CHPTER ONE

Introduction

1.1 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.
A Fluid is any substance that conforms to the shape of its container and it may be defined as a substance that dose not permanently resist distortion and hence, will its shape. *Gases and liquids and vapors* are considered to have the characteristics of fluids and to obey many of the same laws.

In the process industries, many of the materials are in fluid form and must be stored, handled, pumped, and processed, so it is necessary that we become familiar with the principles that govern the flow of fluids and also with the equipment used. Typical fluids encountered include water, acids, air, Co_2, oil, slurries.

If a fluid affected by changes in pressure, it is said to be *"compressible fluid"*, otherwise, it is said to be *"incompressible fluid"*.

Most liquids are incompressible, and gases are can considered to be compressible fluids. However, if gases are subjected to small percentage changes in pressure and temperature, their densities change will be small and they can be considered to be incompressible fluids.

The fluid mechanics can be divided into two branches;
"Fluid static" that means fluid at rest, and
"Fluid dynamics" that means fluid in motion.

1.2 Physical Properties of Fluids

1. Mass density or density [symbol: ρ (rho)]

It is the ratio of mass of fluid to its volume, $\rho = \frac{\text{Mass of fluid}}{\text{Volume of fluid}}$

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

2. 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, $\upsilon = \frac{\text{Volume of fluid}}{\text{Mass of fluid}}$

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

3. Weight density or specific weight [symbol: sp.wt.]

It is the ratio of weight of fluid to its volume, $sp.wt. = \frac{\text{Weight of fluid}}{\text{Volume of fluid}}$

The common units used of density is (N/m^3), ($dyne/cm^3$), (lb_f/ft^3).

4. 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) $sp.gr. = \frac{\text{Mass density of fluid}}{\text{Mass density of water}}$

The common density used of water is (1000 kg/m^3), (1.0g/cm^3), (62.43 lb/ft^3).

5. Dynamic viscosity [symbol: μ (mu)]

It is the property of a fluid, which offers resistance to the movement of one layer of fluid over another adjacent layer of the fluid.

The common units used of dynamic viscosity is (kg/m.s), (g/cm.s), (lb/ft.s), (poise) (N.s/m^2 ≡ Pa.m), (dyne.s/cm^2). [poise ≡ g/cm.s ≡ dyne.s/cm^2] [poise = 100 c.p]

6. Kinematic viscosity [symbol: ν (nu)]

It is the ratio of the dynamic viscosity to mass density of fluid, $\nu = \frac{\mu}{\rho}$

The common units used of kinematics viscosity is (m^2/s), (cm^2/s), (ft^2/s), (stoke). [stoke ≡ cm^2/s] [stoke = 100 c.stoke]

7. Surface tension [symbol: σ (sigma)]

It is the property of the liquid, which enables it to resist tensile stress. It is due to cohesion between surface molecules of a liquid.

The common units used of Surface tension is (N/m), (dyne/cm), (lb_f/ft).

<u>1.3 Useful Information</u>

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 is (N/m^2 ≡ Pa), (dyne/cm^2), (lb_f/ft^2).

2. The 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 ≡ Pa), (dyne/cm^2), (lb_f/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,

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

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

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), (lb_f.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.

4. The 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).

5. **The flow rate**

5.1. Volumetric flow rate [symbol: Q]

It is the volume of fluid transferred per unit time.

$\boxed{Q = u\,A}$ 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).

5.2. Mass flow rate [symbol: $\dot{m}$]

It is the mass of fluid transferred per unit time. $\boxed{\dot{m} = Q\,\rho = u\,A\,\rho}$

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

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

It is the mass flow rate per unit area of flow, $\boxed{G = \frac{\dot{m}}{A} = u\,\rho}$

The common units used for mass flux is (kg/m2.s), (g/cm2.s), (lb/ft2.s).

6. **Ideal fluid**

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

7. **Real fluid**

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

<u>1.4 Important Laws</u>

1. **Law of conservation of mass**

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

2. **Law of conservation of energy**

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

Newton'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. **Newton's first laws of motion**

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

4. **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]

5. **Newton's third laws of motion**

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

6. First 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"

1.5 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 **Laminar** or as **Turbulent** flow.

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

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

1.6 Newton's Law of Viscosity and Momentum Transfer

Consider two parallel plates of area (A), distance (dz) apart shown in Figure (1). The space between the plates is filled with a fluid. The lower plate travels with a velocity (u) and the upper plate with a velocity (u-du). The small difference in velocity (du) between the plates results in a resisting force (F) acting over the plate area (A) due to viscous frictional effects in the fluid.

Thus the force (F) must apply to the lower plate to maintain the difference in velocity (du) between the two plates. The force per unit area (F/A) is known as the shear stress (τ).

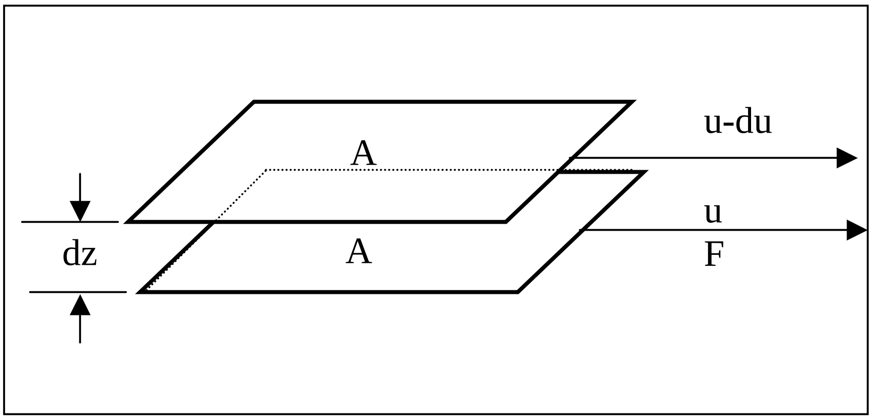


Figure (1) Shear between two plates

Newton's law of viscosity states that:

$$\tau \propto -\frac{du}{dz} \Rightarrow \tau = -\mu \frac{du}{dz}$$

Fluids, which obey this equation, are called "Newtonian Fluids" and Fluids, don't obey this equation, are called "non-Newtonian Fluids".

Note: Newton's law of viscosity holds for Newtonian fluids in laminar flow.

Momentum (shear stress) transfers through the fluid from the region of high velocities to region of low velocities, and the rate of momentum transfer increase with increasing the viscosity of fluids.

1.7 Newtonian and non-Newtonian fluids

The plot of shear stress (τ) against shear rate ($\dot{\gamma} \equiv \frac{du}{dz}$) is different in Newtonian fluids than that in non-Newtonian fluids as shown in Figure (2).

For Newtonian fluids the plot give a straight line from the origin but for non-Newtonian fluids the plot gives different relations than that of Newtonian some of these relations are given in Figure (2).

A- Newtonian fluids

B- non-Newtonian (pseudoplastic)

C- non-Newtonian (dilatant)

D- non-Newtonian (Bingham)

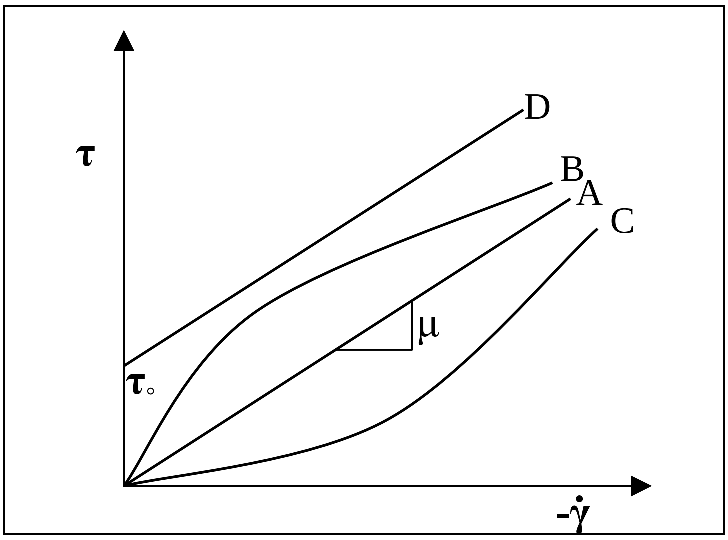


Figure (2): Shear stress (τ) against shear rate ($-\dot{\gamma} \equiv -\frac{du}{dz}$)

Example -1.1-

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

Solution:

$$sp.wt. = \frac{\text{Weight of fluid}}{\text{Volume of fluid}} = \frac{(0.8kg)(9.81m/s^2)}{1x10^{-3}m^3} = 7848\frac{N}{m^3}$$

$$\rho = \frac{(0.8kg)}{1x10^{-3}m^3} = 800\frac{kg}{m^3} \qquad \upsilon = \frac{1}{\rho} = 1.25x10^{-3}\frac{m^3}{kg}$$

$$sp.gr. = \frac{\rho_{\text{liquid}}}{\rho_{\text{water}}} = \frac{800kg/m^3}{1000kg/m^3} = 0.8$$

Example -1.2-

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

Solution:

$$\mu = 4c.p\frac{poice}{100c.p} = 0.04\,poise = 0.04\frac{g}{cm.s} \qquad \nu = 3.6c.s\frac{stoke}{100c.s} = 0.036stoke = 0.04\frac{cm^2}{s}$$

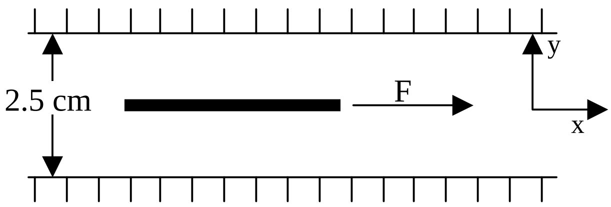
$$\nu = \frac{\mu}{\rho} \Rightarrow \rho = \frac{\mu}{\nu} = \frac{0.04\frac{g}{cm.s}}{0.036cm^2/s} = 1.1111\frac{g}{cc} \qquad \Rightarrow \rho = 1111.1\frac{kg}{m^3} \qquad \Rightarrow sp.gr. = 1.1111$$

Example -1.3-

The space between two large plane surfaces kept 2.5 cm apart is filled with liquid of viscosity 0.0825 kg/m.s. What force is required to drag a thin plate of surface area 0.5 m^2 between the two large surfaces at speed of 0.5 m/s, (i) when the plate is placed in the middle of the two surfaces, and (ii) when the plate is placed 1.5 cm from one of the plates surfaces.

Solution:

(i) Shear stress on the upper side of the plate is



$$\tau_1 = -\mu \frac{du}{dy} = \frac{F_1}{A}$$

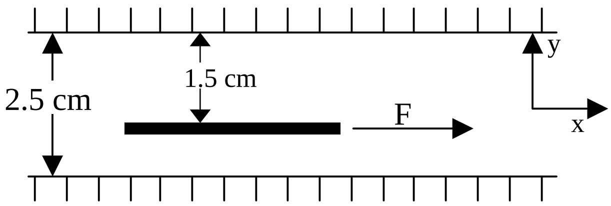
$$\frac{du}{dy} \cong \frac{\Delta u}{\Delta y} = \frac{u|_{y=1.25} - u|_{y=0}}{1.25x10^{-2} - 0} = \frac{0 - 0.5 m/s}{1.25x10^{-2} m} = -40 s^{-1}$$

$$F_1 = A(-\mu \frac{du}{dy}) = 0.5 m^2 [-0.0825 Pa.s(-40 s^{-1})] = 1.65 N$$

Likewise on the lower surface $F_2 = A\tau_2 = 1.65N$

The total force required $= F_1 + F_2 = 3.3N$

(ii) Shear stress on the upper side of the plate is



$$\tau_1 = -\mu \frac{du}{dy} = \frac{F_1}{A}$$

$$\frac{du}{dy} \cong \frac{\Delta u}{\Delta y} = \frac{u|_{y=1.5} - u|_{y=0}}{1.5x10^{-2} - 0} = -\frac{100}{3} s^{-1}$$

$$F_1 = A(-\mu \frac{du}{dy}) = 0.5 m^2 [-0.0825 Pa.s(-\frac{100}{3} s^{-1})] = 1.375 N$$

$$\tau_2 = -\mu \frac{du}{dy} = \frac{F_2}{A} \quad \text{and} \quad \frac{du}{dy} = \frac{0 - 0.5}{0.01} = -50 s^{-1}$$

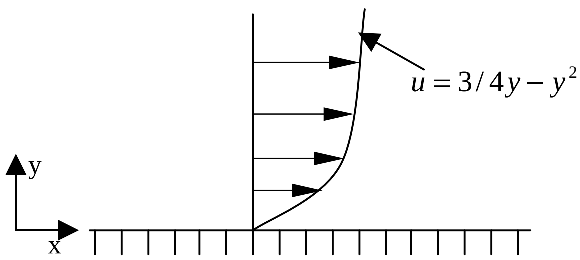
$$F_2 = 0.5 m^2 [-0.0825 Pa.s(-50 s^{-1})] = 2.0625 N$$

The total force required $= F_1 + F_2 = 3.4375N$

Example -1.4-

The velocity distribution within the fluid flowing over a plate is given by $u = 3/4y - y^2$ where u is the velocity in (m/s) and y is a distance above the plate in (m). Determine the shear stress at y=0 and at y=0.2 m. take that μ=8.4 poise.

Solution:



$$u = 3/4y - y^2 \Rightarrow \frac{du}{dy} = \frac{3}{4} - 2y \Rightarrow \frac{du}{dy}\bigg|_{y=o} = \frac{3}{4} s^{-1}$$

and $\frac{du}{dy}\bigg|_{y=0.2} = \frac{3}{4} - 2(0.2) = 0.35 s^{-1}$

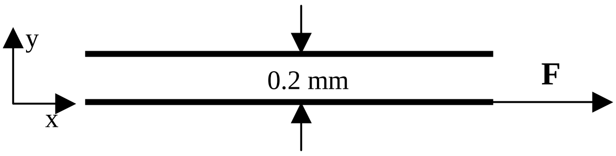
$$\tau = -\mu \frac{du}{dy} = \frac{F}{A}; \; \mu = 8.4 \frac{g}{cm.c}\left(\frac{100cm}{m}\right)\left(\frac{kg}{1000g}\right)$$

$$\tau|_{y=0} = 0.84 Pa.s(3/4 s^{-1}) = 0.63 Pa \quad \text{and} \quad \tau|_{y=0.2} = 0.84 Pa.s(0.35 s^{-1}) = 0.294 Pa$$

Example -1.5-

A flat plate of area 2x10^4 cm^2 is pulled with a speed of 0.5 m/s relative to another plate located at a distance of 0.2 mm from it. If the fluid separated the two plates has a viscosity of 1.0 poise, find the force required to maintain the speed.

Solution:



$$\tau = -\mu \frac{du}{dy} = \frac{F}{A} \quad \mu = 1.0 \frac{g}{cm.c}\left(\frac{100cm}{m}\right)\left(\frac{kg}{1000g}\right)$$

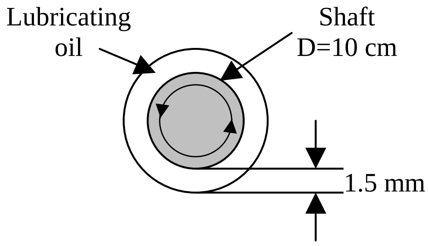
$$\frac{du}{dy} \cong \frac{\Delta u}{\Delta y} = \frac{u_2 - u_1}{y_2 - y_1} = \frac{0 - 0.5m/s}{0.2x10^{-3}m - 0} = -2500s^{-1}$$

$$\tau = 0.1Pa.s(2500s^{-1}) = 250Pa \Rightarrow F = 250Pa(2m^2) = 500N$$

Example -1.6-

A shaft of diameter 10 cm having a clearance of 1.5 mm rotates at 180 rpm in a bearing which is lubricated by an oil of viscosity 100 c.p. Find the intensity of shear of the lubricating oil if the length of the bearing is 20 cm and find the torque.

Solution:



The linear velocity of rotating is

$$u = \pi DN = \frac{\pi(0.1m)180\,rpm}{60\,s/\min} = 0.9425\,m/s$$

$$\mu = 100c.p = 1.0 \frac{g}{cm.c}\left(\frac{100cm}{m}\right)\left(\frac{kg}{1000g}\right) = 0.1Pa.s$$

$$\tau = \mu \frac{du}{dy} = \frac{F}{A} = 0.1Pa.s\left(\frac{0.9425m/s}{0.0015m}\right) = 62.83Pa \Rightarrow F = \tau(\pi DL) = 62.83Pa(\pi\, 0.1(0.2)) = 3.95\,N$$

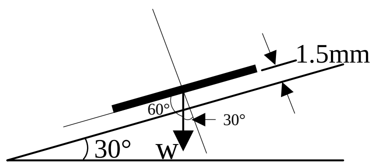
The torque is equivalent to rotating moment

$$\Gamma = F\,\frac{D}{2} = 3.95N(\frac{0.1}{2}) = 0.1975J$$

Example -1.7-

A plate of size 60 cm x 60 cm slides over a plane inclined to the horizontal at an angle of 30°. It is separated from the plane with a film of oil of thickness 1.5 mm. The plate weighs 25kg and slides down with a velocity of 0.25 m/s. Calculate the dynamic viscosity of oil used as lubricant. What would be its kinematic viscosity if the specific gravity of oil is 0.95.

Solution:



Component of W along the plane =W cos(60) =W sin(30)

= 25 (0.5) = 12.5 kg

F = 12.5 kg (9.81 m/s^2) =122.625 N

τ = F/A = 122.625 N/(0.6 x0.6) m^2 = 340.625 Pa

$$\mu = \frac{\tau}{(du/dy)} = \frac{340.625\ Pa}{(0.25/0.0015)s^{-1}} = 2.044Pa.s = 20.44\ poise$$

$$\nu = \frac{\mu}{\rho} = \frac{2.044\ Pa.s}{950\ kg/m^3} = 0.00215\ m^2/s = 21.5\ stoke$$

Home Work

P.1.1

Two plates are kept separated by a film of oil of 0.025 mm. the top plate moves with a velocity of 50 cm/s while the bottom plate is kept fixed. Find the fluid viscosity of oil if the force required to move the plate is 0.2 kg/m^2. Ans. μ= 9.81x10^{-5} Pa.s ?

P.1.2

If the equation of a velocity profile over a plate is u=3 y$^{(2/3)}$ in which the velocity in m/s at a distance y meters above the plate, determine the shear stress at y=0 and y=5 cm. Take μ= 8.4 poise Ans. $\tau_{y=0} = \infty$, $\tau_{y=5}$ = 4.56 Pa.s

P.1.3

The equation of a velocity distribution over a plate is u=1/3 y - y^2 in which the velocity in m/s at a distance y meters above the plate, determine the shear stress at y=0 and y=0.1 m. Take μ= 8.35 poise Ans. $\tau_{y=0}$ =2.78, $\tau_{y=0.1}$= 4.56 dyne/cm^2

P.1.4

A cylinder of diameter 10 cm rotates concentrically inside another hollow cylinder of inner diameter 10.1 cm. Both cylinders are 20 cm long and stand with their axis vertical. The annular space is filled with oil. If a torque of 100 kg cm is required to rotate the inner cylinder at 100 rpm, determine the viscosity of oil. Ans. μ= 29.82poise