A Handbook on

Mechanical Engineering

Revised & Updated

Contains well illustrated formulae
& theory key concepts

For

ESE, GATE, PSUs

& OTHER COMPETITIVE EXAMS

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A Handbook on Mechanical Engineering

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CONTENTS

A Handbook on Mechanical Engineering

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1 Fluid Mechanics and Hydraulic Machines

I Introduction

Ideal Fluid and Real Fluid

- Ideal fluid

  A fluid is said to be ideal if it is assumed to be both incompressible and non-viscous. Its bulk modulus is infinite ($k = \infty$).
- Real fluid

  Real fluids have viscosity, finite compressibility and surface tension.

Remember:

☑ Ideal fluid has no surface tension.

☑ Ideal fluids are imaginary and do not exist in nature.

Specific Weight, Specific Volume, Specific Gravity

- Specific weight or weight density, $w = \dfrac{\text{Weight}}{\text{Volume}} = \dfrac{mg}{V} = \rho g$

  where, ρ = Density, g = Acceleration due to gravity

  S.I. unit of specific weight is N/m^3

  Specific weight of water = 9810 N/m^3
- Specific volume, $v = \dfrac{1}{\text{Density}} = \dfrac{1}{\rho}$

  Specific volume of the water: $v = \dfrac{1}{\rho} = \dfrac{1}{1000} = 0.001\ m^3/kg$
- Specific gravity (s) or Relative density

  $$\text{Specific gravity, } s = \frac{\text{Density of fluid}}{\text{Density of standard fluid}}$$

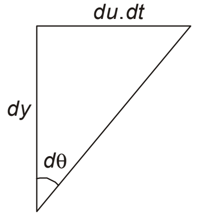
  $$= \frac{\text{Specific weight of fluid}}{\text{Specific weight of standard fluid}}$$

Remember:

☑ Specific gravity for water is 1.0 at 4°C and for mercury it is 13.6

☑ Specific gravity varies with temperature therefore it should be determined at specified temperature (4°C or 25°C).

Newton's Law of Viscosity



$$\tau = \mu \frac{du}{dy} = \mu \frac{d\theta}{dt}$$

where, τ = Shear stress

μ = Coefficient of viscosity or absolute viscosity (or dynamic viscosity)

$\frac{du}{dy}$ = Velocity gradient

$\frac{d\theta}{dt}$ = Rate of angular deformation or Rate of shear strain

- For Newtonian fluid, coefficient of viscosity remains constant.

Dynamic Viscosity and Kinematic Viscosity

Due to viscosity, a fluid offers resistance to flow

(i) Dynamic Viscosity (μ):

- Its SI unit is pascal-second or **Ns/m^2 or kg/ms**
- Its CGS unit is poise
- 1 poise = Dyne-s/cm^2 = 0.1 Ns/m^2

(ii) Kinematic Viscosity,

$$\nu = \frac{\text{Dynamic viscosity } (\mu)}{\text{Mass density } (\rho)}$$

- Its SI unit is m^2/s
- Its CGS unit is cm^2/s or stoke
- 1 stoke = cm^2/s = 10^{-4} m^2/s

Remember:

☑ Viscosity of **liquids** generally decreases with temperature whereas viscosity of **gases** increases with increase in temperature.

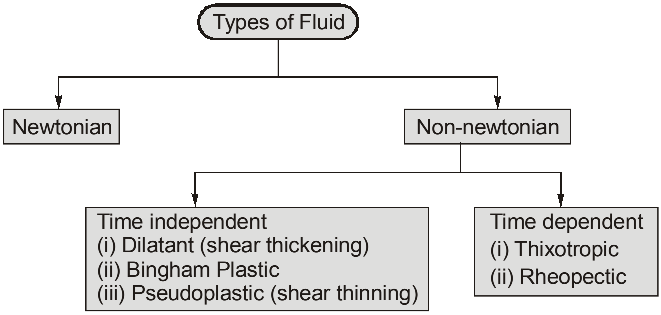
☑ Liquids with increasing order of viscosity are gasoline, water, crude oil, castor oil.

☑ Viscosity of **water** at 20°C is 1 centipoise.

☑ Viscosity is due to

- Intermolecular forces of cohesion [dominant in liquids]
- Transfer of molecular momentum between fluid layers [dominant in gases].

Types of Fluid

- 

- **Non-Newtonian Fluids**

  Non-Neutonian fluids do not follow Newton's law of viscosity. The relation between shear stress and velocity gradient is

$$\tau = A\left(\frac{du}{dy}\right)^n + B$$

  where A and B are constants depending upon type of fluid and condition of flow.

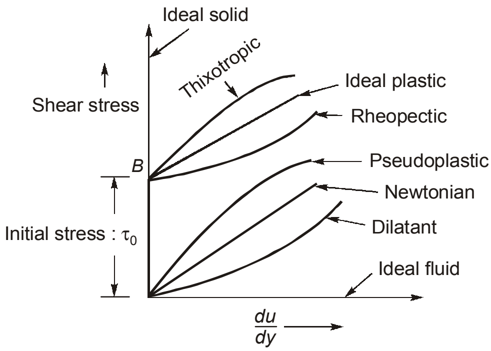
  (i) For Dilatant Fluids: $n > 1$ and $B = 0$,
  Example: Butter, Quicksand.

  (ii) For Bingham Plastic Fluids: $n = 1$ and $B \neq 0$
  Example: Sewage sludge, drilling mud, tooth paste and gel. These fluids always have certain minimum shear stress before they yield.

  (iii) For Pseudoplastic Fluids: $n < 1$ and $B = 0$
  Example: Paper pulp, Rubber solution, Lipsticks, Paints, Blood, Polymetric solutions etc.

  (iv) For Thixotropic Fluids: $n < 1$ and $B \neq 0$
  Viscosity increases with time.
  Example: Printer ink and Enamels.

  (v) For Rheopectic Fluids: $n > 1$ and $B \neq 0$
  Viscosity decreases with time.
  Example: Gypsum solution in water and Bentonite solution.

- 

Compressibility (β), Isothermal Bulk Modulus (k_T) and Adiabatic Bulk Modulus (k_a)

- Compressibility (β)

  It is inverse of bulk modulus of elasticity.

$$\beta = \frac{1}{k} = \frac{-dv}{vdp} = \frac{d\rho}{\rho dp}$$

where, k = Bulk modulus of elasticity

ρ = Density; v = Specific volume

- Isothermal bulk modulus (k_T)

$$k_T = p_{\text{final}} = \rho RT$$

- Adiabatic bulk modulus

$$k_a = \gamma\, p_{\text{final}}$$

Here, $\gamma = \frac{c_p}{c_v}$

c_p = Specific heat at constant pressure

c_v = Specific heat at constant volume

Surface Tension/Pressure Inside Drop, Bubble and Jet

Surface tension occurs at the interface of liquid and a gas or at the interface of two liquids. Surface tension is inversely proportional to temperature and it also acts when fluid is at rest.

- Liquid tends to minimize its surface area and hence surface energy.
- Excess pressure inside drop (Solid like sphere)

$$p = \frac{4\sigma}{d}$$

- Excess pressure inside bubble

$$p = \frac{8\sigma}{d}$$

Remember:

☑ The pressure inside the droplet of soap bubble will be higher than p_{atm}.
☑ The higher the pressure inside the soap bubble the smaller the size of soap bubble.

- Excess pressure inside jet

$$p = \frac{2\sigma}{d}$$

Here, d = Diameter of drop, p = Gauge pressure, σ = Surface tension

Remember:

☑ It is a **surface** phenomenon
☑ It is force per unit length (N/m)
☑ For **water-air** interface at 20°C its value is 0.0736 N/m and air-mercury interface, σ = 0.480 N/m
☑ At critical point, liquid-vapuor state are same thus surface tension = 0
☑ It is due to **cohesion** only

Capillary Action

- Height of water in capillary tube

$$h = \frac{4\,\sigma\cos\theta}{\rho g d}$$

where, h = Rise in capillary, σ = Surface tension of water
d = Diameter of tube
θ = Angle of contact between the liquid and the material.
θ = 0° for water and glass (clean)
θ = 128° for mercury and glass (clean)

	$F_{cohesion} < F_{adhesion}$	$F_{cohesion} > F_{adhesion}$
Level	Rises	Falls
θ	< 90°	> 90°
Ex.:	Water-glass	Mercury-glass

- When a liquid surface supports another liquid of density ρ_b, then rise in capillary is given as

$$h = \frac{4\sigma\cos\theta}{(\rho-\rho_b)gd}$$

- Capillary action is due to **both** adhesion and cohesion.
- For capillary action diameter of tube should be **less** than 3 cm.

II Manometry

Pascal's Law

- The intensity of pressure at any point in a stationary fluid is same in all directions.

$$p_x = p_y = p_z$$

- Pressure varies **only with depth** in stationary fluids, whereas if fluids is in motion pressure may vary in horizontal direction also.
- Fluid pressure is measured as Force/Area and it is expressed in pascal (N/m^2) or bar.

$$1 \text{ bar} = 10^5 \text{ N/m}^2 \text{ or Pa}$$

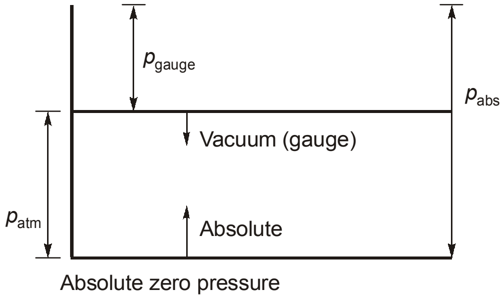
$$1 \text{ MPa} = 10 \text{ bar}$$

- Barometer shows **atmospheric** pressure.
- 1 kgf = 9.81 Newton.
- Pressure is a scalar quantity.

Absolute Pressure

Absolute pressure measured with reference to absolute zero. Absolute pressure cannot be negative

Absolute pressure = Gauge pressure + Local atmospheric pressure



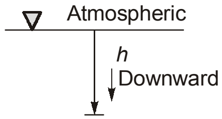
- $$p_{gauge} = \rho g h$$

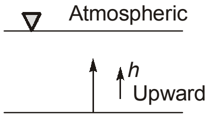
  Here, ρ = Density of fluid, g = Acceleration due to gravity,

  h = Height or depth
- **Gauge** pressure can be positive, negative or zero.
- Atmospheric pressure varies with **altitude**, **temperature** and **local** conditions.
- At **mean sea level** atmospheric pressure is 1.01×10^5 Pa or 1 bar or 10.3 m of height of water or 76 cm height of **mercury**.

Hydrostatic Law

- For h measured downward, $\frac{dp}{dh} = w$





- For upward h, $\frac{dp}{dh} = -w$

Remember:

☑ Hydrostatic pressure shows linear variation with depth below the free surface.

Conversion of one Fluid Column to Another Fluid Column

$$\sigma_1 h_1 = \sigma_2 h_2, \qquad S_1 h_2 = S_2 h_2$$

where, ρ = Density of fluid, S = Relative density

Remember:

☑ Piezometer is suitable for **small** and **positive** pressure measurement.

☑ The manometric liquid should have **high density** and **low vapour pressure**.

☑ Simple manometer/U-tube manometer can measure both **positive** and **negative** pressure.

☑ Aneroid/Mercury barometer used to measure **local** atmospheric pressure on **absolute** scale.

☑ Inclined single column manometer used to increase sensitivity by a factor of $\frac{1}{\sin\theta}$

☑ Inverted column U-tube manometer used for measuring liquid pressure only. [$S_{manometric} < S_{liquid}$]

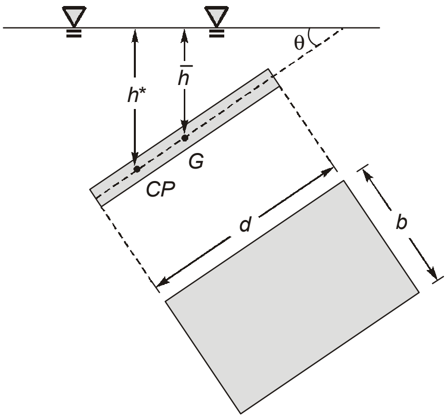
☑ Density of mercury = 13600 kg/m^3

☑ Density of air = 1.24 kg/m^3

III Hydrostatic Force

Hydrostatic Force on Submerged Surface

Case	Force	Center of pressure (h^*)
Horizontal position	$\rho g A\bar{h}$	$h^* = \bar{h}$
Vertical position	$\rho g A\bar{h}$	$h^* = \bar{h} + \frac{I_G}{A\bar{h}}$
Inclined position	$\rho g A\bar{h}$	$h^* = \bar{h} + \frac{I_G}{A\bar{h}} \sin^2\theta$



Note:

☑ Depth of centre of pressure is independent of density of the fluid.

$$I_G = \frac{bd^3}{12} \qquad \text{(For rectangular plate)}$$

$$I_G = \frac{\pi}{64}d^4 \qquad \text{(For circular plate)}$$

where, A = Area of surface touching fluid

I_G = Area moment of inertia about centroidal axis and parallel to free axis.

$\bar{h}$ = Vertical distance of CG body from free surface.

w = Specific weight

θ = Angle at which the surface is inclined with horizontal

Pressure Force on Curved Surface

- **Horizontal Force (F_H)**

  Horizontal component of the resultant hydrostatic force 'F_x' of curved surface may be computed by projecting the surface upon a vertical plane and multiplying the projected area by the pressure at its own centre of area.

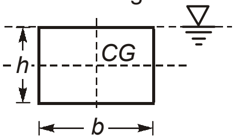
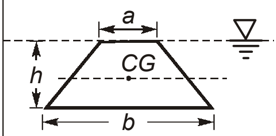
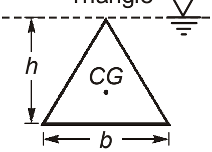
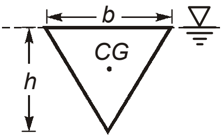
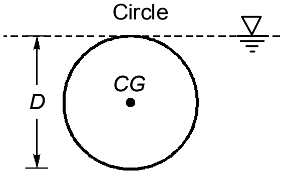
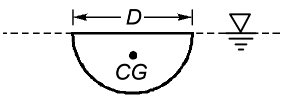
- **Vertical Force (F_V)**

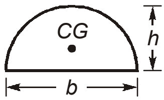
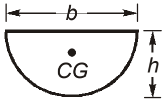
  Vertical component of force 'F_y' is equal to the weight of the liquid block lying above the curved surface upto free surface.

- **Resultant Force,** $F = \sqrt{(F_H)^2 + (F_V)^2}$

  Angle of line of action of resultant force with the horizontal is given by $\tan\theta = \dfrac{F_y}{F_x}$

Depth of Center of Pressure for Some Vertical Plane Surfaces from Liquid Surface

Surface	C.G.($\bar{h}$)	C.P.(h^*)
Rectangle 	$\frac{h}{2}$	$\frac{2h}{3}$
Trapezium 	$\frac{a+2b}{a+b}\cdot\frac{h}{3}$	$\frac{a+3b}{a+2b}\cdot\frac{h}{2}$
Triangle (a) 	$\frac{2h}{3}$	$\frac{3h}{4}$
(b) 	$\frac{h}{3}$	$\frac{h}{2}$
Circle 	$\frac{D}{2}$	$\frac{5D}{8}$
Semi Circle 	$\frac{2D}{3\pi}$	$\frac{3\pi D}{32}$

Parabola		
(a) 	$\frac{3h}{5}$	$\frac{5h}{7}$
(b) 	$\frac{2h}{5}$	$\frac{4h}{7}$

Remember:

- ☑ In case of vertical surface, when depth of immersion $(\bar{h})$ is very large then centre of pressure ≈ centre of gravity or $h^* \approx \bar{h}$.
- ☑ Magnitude of hydrostatic forces on a plane surface does not change with rotation in a horizontal plane as $\bar{h}$ remains same.

IV Buoyancy and Floatation

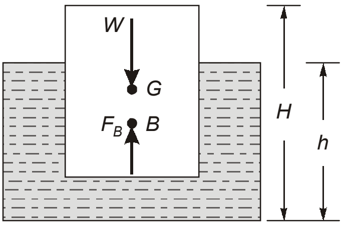
Archimedes Principle

When a body is submerged either fully or partially then it is acted upon by a force of buoyancy vertically up which is equal to weight of liquid displaced by the body.

Remember:

- ☑ This force of buoyancy always acts through the centroid of liquid displaced.
- ☑ Centre of buoyancy is that point through which buoyant force acts.

Principal of Flotation



At equilibrium

$$F_B = W$$

$$\rho_{Body} \times V = \rho_{fluid} \times \forall$$

$$H\rho_{Body} = h\rho_{fluid}$$

(for constant cross - section area)

Here, H = Height of body

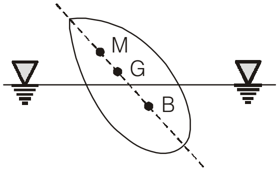
h = Height of body that is submerged in fluid

Condition for Equilibrium for Floating/Submerged Body

For stable equilibrium

- In case of **floating body**, metacenter should be above centre of gravity.

GM Positive $\Rightarrow$ *M* above *G*, $BM > BG$



Stable equilibrium

$$GM = BM - BG = \frac{I_{min}}{\forall_{immersed}} - BG$$

- In case of **submerged body**, center of buoyancy should be above centre of gravity.
  $\Rightarrow$ *B* above *G*
- Distance between metacenter and centre of buoyancy (BM) =

$$\frac{I_{min}}{V_{immersed}} \text{ (Metacentric radius)}$$

Here,

I_{min} = Moment of inertia of top view of floating body about longitudinal axis

V = Volume of body immersed in liquid

Remember:

☑ Metacentric height for rolling condition will be less than metacentric height for pitching condition.

☑ For neutral equilibrium, $M = G$.

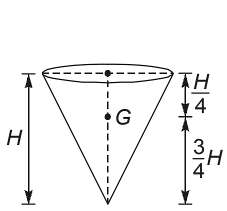
Time Period of Oscillation

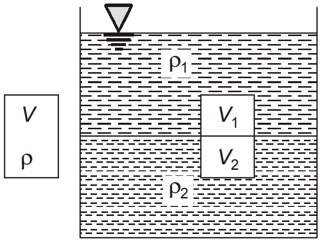
If a floating body oscillates then its time period of transverse oscillation is given by

$$T = 2\pi\sqrt{\frac{K_G^2}{g \cdot GM}}$$

Here, K_G = Least radius of gyration, GM = Meta-centric height

For cone the center of gravity lies at $\frac{3}{4}H$ from the pointed end.





$$\frac{V_2}{V} = \frac{\rho - \rho_1}{\rho_2 - \rho_1}$$

V Fluid Kinematics

- Lagrangian concept is for single fluid particle
- Eularian concept is for particular section or point

Steady and Unsteady Flow

If the fluid and flow characteristics (such as density, velocity, pressure, etc.) **at a point** do not change with time, the flow is said to be steady flow.

$$\frac{dv}{dt} = 0, \frac{dp}{dt} = 0, \frac{d\rho}{dt} = 0 \quad v = \text{velocity}, \ \rho = \text{density} \quad \text{(For steady flow.)}$$

- It is applicable for **all** properties.
- If the fluid and flow variables at a point may **change** with time, the flow will be **unsteady**.

Uniform and Non-Uniform Flow

If the velocity vector at all points in the flow is same **at any instant of time**, the flow is **uniform flow.** If the velocity vector **varies** from point to point at any instant of time, the flow will be **non-uniform**.

$$\frac{dv}{ds} = 0$$

- It is applicable **only** for velocity.

Laminar and Turbulent Flow

In laminar flow, the particles move in layers sliding smoothly over the adjacent layers while in turbulent flow particles have the random and erratic movement, intermixing in the adjacent layers.

Streakline

When a dye is injected in a liquid or smoke in a gas so as to trace the subsequent motion of fluid particles passing a fixed point, the path followed by the dye or smoke is called the streakline.

Pathline

A pathline is a curve traced by a single fluid particle during its motion.

Streamline

A streamline is an imaginary line drawn in a flow field such that a tangent drawn at any point on this line represents the direction of velocity vector at that point.

Remember:

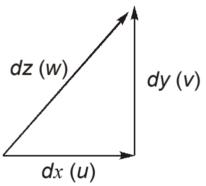
- ☑ There is no **velocity** component normal to stream lines.
- ☑ In steady flow streakline, pathline and streamline are Identical.
- ☑ There is no discharge across a streamline.

Equation of stream line

Tangent to stream line gives velocity

$$\vec{V} \times \overrightarrow{dx} = 0$$

$$\begin{vmatrix} \hat{i} & \hat{j} & \hat{k} \\ u & v & w \\ dx & dy & dz \end{vmatrix} = 0$$



$$\frac{dx}{u} = \frac{dy}{v} = \frac{dz}{w}$$

Here, u, v, w = Components of velocity in x, y, z direction

Continuity Equation (Conservation of Mass)

$$\rho_1 A_1 V_1 = \rho_2 A_2 V_2 \quad \text{for compressible flow}$$

Here, ρ = Density, A = Area, V = Velocity

- For incompressible fluid density will be constant thus continuity equation will be

$$A_1 V_1 = A_2 V_2 \quad \text{for incompressible flow}$$

General Continuity Equation

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x}(\rho u) + \frac{\partial}{\partial y}(\rho v) + \frac{\partial}{\partial z}(\rho w) = 0$$

$$\frac{d\rho}{dt} + \rho(\nabla \vec{V}) = 0 \quad \text{(Vector form)}$$

Special Case:

- If flow is steady then $\left(\frac{\partial \rho}{\partial t} = 0\right)$

  Thus continuity equation will be