Chapter One

Fluid Mechanics

1.1 Definitions

Fluid Mechanics: is a science which is specialized in studying fluids (liquids & gases) in statics and dynamics and the forces that acting on them.

Matters in nature are divided into two kinds:

1. Solid Matters
2. Fluid Matters
    a. Liquid Matters
    b. Gaseous Matters

Hydraulics: is specialized in water as a liquid matter within the fluid matters.

Hydrodynamics: studies the flow fields for matters that are considered non viscous and incompressible even its weight is negligible i.e. Ideal Fluid.

The existence of matters in any of the above states depends on: Activity, Structure of the molecules and Space between these molecules.

The spacing s big between the molecules in gases and is very small in liquids and solids. However, the activity of the molecules in gases is much bigger than the activity in liquids & gases. Therefore, Cohesiveness between the molecules in solid is very big but relative movement between them is negligible.

Solid Matters are elastic

for Compression or Tension

There is Strain , the result is

deformation . Behaves the same under shearing stress

They return back to their original shape when Compression, Tension or Shear Stress is removed. If they are more than the elastic ability of the matter, permanent deformation occur.

Liquids are elastic under positive direct pressure. But it has very small ability for negative pressure. This is due to the small cohesiveness between the molecules. Due to the big cohesiveness between the molecules in solids, They resist the forces un static or dynamic states. However, liquids cannot sustain shearing stress. Under this type of shearing stress liquid flow.

1.2 Dimensions & Units

The dimensions are: Mass (M) , Force (F) , Length (L) and Time (T) .

It is possible to describe most characteristics and properties of fluid by M - L - T or F - L - T systems. Dimensions can be changed from one system to another by Newton Second Law of motion:

$$F = M\,a \qquad \text{..} \quad (1.1)$$

Where a is the acceleration of mass (M) which is caused by the force F

$$F = M\left(\frac{L}{T^2}\right) = \left(\frac{M\,L}{T^2}\right) \qquad \text{... ... ...} \quad (1.2)$$

Units Three kinds

(a) English units **(b)** Metric units **(c)** SI units

For the English units: Mass (M) in (slug) , Force (F) in (pound) , Length (L) in (foot) and Time (T) in (second)

For metric units: Mass (M) in (Gram) , Force (F) in (Dyne) , Length (L) in (centimeter) and Time (T) in (second) (s)

For SI units: Mass (M) in (kg) , Force (F) in (Newton N) , Length (L) in (m) and Time (T) in (s)

State the Newton Second Law of motion for each set of unit ….

Large units	Small units
Mega = 10^6	Micro = 10^{-6}
Kilo = 10^3	Milli = 10^{-3}

1.3 Flow Characteristics

Characters of flow that change with time and space.

1.3.1 Velocity (v)

Is the average displacement change per unit time. It is vector quantity have magnitude and direction.

$$v = \frac{ds}{dt}$$

Dimensions : $\left(\frac{L}{T}\right)$, units : $\left(\frac{m}{s}\right)$

1.3.2 Pressure (p)

Is the force per unit area. The pressure scalar quantity has magnitude only.

Dimensions : $\left(\frac{F}{L^2}\right)$, units : $\left(\frac{N}{m^2}\right)$

1.3.3 Shear Stress (τ)

Is the force per unit surface area that resists the sliding of the fluid layers. It is vector quantity.

Dimensions : $\left(\frac{F}{L^2}\right)$, units : $\left(\frac{N}{m^2}\right)$

1.3.4 Discharge (Q)

Is the volume of fluid transferred per unit time through across sectional area.

Dimensions : $\left(\frac{L^3}{T}\right)$, units : $\left(\frac{m^3}{s}\right)$

1.3.5 Force (F)

Is any interaction that, when unopposed, will change the motion of an object. It is vector quantity.

Dimensions : F , units : N

1.3.6 Time (t)

A period between two moments. It is scalar quantity.

Dimensions : T , units : s

1.3.7 Acceleration (a)

Is the average velocity change per unit time. It is vector quantity have magnitude and direction.

$$a = \frac{dv}{dt}$$

Dimensions : $\left(\frac{L}{T^2}\right)$, units : $\left(\frac{m}{s^2}\right)$

1.4 Properties of Fluids

1.4.1 Mass Density (ρ)

It is the ratio of mass of fluid to its volume.

$$\rho = \frac{Mass}{Volume}$$

Dimensions : $\left(\frac{M}{L^3}\right)$ or $\left(\frac{F\,T^2}{L^4}\right)$, units : $\left(\frac{kg}{m^3}\right)$

1.4.2 Weight Density (ɤ)

It is the ratio of weight of fluid to its volume.

$$\gamma = \frac{Weight}{Volume}$$

Dimensions : $\left(\frac{F}{L^3}\right)$, units : $\left(\frac{N}{m^3}\right)$

$\gamma = \rho\, g$ .... (1.3)

Relative Density (r.d.)

It is the ratio of mass density of fluid to mass density

$$r.d = \frac{\rho}{\rho_{H_2O} \quad at\ 4\ C^{\circ}} \quad , \quad \frac{\gamma}{\gamma_{H_2O} \quad at\ 4\ C^{\circ}}$$

So : r.d for H_2O = 1 r.d for Hg = 13.55

Specific Volume (s.v)

It is the ratio of volume of fluid to its weight; it is the reciprocal its weight density.

Dimensions : $\left(\frac{L^3}{F}\right)$, units : $\left(\frac{m^3}{N}\right)$

$$s.v = \frac{1}{\gamma}$$

Example 1.1

A vessel is full of oil. If the weight of the oil is 1.9 KN and the volume of the vessel is 200 Liters. Find weight density , mass density , relative density and specific volume for the oil ?

Solution

$$\gamma = \frac{1.9\ KN}{0.2\ m^3} = 9.5\ KN/m^3$$

$$\rho = \frac{\gamma}{g} = \frac{9.5\ KN/\ m^3}{9.8\ m/s^2} = 0.969\ \frac{KN\ .\ s^2}{m^4}$$

N = (kg) (m/s^2)

ρ = (0.969) [1000 kg . m/s^2] . s^2/m^4 = 969 kg / m^3

$$r.d. = \frac{\rho\ (oil)}{\rho\ (H_2O} = \frac{969\ \ kg/m^3}{1000\ \ kg/m^3} = 0.969$$

$$s.v = \frac{1}{\gamma} = \frac{1}{9.5\ \ KN/m^3} = 0.105\ \ m^3/KN$$

1.4.3 Compressibility & Elasticity

Compressibility: is the ability of the fluid to change its volume when it is exposed to external forces. It is measured by the bulk modulus of elasticity (E).

Elasticity: is the ability of fluid to return back to its original shape when the effect of external force is released.

V_o is the volume before putting the force Fig. 1.1 then the volume becomes V_1 , V_2 , V_3 , V_4 , V_5 under the forces F_1 , F_2 , F_3 , F_4 and F_5 . For every pressure F/A , there is a strain V/V_o …. so on.

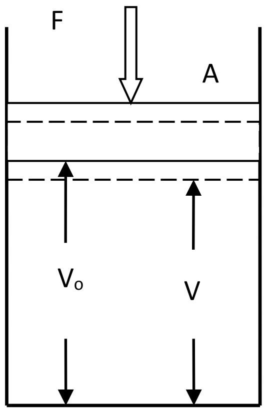


Fig. 1.1

$$E = -\frac{d(F/A)}{d(V/V_o)} \qquad \dots\dots\dots\dots\dots\dots\ (1.4)$$

E = Bulk Modulus of Elasticity

Equation 1.4 can be written as:

$$E = -\frac{dp}{dV/V_o} \qquad \dots\dots\dots\dots\dots\dots\dots\ (1.5)$$

And can also be written as:

$$E = \frac{dp}{d\rho/\rho_o} = \frac{dp}{d\gamma/\gamma_o} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (1.6)$$

Example 1.2

The volume of a liquid becomes 1.4 m^3 when is subjected to a force of 1.2 kpa and the volume is reduced to 1.3996 m^3 when the force is doubled. Find the bulk modulus of elasticity for the liquid?

Solution

$$E = -\frac{dp}{dV/V_o} = -\frac{p_2 - p_1}{(V_2 - V_1)/V_1} = -\frac{2.4\,kpa - 1.2\,kpa}{(1.3996\,m^3 - 1.4\,m^3)/1.4\,m^3}$$

$$= \frac{1.2}{0.0004/1.4}\ \text{kpa}$$

$$\therefore\ E = 4.2 * 10^3\ \ kpa = 4.2 *\ 10^6\ \ pa$$

1.4.4 Viscosity (μ)

Viscosity is the result of cohesiveness of molecules and exchange of momentum between different layers at different heights. So, we have real fluid or viscous fluid.

The result is friction between layers when in motion Laminar flow and Turbulent flow.

This is due to viscosity Ideal flow.

$$\tau = \mu \frac{dv}{dy} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (1.7)$$

μ = viscosity or coefficient of viscosity or dynamic viscosity

Its dimensions : $\frac{F-T}{L^2}$ $, its\ units:\ \frac{N-s}{m^2}\ \ or\ pa\ .s\ it\ is\ equal\ to\ \ \frac{\tau}{dv/dy}$

The units of μ , (pa . s) = $\frac{N}{m^2}$. s

One Newton N = kg . m/s^2 , so the units of viscosity is kg/m.s

, 1/10 of this = 1 poise

$$\nu = \frac{\mu}{\rho} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (1.8)$$

$$\nu = \frac{\frac{kg}{m\,.\,s}}{\frac{kg}{m^3}} = \left(\frac{\mathrm{m}^2}{\mathrm{s}}\right) \qquad \text{with no units of force , so it is}$$

called kinematic viscosity

One stoke = 10^{-4} (m^2/s) or one m^2/s = 10^4 stokes

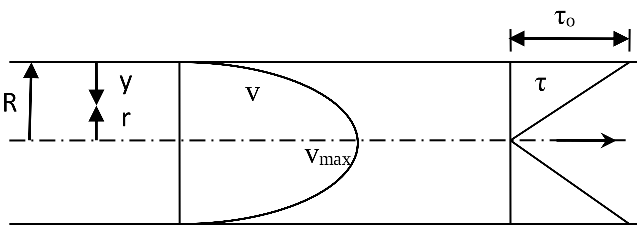
$\mu_{H2O} >> \mu_{air}$ but , $\nu_{H2O} < \nu_{air}$ due to ρ of air which is very small.

The base for measurement of viscosity is μ.

Example 1.3

Oil with (r.d) = 0.85 flows in 200 mm pipe. It is known that τ_o = 0.07 N/m^2 and the velocity distribution is given by : ($v = 1 - 100\ r^2$) with v in (m/s) and r in (m). If the flow is laminar, find the kinematic viscosity for the oil?

Solution



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

r = (R – y)

dr = - dy or dy = - dr

$$\tau = -\mu \frac{dv}{dr} \quad , from\ (v.d.)\ \frac{dv}{dr} = -200\, r \ \rightarrow\ have\ units\ of\ \left(\frac{1}{s}\right)$$

$\tau = 200\ \mu\ r$ = shear distribution equation (Linear equation)

$\tau_o = 200\ \mu\ (0.1)\ 1/s = 0.07\ \ N/m^2$

$\mu = 0.07/20\ \ N.s/m^2 = 0.0035\ \ pa.s$

$$\nu = \frac{\mu}{\rho} = \frac{0.0035\ \ N.s/m^2}{850\ \ kg/m^3} = 4.1176 * 10^{-6}\ \frac{N.s.m}{kg}\ but\ 1\ kg = \frac{N.s^2}{m}$$

$\nu = 4.1176 * 10^{-6}\ \ m^2/s$

1.4.5 Surface Tension and Capillarity

The surface tension in liquids is measured along the surface when they contact solid or fluid surfaces is due to cohesiveness and adhesiveness of molecules.

For water adhs. > cohs. it will rise

For Hg adhs. < cohs. it will fall

Angle of contact (Θ) is the angle between the solid surface and the extension of the liquid surface beyond the solid surface.

If the solid surface is clean glass , then $\Theta = 0^o$ with water and 130^o with mercury.

Surface tension force is small , if it compares with the rest of forces in liquids. So, it is usually neglected. It is important in studying rise of liquids in capillary tubes. This phenomena is called capillarity. In Fig. 1.2 , the weight of the rising liquid is $(\gamma)\ (\pi\ r^2\ h)$ should equal the vertical component of the surface tension force or $(2\ \pi\ r\ \cos\Theta)\ \sigma$

So : $2\ \pi\ r\ \sigma\ \cos\Theta = \gamma\ \pi\ r^2\ h$ or

$$h = \frac{2\ \sigma\ cos\theta}{\gamma\ r} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots. \ (1.9)$$

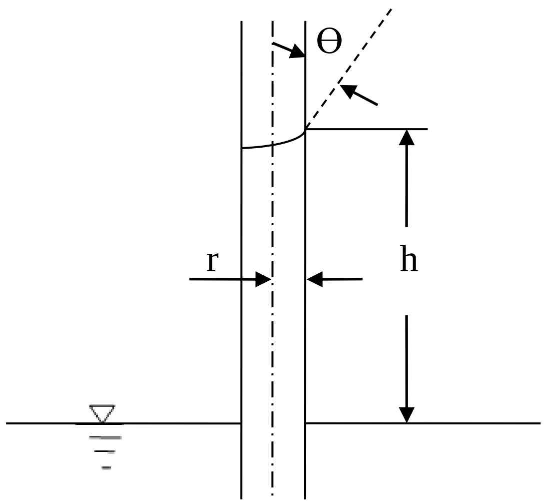


Fig. 1.2

Example 1.4

Find the diameter of glass tube that can be used where the capillarity does not affect the reading of water level more than 5 mm? Consider water with T = 20° C.

Solution

Suppose clean glass , then Θ = 0 , and equation 1.9 becomes:

$$h = \frac{2\,\sigma}{\gamma\, r}$$

From table , σ = 0.0728 N/m , γ = 9.789 KN/m^3

So: $$0.005\,m = \frac{(2)(0.00728)\,\frac{N}{m}}{9.789 * 10^3 \frac{N}{m^3}\,(r)}$$

$$r = \frac{0.1456\,\frac{N}{m}}{(0.005\,m)(9.789 * 10^3\,\frac{N}{m^3})} = 0.002975\,m = 2.975\,mm$$

Use a capillary tube with diameter not less than 6 mm.

1.4.6 Vapor Pressure (p_v)

Vapor pressure (p_v) is the result of the pressure of the molecules that leave the liquid surface continuously. With the increase of temperature , the molecules become more active and more of them can leave the liquid surface, so p_v will increase also. Boiling occurs when saturated $p_v = p_{atm}$. This is whey boiling occurs at different temperatures according to the values of atmospheric pressures.

Water boils at 100^o C when atmospheric pressure is 101.3 kpa. But boils at lowers temperature with lower atmospheric pressure.

Example 1.5

How much the atmospheric pressure should be reduced in order for the water to boil at 80^o C?

Solution

Vapor pressure p_v at 80^o C = 37.34 kpa.

Standard atmospheric pressure = 101.3 kpa so

this pressure should be reduced by the amount

101.3 kpa – 37.34 kpa = 63.96 kpa.