Military Institute of Science and Technology

EWCE 261

Fluid Mechanics

3 Credit Hour

Md. Atikuzzaman

Lecturer

Department of Environmental, Water Resources and Coastal Engineering

Syllabus:

1. Development and Scope of Fluid Mechanics
2. Fluid Properties
3. Fluid Statics
4. Similitude and Dimensional Analysis
5. Steady Incompressible Flow in Pressure Conduits: Laminar Flow and Turbulent Flow
6. General Equation for Fluid Friction
7. Empirical Equation for Pipe Flow
8. Minor Losses in Pipe Flow
9. Fluid Measurement: pitot tube, orifice, mouthpiece, nozzle, venturimeter, weir.
10. Pipe Flow Problems: Pipes in Series and Parallel, Branching Pipes, Pipe Networks

Syllabus: (To be Covered in Part A)

1. Kinematics of Fluid Flow
2. Fluid Flow Concepts and Basic Equations: Continuity Equation, Bernoulli's Equation, Energy Equation
3. Momentum Equation and Forces in Fluid Flow

Reference Books

- Fluid Mechanics with Engineering Application by E. Finnermore & J. Franzini
- Fluid Mechanics by Md. Abdul Halim
- A Textbook of Fluid Mechanics and Hydraulic Machines by Dr. R.K. Bansal.
- A Textbook of Hydraulics, Fluid Mechanics and Hydraulic Machines by R.S. Khurmi

Development of Fluid Mechanics
Scope of Fluid Mechanics
Fluid Properties

Application and scope of fluid mechanics



Fluid is a substance capable of flowing. Fluid Mechanics is a branch of science that deals with the behavior of fluids (liquid or gas) at rest as well as motion. Thus this branch deals with statics, kinematics and dynamic aspects of fluids.

The study of fluid at rest – fluid statics

The study of fluid at motion without considering pressure forces – fluid kinematics but velocity acceleration, patterns of flow are considered.

The study of fluid at motion with considering pressure forces – fluid dynamics

Fluid dynamics deals with the relation between velocities and accelerations of fluids.

Scope of Fluid Mechanics:

Some practical phenomena related to fluid are:

- Air as a transportation mean
- Air resistance to slow down a landing
- Water surface for boating
- Hydroelectric dams
- The currents in the oceans and the seas
- Dispersion of wastes in lakes, rivers and oceans
- Passage of blood through our veins etc.

The design of almost all means of **transportation** requires application of the principles of fluid mechanics. Included are **aircraft**, **vertical takeoff** and **landing aircraft requiring minimum runway length**, **surface ships**, **submarines**, **automobiles** etc. The design of **propulsion systems for space flight** as well as for **toy rockets** is based on the principles of fluid mechanics.

The design of all types of fluid machinery including pumps, compressors and turbines clearly requires knowledge of the basic principles of fluid mechanics. **Lubrication** is an application of considerable importance in fluid mechanics. **Heating** and **ventilating systems** for private homes, large office buildings and underground tunnels and the **design of pipeline systems** are further examples of technical problem areas requiring knowledge fluid system.

Knowledge of fluid mechanics is essential in such diverse branches of engineering as aeronautics, automobile engineering, biomedical engineering, structural engineering, mining and metallurgical engineering, naval architecture, water resources engineering.

The design of **blood substitutes**, **breathing aids** and other such devices must rely on the basic principles of fluid mechanics. It is commonplace today to perform **model studies** to determine the aerodynamic forces on and flow fields around various structures.

Application and scope of fluid mechanics

- Water surface for boating
- Hydroelectric dams, other hydraulic structures
- The currents in oceans and seas
- Dispersion of wastes in lakes, rivers and oceans
- Design of pipeline system

Application and scope of fluid mechanics

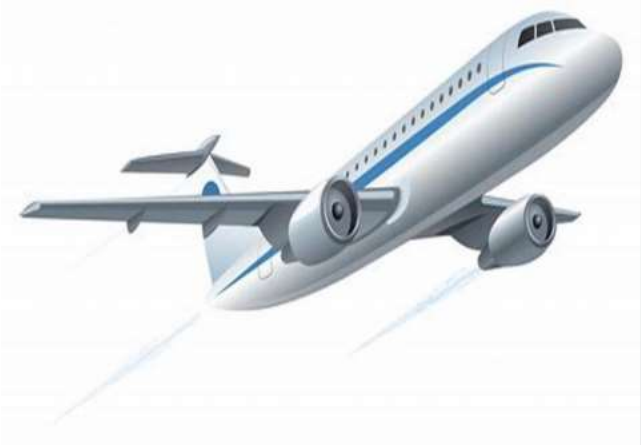


Application and scope of fluid mechanics

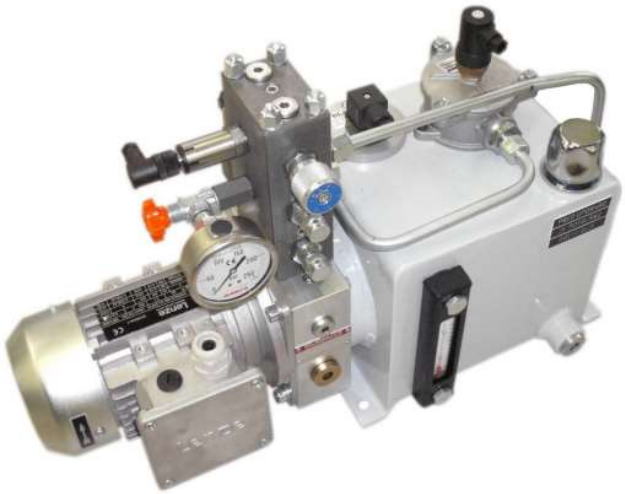




Application and scope of fluid mechanics









Definition of Fluid and its Type

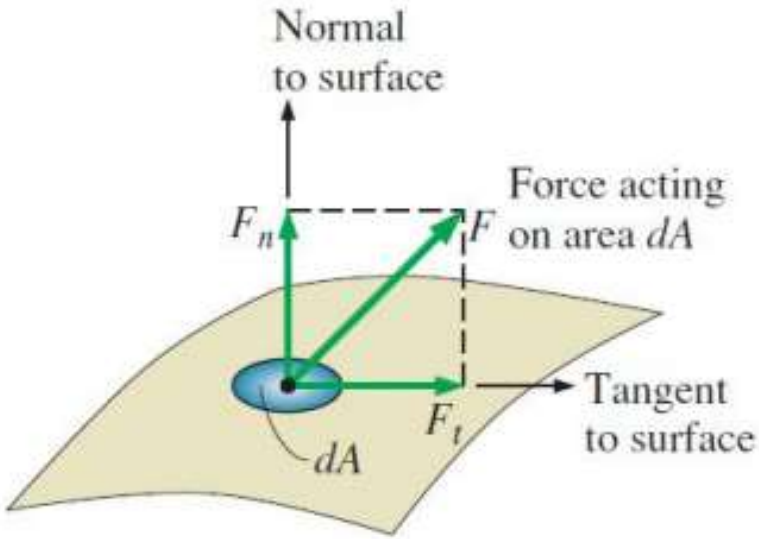
Stress: Force per unit area.

Normal stress: The normal component of a force acting on a surface per unit area.

Shear stress: The tangential component of a force acting on a surface per unit area.

Pressure: The normal stress in a fluid at rest.

Zero shear stress: A fluid at rest is at a state of zero shear stress.



$$\text{Normal stress: } \sigma = \frac{F_n}{dA}$$

$$\text{Shear stress: } \tau = \frac{F_t}{dA}$$

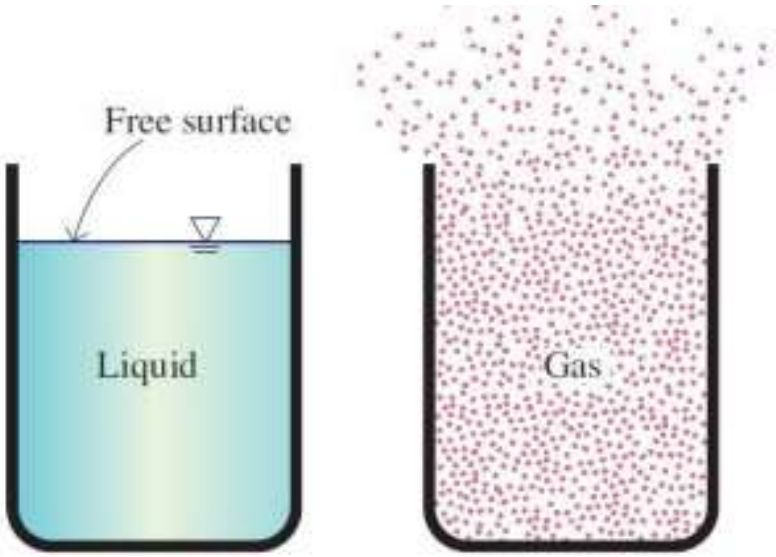
The normal stress and shear stress at the surface of a fluid element.
For fluids at rest, the shear stress is zero and pressure is the only normal stress.

Definition of Fluid and Its Types

In a liquid, groups of molecules can move relative to each other, but the volume remains relatively constant because of the strong cohesive forces between the molecules. As a result, a liquid takes the shape of the container it is in, and it forms a free surface in a larger container.

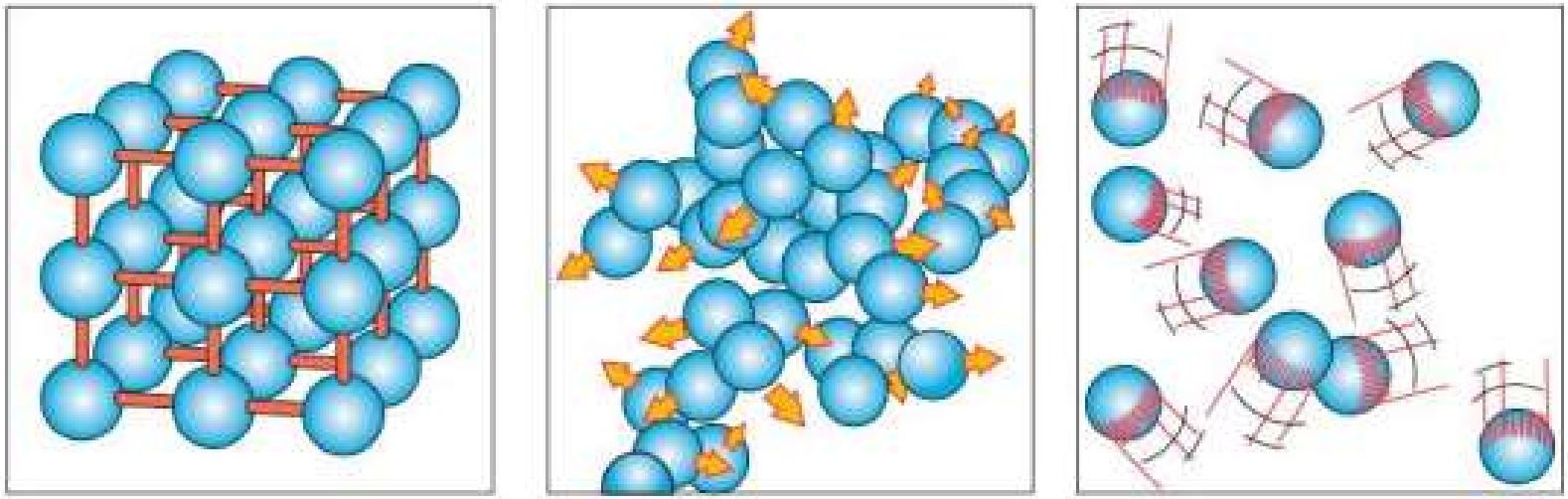
A gas expands until it encounters the walls of the container and fills the entire available space. This is because the gas molecules are widely spaced, and the cohesive forces between them are very small. Unlike liquids, a gas in an open container cannot form a free surface.

Definition of Fluid and Its Types



Unlike a liquid, a gas does not form a free surface, and it expands to fill the entire available space.

Definition of Fluid and Its Types



The arrangement of atoms in different phases: (a) molecules are at relatively fixed positions in a solid, (b) groups of molecules move about each other in the liquid phase, and (c) individual molecules move about at random in the gas phase.

Physical Properties of Fluid

Density: It is defined as mass of the fluid per unit volume.

$\rho = m/V$

The SI unit for the mass density is kg/m^3

Density of water , $\rho = 1000$ kg/m

1. Oil floats on water because it is less denser.

2. 2.Boat Floats on water as boat is less denser than water

Physical Properties of Fluid

Specific Weight or Weight Density: It is defined as weight of the fluid per unit volume.

$\gamma = W/V = mg/V = (m/V)g = \rho g$

The SI unit for the specific weight is N/m^3 while the English unit is lb/ft^3

Physical Properties of Fluid

Specific Volume: Specific volume is the volume occupied by unit mass of the fluid. It is represented by Vs. It is the reciprocal of density.

$V_s = V/M = 1 / \rho$

UNIT: m^3 / Kg

Specific Gravity: It is the ratio of density of a substance to the density of reference substance (fluid: water, gas: air). Denoted by S.

Specific Gravity of water is 1.

Physical Properties of Fluid

Specific Volume: Specific volume is the volume occupied by unit mass of the fluid. It is represented by Vs. It is the reciprocal of density.

$Vs = V/M = 1 / \rho$

UNIT: m^3 / Kg

Specific Gravity: It is the ratio of density of a substance to the density of reference substance (fluid: water, gas: air). Denoted by S.

Specific Gravity of water is 1.

Physical Properties of Fluid

Surface Tension: This property enables fluid to resist tensile stress. Due to this property, liquid free surface assumes minimum surface area. Dimension is force per unit length.

- It enables water to support small materials like dust particles, needles etc.
- Small insects can walk on water surface due to this property.
- Falling drops of water, soap bubbles become spherical.
- Capillary rise or fall in a narrow tube.

Physical Properties of Fluid

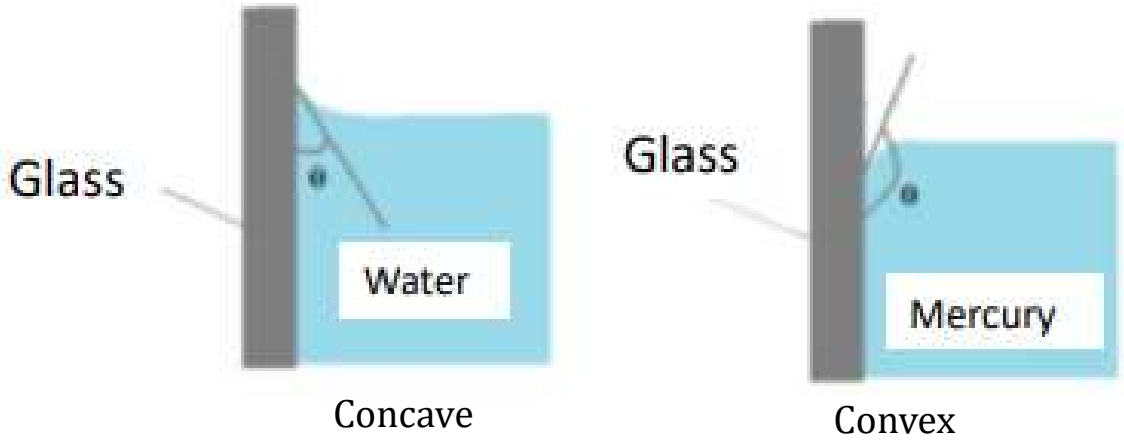
Cohesion: Attraction between same molecules. This property enables the liquids to resist small tensile stress.

Adhesion: Attraction between different molecules. This enables the two different liquids to adhere to each other or to a liquid to adhere to another body.

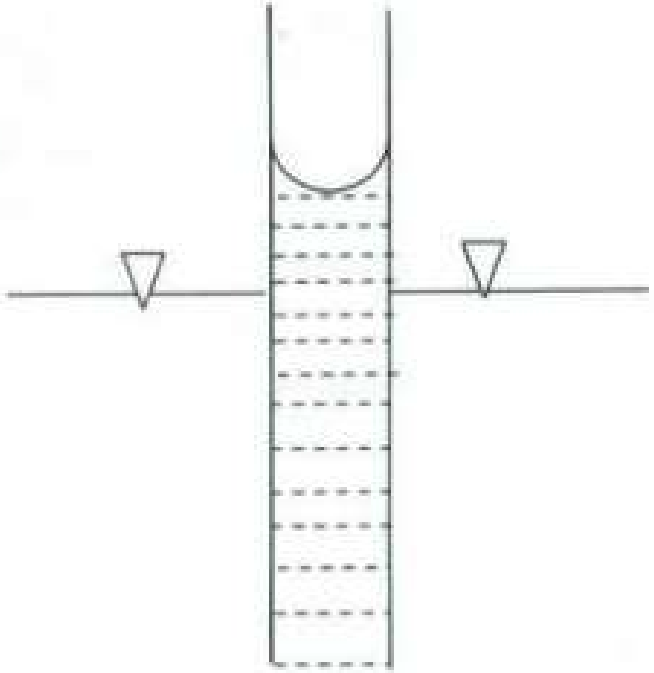
Capillarity: It can be defined as the tendency of a liquid in a capillary tube to rise or fall as a result of surface tension when the tube is dipped in liquid.

Physical Properties of Fluid

Angle of Contact: When the liquid is contact with solid, the angle between the solid surface and the tangent to the free surface of the liquid at the point of contact measured from inside the liquid is called angle of contact.

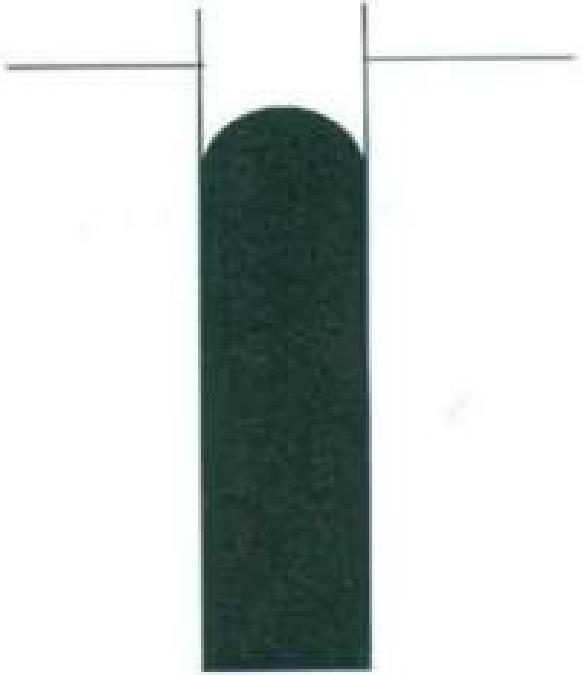


Adhesion>Cohesion



Water meniscus in glass tube

Cohesion>Adhesion



Mercury meniscus in glass tube

Fig.1.6: Behavior of water and mercury meniscus inside a tube

1.6.4 Capillarity. Capillarity is defined as a phenomenon of rise or fall of a liquid surface in a small tube relative to the adjacent general level of liquid when the tube is held vertically in the liquid. The rise of liquid surface is known as capillary rise while the fall of the liquid surface is known as capillary depression. It is expressed in terms of cm or mm of liquid. Its value depends upon the specific weight of the liquid, diameter of the tube and surface tension of the liquid.

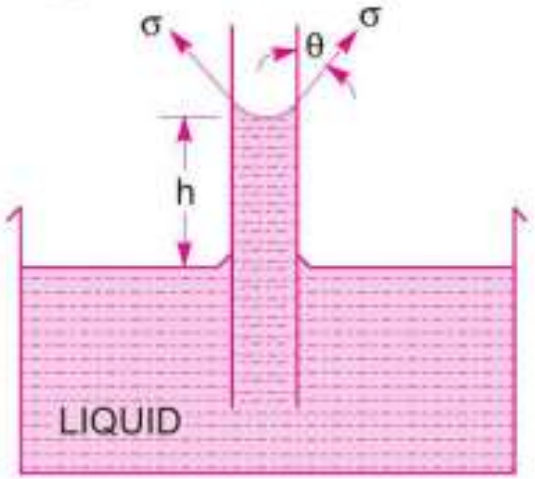


Fig. 1.13 *Capillary rise.*

Expression for Capillary Rise. Consider a glass tube of small diameter 'd' opened at both ends and is inserted in a liquid, say water. The liquid will rise in the tube above the level of the liquid.

Let h = height of the liquid in the tube. Under a state of equilibrium, the weight of liquid of height h is balanced by the force at the surface of the liquid in the tube. But the force at the surface of the liquid in the tube is due to surface tension.

Let σ = Surface tension of liquid

θ = Angle of contact between liquid and glass tube.

The weight of liquid of height h in the tube = (Area of tube $\times$ h) $\times$ ρ $\times$ g

$$= \frac{\pi}{4} d^2 \times h \times \rho \times g$$

where ρ = Density of liquid

Vertical component of the surface tensile force

$$= (\sigma \times \text{Circumference}) \times \cos\theta$$

$$= \sigma \times \pi d \times \cos\theta \qquad \ldots(1.18)$$

For equilibrium, equating (1.17) and (1.18), we get

$$\frac{\pi}{4} d^2 \times h \times \rho \times g = \sigma \times \pi d \times \cos\theta$$

or

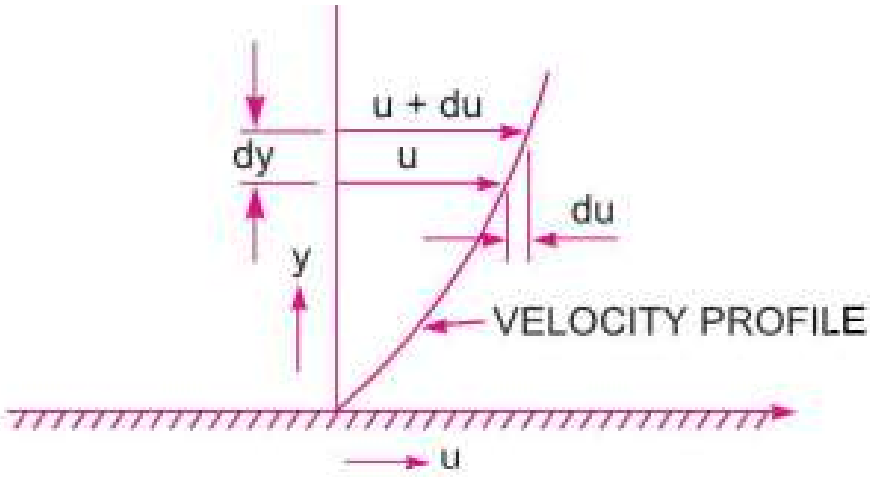
$$h = \frac{\sigma \times \pi d \times \cos\theta}{\frac{\pi}{4} d^2 \times \rho \times g} = \frac{4\sigma \cos\theta}{\rho \times g \times d} \qquad \ldots(1.19)$$

The value of θ between water and clean glass tube is approximately equal to zero and hence $\cos\theta$ is equal to unity. Then rise of water is given by

$$h = \frac{4\sigma}{\rho \times g \times d} \qquad \ldots(1.20)$$

Physical Properties of Fluid

Viscosity: Viscosity is the property of fluid by virtue of which it offers resistance to shear or angular deformation. So, the viscosity of fluid is a measure of its resistance to flow. Newton postulated that shearing or frictional stress is proportional to the spatial rate of change of velocity (i.e. velocity gradient) normal to the flow.



Mathematically, $\tau \propto \frac{du}{dy}$

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

Velocity Gradient

Dynamic Viscosity

Dynamic Viscosity

Unit:

$$\mu = \frac{\tau}{\frac{du}{dy}} = \frac{\text{shear stress}}{\frac{\text{velocity}}{\text{displacement}}} = \frac{\frac{N}{m^2}}{\frac{m/s}{m}}$$

$$= \frac{N/m^2}{\left(\frac{m}{s} \times \frac{1}{m}\right)} = \frac{N.s}{m^2}$$

$= Nsm^{-2}$ or Pa.s

SI Unit

C.G.S. unit $\mu = \frac{\text{dyne.sec}}{cm^2}$ (1 poise)

$$1 \text{ poise} = \frac{\text{dyne.sec}}{cm^2} = \frac{10^{-5} N.sec}{\left(\frac{1}{100} m\right)^2} = \frac{10^{-5}}{\frac{1}{10^4}} N.s/m^2$$

[1 dyne $= 10^{-5} N$]

$$= 10^{-5} . 10^4 \ N.S/m^2$$

$$= 10^{-1} \ N.S/m^2$$

$$\therefore 1 \text{ poise} = \frac{1}{10} N.S/m^2$$

Kinematic Viscosity

→ Kinematic viscosity is the ratio of dynamic viscosity of the fluid to its density.

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

unit: Kinematic viscosity, $\nu = \frac{\mu}{\rho} = \frac{N \cdot s/m^2}{kg/m^3} = \frac{\left[kg \cdot \frac{m}{s^2}\right] \cdot s/m^2}{kg/m^3}$

$= kg \cdot \frac{m}{s^2} \cdot \frac{s}{m^2} \times \frac{m^3}{kg}$

$= m^2/sec$ (SI unit)

CGS unit: cm^2/sec (1 stoke)

$cm^2/sec = \left(\frac{1}{100}\right)^2 m^2/sec = 10^{-4} m^2/sec$

1 centistoke $= \frac{1}{100}$ stoke

Physical Properties of Fluid

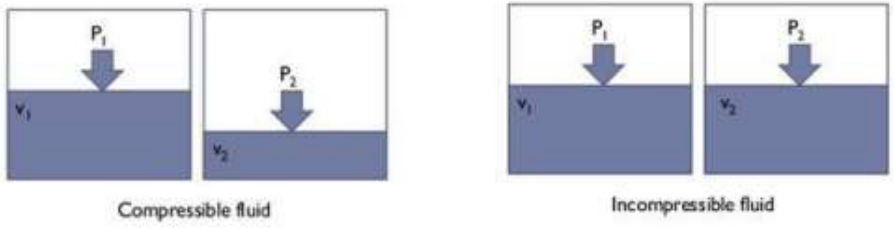
Effect of Temperature on Viscosity: As the temperature of the liquid fluid increases its viscosity decreases. When the liquid is heated the cohesive forces between the molecules reduce thus the forces of attraction between them reduce, which eventually reduces the viscosity of the liquids.

The viscosity of the gases increases as the temperature of the gas increases. In the gases the cohesive forces between the molecules is lesser, when we increase the temperature the collision between the molecules will be high as because the kinetic energy will be high, so molecular momentum transfer will be high. As a result viscosity will increase.

Physical Properties of Fluid

Compressibility: For solids it is tight so solids cannot be compressed. For gases, the atoms are loosely packed and it is easily compressible. Generally all fluids are compressible and in case of liquids, the compressibility is less. For most practical problem, water is considered to be incompressible. But in case of water flowing through pipes, when sudden or larger changes in pressure occur, the compressibility can not be neglected.

Compressible and Incompressible flows



1.6 COMPRESSIBILITY

Fluids may be compressed by an external pressure applied to a volume of fluid. Gases, however, are compressed by an external pressure to a much greater degree than liquids.

The compressibility of a fluid may be defined as the variation of its volume with the variation of pressure and is inversely proportional to its bulk modulus of elasticity. Consider that a force is applied to any fluid so that the volume of the fluid V decreases by an amount ΔV. The decrease per unit volume is proportional to the force per unit area (i.e. pressure) of the fluid. So

$$p \propto \frac{-dV}{V}$$

or

$$p = -K\frac{dV}{V}$$

or

$$K = -\frac{p}{dV/V} \qquad (1.3)$$

Compressibility = $\frac{1}{k}$

where K is the volume or bulk modulus of elasticity which has the dimensions of pressure, i.e. force per unit area (N/m^2).

Types of Fluid

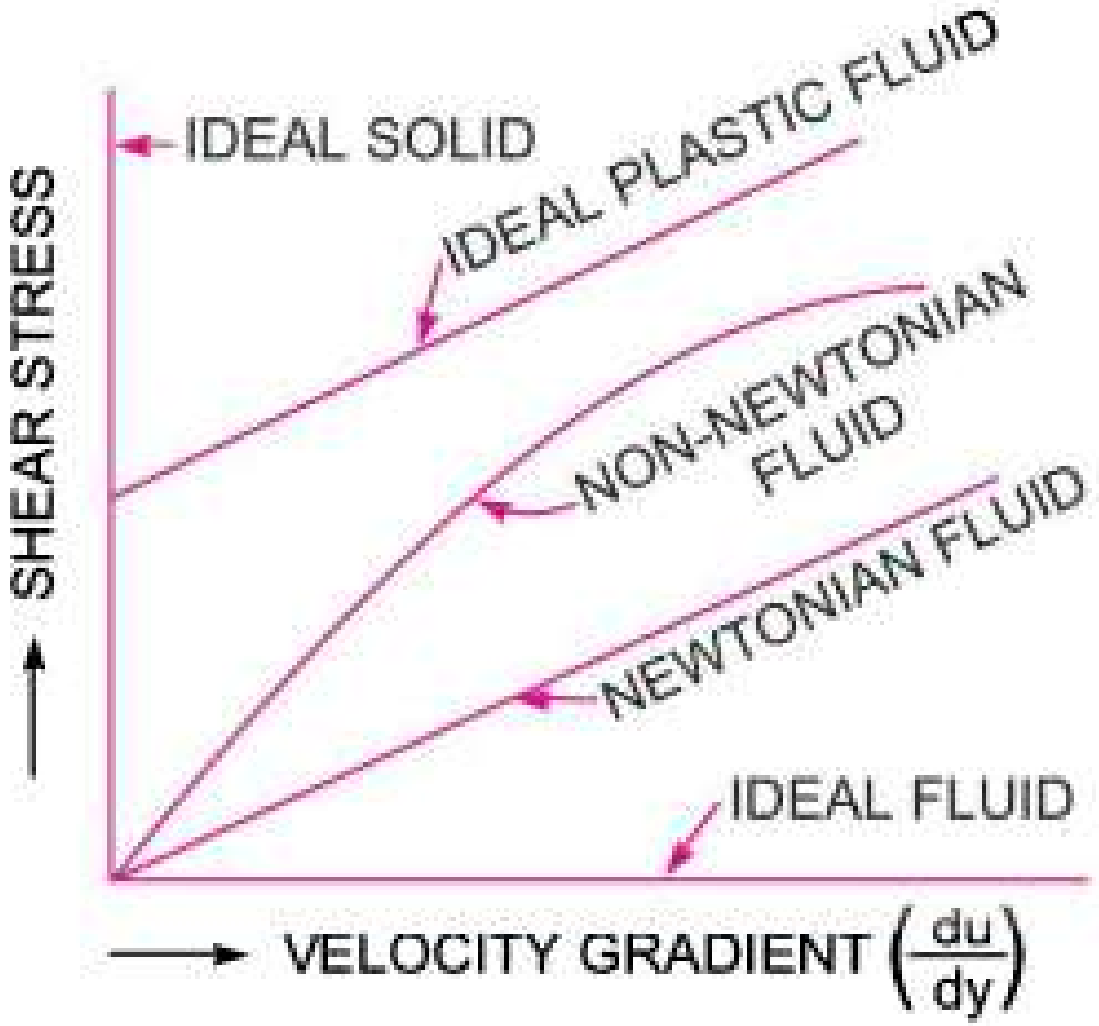
Ideal Fluid: Incompressible and no viscosity. This is an imaginary fluid.

Real Fluid: Have viscosity. In actual practice all fluids are real fluid.

Newtonian Fluid: A real fluid in which shear stress is directly proportional to the velocity gradient.

Non-Newtonian Fluid: A real fluid in which shear stress is not directly proportional to the velocity gradient.

Ideal Plastic Fluid: Shear stress is more than yield value and shear stress is proportional to velocity gradient.


IDEAL SOLID
IDEAL PLASTIC FLUID
NON-NEWTONIAN FLUID
NEWTONIAN FLUID
IDEAL FLUID
SHEAR STRESS
VELOCITY GRADIENT (du/dy)

Mathematical Problems

Example 1.1

A liquid weighs 29.42 kN and occupies 4 m^3. Determine its specific weight, mass density and specific gravity.

Solution

Specific weight, $\gamma = \frac{W}{V} = \frac{29.42 \times 1000}{4} = 7355\ N/m^3$

Mass density, $\rho = \frac{\gamma}{g} = \frac{7355}{9.81} = 749.75\ kg/m^3$

Specific gravity, $S = = \frac{749.55}{1000} = 0.74975$

Example 1.3

A capillary tube having an inside diameter of 6 mm is dipped into water at 20°C. Determine the height of capillary rise. Take $\alpha = 30^0$ and $g = 9.81\ m/s^2$.

Solution From Table 1.1, we have for water at 20°C, $\sigma = 0.073$ N/m and $\rho = 998\ kg/m^3$. Therefore, we obtain

$$h = \frac{4\sigma \cos\alpha}{\rho g d} = \frac{4 \times 0.073 \times \cos 30^0}{998 \times 9.81 \times 6 \times 10^{-3}} = 4.30 \times 10^{-3}\ m = 4.30\ mm$$

Table 1.1 Properties of water

Tempe-rature T(^{o}C)	Density ρ(kg/m^{3})	Kinematic viscosity ν (m^{2}/s)*10^{-6}	Surface tension σ (N/m)	Bulk modulus of elasticity K(N/m^{2})*10^{9}
0	999.87	1.787	0.0757	1.98
1	999.93	1.728	0.0755	
2	999.97	1.671	0.0753	
3	999.99	1.618	0.0751	
4	1000.00	1.567	0.0749	
5	999.99	1.519	0.0748	2.03
6	999.97	1.472	0.0747	
8	999.88	1.386	0.0745	
10	999.73	1.307	0.0742	2.09
12	999.52	1.235	0.0740	
14	999.27	1.169	0.0737	2.14
16	998.97	1.109	0.0734	
18	998.62	1.053	0.0731	
20	**998.23**	**1.002**	**0.0728**	**2.19**
25	997.08	0.890	0.0720	
30	995.68	0.798	0.0712	2.25
35	994.06	0.719	0.0704	
40	992.25	0.653	0.0696	2.26
45	990.25	0.596	0.0689	
50	988.07	0.547	0.0680	2.26
60	983.24	0.467	0.0661	2.25
70	977.81	0.404	0.0643	2.22
80	971.83	0.355	0.0626	2.17
90	965.34	0.315	0.0607	
100	958.38	0.282	0.0589	

Example

The specific weight of water at ordinary pressure and temperature is 9.81 kN/m^3. The specific gravity of mercury is 13.55. Calculate the density of water and the specific weight and density of ~~water.~~ mercury.

Solution:

$$\rho_{water} = \frac{\gamma_{water}}{g} = \frac{9.81\,kN/m^3}{9.81\,m/s^2} = 1.00\,Mg/m^3 = 1.00\,g/mL$$

$$\gamma_{mercury} = S_{mercury} \times \gamma_{water} = 13.55 \times 9.81 = 133\,kN/m^3$$

$$\rho_{mercury} = S_{mercury} \times \rho_{water} = 13.55 \times 1 = 13.55\,Mg/m^3$$

Unit Transformation

$$\frac{KN}{m^3} \times \frac{s^2}{m}$$

$$= \frac{1000\ N}{m^3} \times \frac{s^2}{m}$$

$$= \frac{1000 \times kg\, ms^{-2}}{m^3} \times \frac{s^2}{m}$$

$$= \frac{1000 \times 1000\, gm.\, ms^{-2}}{m^3} \times \frac{s^2}{m}$$

$$= \frac{10^6\, gm.\, m}{m^3 \times s^2} \times \frac{s^2}{m}$$

$$= 10^6 \frac{gm}{m^3} = 1\ Mg/m^3 \quad [\because 1\ Mg = 10^6\, gm]$$

Megagram

Example: The specific gravity of water at 20° c is 0.998 and its viscosity is 0.001 N.s/m^2. Determine its kinematic viscosity.

Solution. For water at 20° c, $\mu = 0.001$ N.s/m^2 and $\rho = 0.998 \times 1000 = 998$ Kg/m^3

$v = \mu / \rho = 0.001/998 = 1.002 \times 10^{-6}$ m^2 /s

Example: A vessel of 4 m^3 volume contains an oil, which weighs 30.2 KN. Determine the specific gravity of oil.

Solution. We know, specific weight, $\gamma = W/V = 30.2/4 = 7.55$ KN/m^3

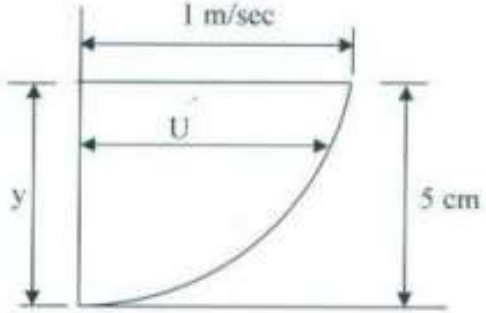
Specific gravity of oil = Specific weight of liquid/Specific weight of water = 7.55/9.81 = 0.77

Example: A fluid has a dynamic viscosity of 0.5 poise. Calculate the velocity gradiant and the intensity of shear stress at the boundary. If the fluid is filled between two parallel plates 5 cm apart and one plate is moving at a velocity of 1 m/s, other plate is stationary. Assume that distribution of velocity is $U=100-k(5-y)^2$

Solution:

The equation of parabola is given by

$$U = 100 - k(5-y)^2$$



$U = 0$, when $y = 0$. Therefore, $k = 4$, and the equation becomes

$$U = 100 - 4(5-y)^2$$

$$\text{Or, } \frac{du}{dy} = 8(5-y)$$ **Ignoring the negative sign**

From equation 1.3 we have $\tau = \mu \frac{du}{dy}$

Therefore, $\tau = \mu * 8(5-y)$

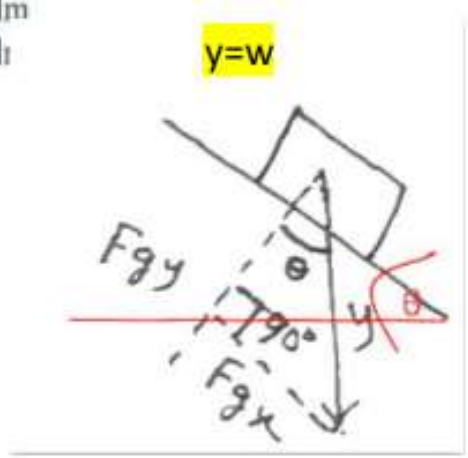
The maximum shear stress occurs at the lower plate, where $y = 0$.

$\tau_{max} = 0.5 \times 8 \times 5$

$= 20$ dynes/cm^2

Example

A cubical block weighing 200 gm and having a 20 cm edge is allowed to slide down on an inclined plane surface making an angle of 20^0 with the horizontal on which there is a thin film having a viscosity of 2.2×10^{-3} N-s/m^2. What terminal velocity will be attained if the film thickness is estimated to be 0.025 mm?



Solution:

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

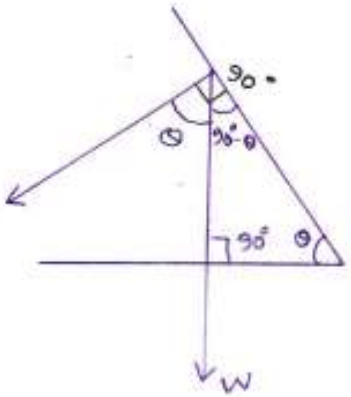
Here, $\mu = 2.2\times10^{-3}$, $\tau = \frac{Force}{Area}$ and dy $= 0.025\times10^{-3}$ m.

So, $\tau = \frac{0.20\times9.81\times\sin 20^0}{0.2\times0.2} = 16.78$ N/m^2

Now we get, $16.78 = 2.2\times10^{-3}\times\frac{du}{dy}$

So $\frac{du}{dy} = 762.55\times10^2$

So **du = 1.91 cm/sec.**



$$\sin\theta = \frac{Fgx}{y}$$

$$\Rightarrow Fgx = y\sin\theta$$

$$= w\sin\theta$$