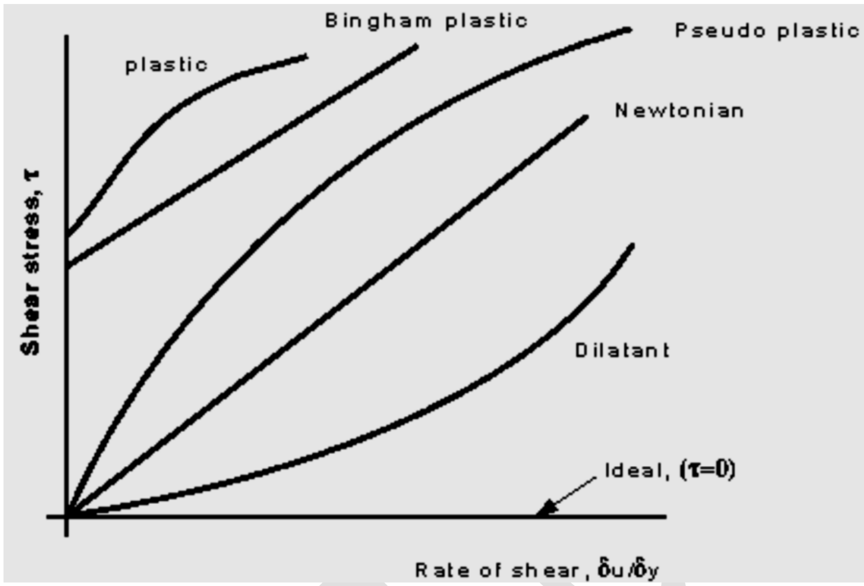
Solid and Fluid Distinction

- **-Molecular of solid are much closer together than fluid**
- **-Solid tries to return to its original shape due to large attraction between solid molecules**
- **-Fluids have very week inter-molecular attraction so that fluids flow under the applied force.**

Newtonian / Non-Newtonian Fluids

Even among fluids which are accepted as fluids there can be wide differences in behaviour under stress. Fluids obeying Newton's law where the value of μ is constant are known as Newtonian fluids. If μ is constant the shear stress is linearly dependent on velocity gradient. This is true for most common fluids. Fluids in which the value of μ is not constant are known as non-Newtonian fluids. There are several categories of these, and they are outlined briefly below.

These categories are based on the relationship between shear stress and the velocity gradient (rate of shear strain) in the fluid. These relationships can be seen in the graph below for several categories



Shear stress vs. Rate of shear strain δu/δy

Each of these lines can be represented by the equation

$$\boldsymbol{\tau = A + B\left(\frac{\delta u}{\delta y}\right)^{n}}$$

Where A, B and n are constants. For Newtonian fluids A = 0, B = μ and n = 1.

Below is brief description of the physical properties of the several categories:

• ***Plastic:*** **Shear stress must reach a certain minimum before flow commences.**

• ***Bingham plastic:*** **As with the plastic above a minimum shear stress must be achieved. With this classification n = 1. An example is sewage sludge.**

• ***Pseudo-plastic:*** **No minimum shear stress necessary and the viscosity decreases with rate of shear, e.g. colloidal substances like clay, milk and cement.**

• ***Dilatant substances;*** **Viscosity increases with rate of shear e.g. quicksand.**

• ***Thixotropic substances:*** **Viscosity decreases with length of time shear force is applied e.g. thixotropic jelly paints.**

• ***Rheopectic substances:*** **Viscosity increases with length of time shear force is applied**

• ***Viscoelastic materials:*** **Similar to Newtonian but if there is a sudden large change in shear they behave like plastic.**

There is also one more - which is not real, it does not exist - known as the ideal fluid. This is a fluid which is assumed to have no viscosity. This is a useful concept when theoretical solutions are being considered - it does help achieve some practically useful solutions.

Liquids vs. Gasses

Although liquids and gasses behave in much the same way and share many similar characteristics, they also possess distinct characteristics of their own. Specifically

- **A liquid is difficult to compress and often regarded as being incompressible.**

A gas is easily to compress and usually treated as such - it changes volume with pressure.

- **A given mass of liquid occupies a given volume and will occupy the container it is in and form a free surface (if the container is of a larger volume). A gas has no fixed volume; it changes volume to expand to fill the containing vessel. It will completely fill the vessel so no free surface is formed.**

Causes of Viscosity in Fluids

1.3.1 Viscosity in Gasses

The molecules of gasses are only weakly kept in position by molecular cohesion (as they are so far apart). As adjacent layers move by each other there is a continuous exchange of molecules. Molecules of a slower layer move to faster layers causing a drag, while molecules moving the other way exert an acceleration force. Mathematical considerations of this momentum exchange can lead to Newton law of viscosity. If temperature of a gas increases the momentum exchange between layers will increase thus increasing viscosity. Viscosity will also change with pressure - but under normal conditions this change is negligible in gasses.

1.3.2 Viscosity in Liquids

There is some molecular interchange between adjacent layers in liquids - but as the molecules are so much closer than in gasses the cohesive forces hold the molecules in place much more rigidly. This cohesion plays an important role in the viscosity of liquids. Increasing the temperature of a fluid reduces the cohesive forces and increases the molecular interchange.

Reducing cohesive forces reduces shear stress, while increasing molecular interchange increases shear stress. Because of this complex interrelation the effect of temperature on viscosity has something of the form:

$$\boldsymbol{\mu_T = \mu_{\circ}(1 + AT + BT)}$$

Where μ_T is the viscosity at temperature T°C, and μ0 is the viscosity at temperature 0°C. A and B are constants for a particular fluid.

High pressure can also change the viscosity of a liquid. As pressure increases the relative movement of molecules requires more energy hence viscosity increases.

3.2 Properties of Fluids

3.2.1 Density

The density of a substance is the quantity of matter contained in a unit volume of the substance.

3.2.2 Mass Density [symbol: ρ (rho)]

Mass Density, ρ , is defined as the mass of substance per unit volume.

$$\boldsymbol{\rho = \frac{Mass\ of\ fluid}{Volume\ of\ fluid}}$$

Units: Kilograms per cubic meter, kg / m^3 (or kgm^{-3})

Dimensions: ML^{-3}

Typical values: Water = 1000 kgm^{-3} , Mercury = 13546 kgm^{-3} Air = 1.23 kgm^{-3} , Paraffin Oil = 800 kgm^{-3} . (at pressure =1.013 × 10^{-5} $N\,m^{-2}$ and Temperature = 288.1K.)

3.2.3 Specific Volume [symbol: υ(upsilon)]

It is the ratio of volume of fluid to its mass (or mole); it is the reciprocal of its density,

$$\boldsymbol{\upsilon = \frac{Volume\ of\ fluid}{Mass\ of\ fluid}}$$

The common units used of density are (m^3/ kg), (cm^3/g), (ft^3/lb).

3.2.4 Weight density or specific weight

Specific Weight ω , (sometimes γ, and sometimes known as *specific gravity*) is defined as the weight per unit volume.

The force exerted by gravity, g, upon a unit volume of the substance.

The Relationship between g and ω can be determined by Newton's 2nd Law, since

$$\text{Weight per unit volume} = \text{mass per unit volume} \times g$$

$$\omega = \rho g$$

Units: Newton's per cubic metre, N/m^3 (or $N\,m^{-3}$)

Dimensions: $ML^{-2}T^{-2}$.

Typical values:

Water =9814 $N\,m^{-3}$, Mercury = 132943 $N\,m^{-3}$, Air =12.07 $N\,m^{-3}$, Paraffin Oil =7851 $N\,m^{-3}$

3.2.5 Specific Gravity [symbol: sp.gr.]

It is the ratio of mass density or (density) of fluid to mass density or (density) of water, Physicists use 39.2°F (4°C) as the standard, but engineers ordinarily use 60°F (15.556°C)

$$\mathbf{sp.gr} = \frac{\boldsymbol{Mass\ density\ of\ fluid}}{\boldsymbol{Mass\ density\ of\ water}}$$

$$\mathbf{sp.gr} = \frac{\rho}{\rho_{ref}} \quad where\ \ \rho_{ref} = \frac{1000kg}{m^3},\frac{1g}{cm^3},\frac{62.4lb_m}{ft^3},\frac{8.33lb_m}{gal}$$

3.2.6Viscosity

The viscosity of a fluid measures its resistance to flow under an applied shear stress, as shown in Fig.3.1 (a). There, the fluid is ideally supposed to be confined in a

relatively small gap of thickness *h* between one plate that is stationary and another plate that is moving steadily at a velocity *V* relative to the first plate.

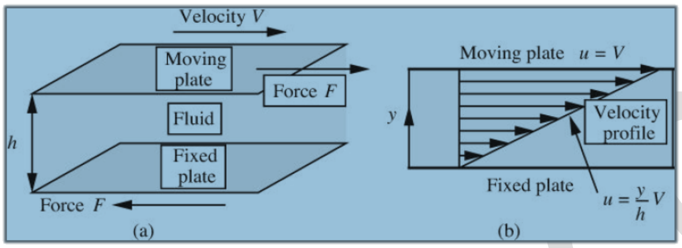


Fig. 3.1 (a) Fluid in shear between parallel plates; (b) the ensuing linear velocity profile.

A steady force *F* to the right is applied to the upper plate (and, to preserve equilibrium, to the left on the lower plate) in order to maintain a constant motion and to overcome the viscous friction caused by layers of molecules sliding over one another. Under these circumstances, the velocity u of the fluid to the right is found experimentally to vary linearly from zero at the lower plate (y = 0) to V itself at the upper plate, as in Fig. 3.1(b), corresponding to no-slip conditions at each plate. At any intermediate distance y from the lower plate, the velocity is simply:

$$\boldsymbol{u = \frac{y}{h}V}$$

Recall that the shear stress τ is the tangential applied force F per unit area:

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

in which A is the area of each plate. Experimentally, for a large class of materials, called Newtonian fluids, the shear stress is directly proportional to the velocity gradient:

$$\tau = \mu \frac{du}{dy} = \mu \frac{V}{h}$$

The proportionality constant μ is called the viscosity of the fluid; its dimensions can be found by substituting those for F (ML/T^2), A (L^2), and du/dy (T^{-1}), giving:

$$\mu [=] \frac{M}{LT}$$

Representative units for viscosity are g/cm s (also known as *poise*, designated by P), kg/m s, and lb_m/ft hr. The *centipoise* (cP), one hundredth of a poise, is also a convenient unit, since the viscosity of water at room temperature is approximately 0.01 P or 1.0 cP.

3.2.7 Kinematic viscosity [symbol: ν (nu)]

Kinematic Viscosity, ν , is defined as the ratio of dynamic viscosity to mass density.

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

The common units used of kinematics viscosity are (m^2/s), (cm^2/s), (ft^2/s),
(Stoke). [Stoke = cm^2/s] [Stoke = 100 c.stoke]
Dimensions: $L^2 T^{-1}$.

Typical values:

Water =$1.14 \times 10^{-6}\ m^2\ s^{-1}$, Air =1.46 × 10–5 $m^2\ s^{-1}$, Mercury =$1.145 \times 10^{-4}\ m^2\ s^{-1}$, Paraffin Oil =$2.375 \times 10^{-3}\ m^2\ s^{-1}$.

3.2.8 Surface tension [symbol: σ(sigma)]

It results from the attractive forces between molecules. It allows steel to float, droplets to form, and small droplets and bubbles to be spherical. Consider the free-body diagram of a spherical droplet and a bubble, as shown in Fig. (4). The pressure force inside the droplet balances the force due to surface tension around the circumference:

$$P\pi r^2 = 2\pi\sigma r$$

$$P = \frac{2\sigma}{r}$$

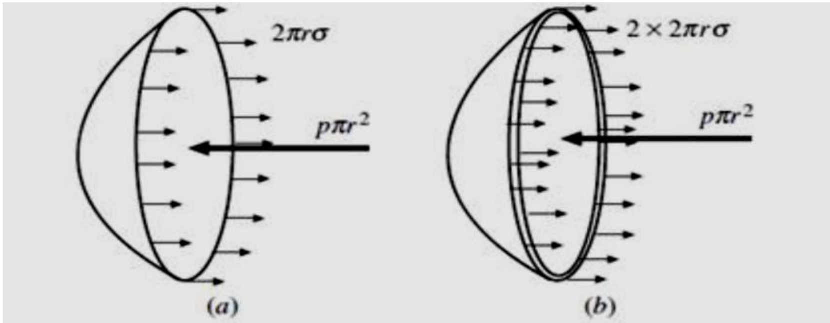


Figure 4 Free-body diagrams of (*a*) a droplet and (*b*) a bubble.

Notice that in a bubble there are two surfaces so that the force balance provides

$$\boldsymbol{P = \frac{4\sigma}{r}}$$

So, if the internal pressure is desired, it is important to know if it is a droplet or a bubble. A second application where surface tension causes an interesting result is in the rise of a liquid in a capillary tube. The free-body diagram of the water in the tube is shown in Fig. (5). Summing forces on the column of liquid gives

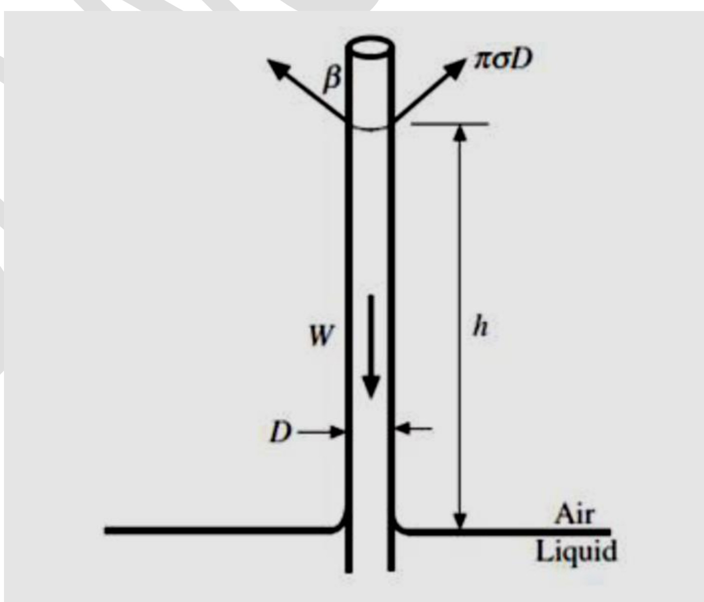


Figure 5 The rise of a liquid in a small tube.

$$\sigma \pi D cos B = \rho g \frac{\pi D^2}{4} h$$

Where the right-hand side of the equation is the weight W. This provides the height the liquid will climb in the tube:

3.2.9Vapor Pressure

When a liquid in a closed container, small air space, a pressure will developed in the space as a result of vapor that is formed by escaping molecules.

When equilibrium is reached so that the molecules leaving the surface are equal to the entering – vapor is said to be saturated and the pressure exerted by the vapor on the liquid surface is termed as vapor pressure.

3.2.9.1 It increase with temperature

Its called vapor pressure or vapor saturated pressure

Its called partial pressure when its mixed with other gases

The temperature at which the vapor pressure is equal to the atmospheric pressure is called the boiling point.

3.3 Useful Information

3.3.1 The shear stress [symbol: τ(tau)]

It is the force per unit surface area that resists the sliding of the fluid layers. The common units used of shear stress are ($N/m^2 \equiv Pa$), ($dyne/cm^2$), (lbf/ft^2).

3.3.2The pressure [symbol: P]

It is the force per unit cross sectional area normal to the force direction. The common units used of shear stress is ($N/m^2 \equiv Pa$), ($dyne/cm^2$), (lbf/ft^2) (atm) (bar) (Psi) (torr ≡mmHg). The pressure difference between two points refers to (ΔP).

The pressure could be expressed as liquid height (or head) (h) where,

$$P = h\rho g = \Delta P = \Delta h \rho g$$

h: is the liquid height (or head), units (m), (cm), (ft).

3.3.3-The energy [symbol: E]

Energy is defined as the capacity of a system to perform work or produce heat.

There are many types of energy such as [Internal energy (U), Kinetic energy (K.E), Potential energy (P.E), Pressure energy (Prs.E), and others. The common units used for energy is (J ≡N.m), (erg ≡dyne.cm), (Btu), (lbf.ft) (cal).

The energy could be expressed in relative quantity per unit mass or mole (J/kg or mol).The energy could be expressed in head quantity [(m) (cm) (ft)] by dividing the relative energy by acceleration of gravity.

3.3.4The Power [symbol: P]

It is the energy per unit time. The common units used for Power is (W ≡J/s), (Btu/time), (lb_f.ft/time) (cal/time), (hp).

3.4 The flow rate

3.4.1 Volumetric flow rate [symbol: Q]

It is the volume of fluid transferred per unit time.

$$Q = uA$$

Where A: is the cross sectional area of flow normal to the flow direction. The common units used for volumetric flow is (m^3/s), (cm^3/s), (ft^3 /s).

3.4.2 Mass flow rate [symbol: m]

It is the mass of fluid transferred per unit time.

$$\dot{m} = Q\rho$$

The common units used for volumetric flow is (kg/s), (g/s), (lb/s).

3.4.3 Mass flux or (mass velocity) [symbol: G]

It is the mass flow rate per unit area of flow,

$$G = \frac{\dot{m}}{A} = u\rho$$

The common units used for mass flux is (kg/m^2.s), (g/cm^2.s), (lb/ft^2.s).

3.5 -Ideal fluid

An ideal fluid is one that is incompressible It is a fluid, and having no viscosity (μ= 0). Ideal fluid is only an imaginary fluid since all the fluids, which exist, have some viscosity.

3.6 Real fluid

A fluid, which possesses viscosity, is known as real fluid. All the fluids, an actual practice, are real fluids.

3.7 Important Laws

3.7.1 Law of conservation of mass

"The mass can neither be created nor destroyed, and it cannot be created from nothing"

3.7.2Law of conservation of energy

"The energy can neither be created nor destroyed, though it can be transformed from one form into another"

3.7.3Newton's Laws of Motion

Newton has formulated three law of motion, which are the basic postulates or assumption on which the whole system of dynamics is based.

3.7.4 Newton's first laws of motion

"Everybody continues in its state of rest or of uniform motion in a straight line, unless it is acted upon by some external forces"

3.7.5 Newton's second laws of motion

"The rate of change in momentum is directly proportional to the impressed force and takes place in the same direction in which the force acts" [momentum = mass × velocity]

3.7.6Newton's third laws of motion

"To every action, there is always an equal and opposite reaction"

3.7.7First law of thermodynamics

"Although energy assumes many forms, the total quantity of energy is constant, and when energy disappears in one form it appears simultaneously in other forms"

3.8 Flow Patterns

The nature of fluid flow is a function of the fluid physical properties, the geometry of the container, and the fluid flow rate. The flow can be characterized either as <u>Laminar</u> or as <u>Turbulent</u> flow.

<u>Laminar</u> flow is also called "viscous or streamline flow". In this type of flow layers of fluid move relative to each other without any intermixing.

<u>Turbulent</u> flow in this flow, there is irregular random movement of fluid in directions transverse to the main flow.

Example (1)

One liter of certain oil weighs 0.8 kg, calculate the specific weight, density, specific volume, and specific gravity of it.

$$sp.wt = \frac{weight\ of\ fluid}{volume\ of\ fluid} = \frac{0.8 \times 9.81}{1 \times 10^{-3}} = 7848\,\frac{N}{m^3}$$

$$\rho = \frac{0.8}{1 \times 10^{-3}} = 800\,\frac{kg}{m^3}$$

$$v = \frac{1}{\rho} = \frac{1}{800} = 1.25 \times 10^{-3}\,\frac{m^3}{kg}$$

$$sp.gr = \frac{\rho_{Liquid}}{\rho_{water}} = \frac{800}{1000} = 0.8$$

Homework NO(1)

Determine the specific gravity of a fluid having viscosity of 4.0 c.poice and kinematic viscosity of 3.6 c.stokes.