Chapter 5 Solids and Fluid Dynamics

Learning Objectives

After studying this chapter, the students will be able to:

- Distinguish between the structures of crystalline, amorphous, and polymeric solids.
- Describe that deformation of solids in one dimension [That it is caused by a force and that in one dimension, the deformation can be tensile or compressive.]
- Define and use the terms stress, strain and the Young's modulus
- Describe an experiment to determine the Young's modulus of a metal wire.
- Describe and use the terms elastic deformation, plastic deformation and elastic limit
- Justify why and apply the fact that the area under the force-extension graph represents the work done
- Determine the elastic potential energy of a material [That is deformed within its limit of proportionality from the area under the force-extension graph. Also state and use $E_p = \frac{1}{2}kx^2$ for a material deformed within its limit of proportionality]
- State and use Archimedes' principle and flotation
- Justify how ships are engineered to float in the sea
- Define and apply the terms: steady (streamline or laminar) flow, incompressible flow and non - viscous flow as applied to the motion of an ideal fluid.
- State and use equation of continuity to solve problems
- Explain that squeezing the end of a rubber pipe results in increase in flow velocity
- Justify that the equation of continuity is a form of the principle of conservation of mass.
- Justify that the pressure difference can arise from different rates of flow of a fluid [Bernoulli effect]
- Explain and apply Bernoulli's equation for horizontal and vertical fluid flow.
- Explain why real fluids are viscous fluids.
- Describe how viscous forces in a fluid cause a retarding force on an object moving through it.
- Describe super fluidity [As the state in which a liquid will experience zero viscosity. Students should know the implications of this state e.g. this allows for super fluids to creep over the walls of containers to 'empty' themselves. It also implies that if you stir a superfluid, the vortices will keep spinning indefinitely.]
- Analyze the real-world applications of the Bernoulli effect [For example, atomizers in perfume bottles, the swinging trajectory of a spinning cricket ball and the lift of a spinning golf ball (the Magnus effect), the use of Venture ducts in filter pumps and car engineers to adjust the flow of fluid, etc.]

Materials have specific uses depending upon their characteristics and properties, such as hardness, ductility, malleability, etc. What makes a metal hard and other soft? It depends upon the structure, the particular order and bonding of atoms and molecules in a material. Similarly, the study of fluids in motion is relatively complicated but analysis can be simplified by making a few assumptions. The analysis is further simplified by the use of two important conservation principles, the conservation of mass and conservation of energy. The law of conservation of mass gives us the equation of continuity while the law of conservation of energy is the basis of Bernoulli's equation.

5.1 CLASSIFICATION OF SOLIDS

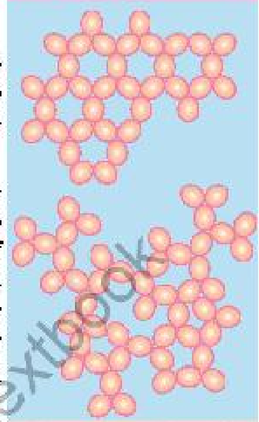
Crystalline Solids

In crystalline solids, there is a regular arrangement of atoms and molecules. The neighbours of every molecule are arranged in a regular pattern that is consistent throughout the crystal. There is, thus, an ordered structure in crystalline solids.

Most solids, like metals and ceramics have a crystalline structure. This means their atoms, molecules or ions are arranged in a regular pattern. The arrangement of molecules, atoms or ions within all types of crystalline solids can be studied using various techniques such as X-ray Diffraction (XRD) and Transmission Electron Microscopy (TEM). It should be noted that atoms, molecules or ions in a crystalline solid are not static. For example, each atom in a crystal vibrates about a fixed point with an amplitude that increases with rise in temperature. It is the average atomic positions which are perfectly ordered over large distances.

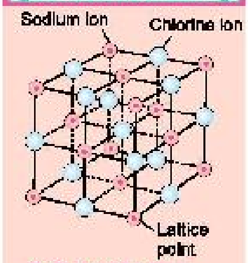
The cohesive forces between atoms, molecules or ions in crystalline solids maintain the strict long-range order inspite of atomic vibrations. For every crystal, however, there is a temperature at which the vibrations become greater that the structure suddenly breaks up, and the solid melts. The transition from solid (order) to liquid (disorder) is, therefore, abrupt or discontinuous. Every crystalline solid has a definite melting point e.g., Quartz, Calcite, Sugar, Mica, diamond, etc.

For your information



Glassy and crystalline-solid-short and long-range order.

For your information

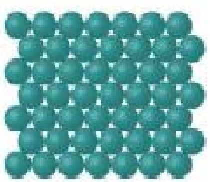


NaCl crystal lattice

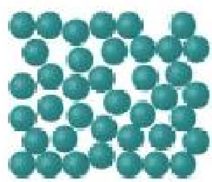
Amorphous or Glassy Solids

The word amorphous means without form or structure. Thus, in amorphous solids there is no regular arrangement of molecules like that in crystalline solids. We can, therefore, say that amorphous solids are more like liquids with the disordered structure frozen in.

For example, ordinary glass, which is a solid at ordinary temperature, has no regular arrangement of molecules. On heating, it gradually softens into a paste like state before it becomes a very viscous liquid at almost 800°C. Thus, amorphous solids are also called glassy solids. This type of solids has no definite melting point e.g., plastic, glass, fused silicon, etc.



Crystalline solids



Amorphous solids

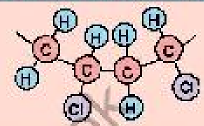
Polymeric Solids

Polymers are solid materials with a structure that is intermediate between order and disorder. They can be classified as partially or poorly crystalline solids.

Polymers form a large group of naturally occurring and synthetic materials. Plastics and synthetic rubbers are termed as polymers because they are formed by polymerization reactions in which relatively simple molecules are chemically combined into massive long chain molecules, or three-dimensional structures. These materials have rather low specific gravity compared with even the lightest of metals, and yet exhibit good strength to weight ratio.

Polymers consist wholly or in part of chemical combinations of carbon with oxygen, hydrogen, nitrogen and other metallic or non metallic elements. Polythene, polystyrene and nylon, etc. are examples of polymers. Natural rubber is composed in the pure state entirely of a hydrocarbon with the formula $(C_5H_8)_n$.

For your information



Parts of a PVC molecule

5.2 MECHANICAL PROPERTIES OF SOLIDS

Deformation in Solids

If we hold a soft rubber ball in our hand and then squeeze it, the shape or volume of the ball will change. However, if we stop squeezing the ball, and open our hand, the ball will return to its original spherical shape. This has been illustrated schematically in Fig. 5.1.

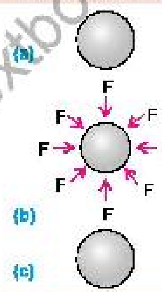
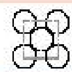


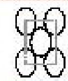
Fig. 5.1:
(a) Original rubber ball
(b) Squeezed rubber ball subjected force F by the hand
(c) Rubber ball after removing force

Similarly, if we hold two ends of a rubber string in our hands, and move our hands apart to some extent, the length of the string will increase under the action of the applied force exerted by our hands. Greater the applied force, larger will be the increase in length. Now on removing the applied force, the string will return to its original length. From these examples, it is concluded that deformation (i.e., change in shape, length or volume) is produced when a body is subjected to some external force.

In crystalline solids, atoms are usually arranged in a certain order. These atoms are held about their equilibrium position, which depends on the strength of the inter-atomic cohesive force between them. Under the influence of external force, distortion occurs in the solid bodies because of the displacement of the atoms from their equilibrium position and the body is said to be in a state of stress. After the removal of external force, the atoms return to their equilibrium position, and the body regains its original shape, provided that external applied force was not too great. The ability of the body to return to its original shape is called elasticity. Figure 5.2. illustrates deformation produced in a unit cell of a crystal subjected to an external applied force.

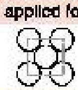


(a) Unstretched unit cell



(b) Unit cell under outward stretching force

(c) Unit cell under inward applied force



(d) Unit cell after removing applied force

Fig. 5.2

5.3 STRESS, STRAIN AND YOUNG'S MODULUS

The results of mechanical tests are usually expressed in terms of stress and strain, which are defined in terms of applied force and deformation.

Stress

It is defined as the force applied per unit area to produce any change in the shape, volume or length of a body. Mathematically, it is expressed as:

$$\text{Stress } (\sigma) = \frac{\text{Force } (F)}{\text{Area } (A)} \quad \ldots\ldots\ldots \quad (5.1)$$

The SI unit of stress (σ) is newton per square metre (N m^{-2}), which is given the name pascal (Pa). Stress may cause a change in length, volume and shape. When a stress changes length, it is called the tensile stress, when it changes the volume, it is called the volume stress and when it changes the shape, it is called the shear stress.

Strain

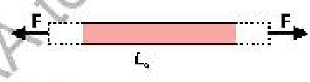


Fig. 5.3(a): Tensile strain

Strain is a measure of the deformation of a solid when stress is applied to it. In the case of deformation in one dimension, strain is defined as the fractional change in length. If ΔL is the change in length and L_o is the original length (Fig. 5.3-a), then strain is given by

$$\text{Strain } (\varepsilon) = \frac{\text{Change in length } (\Delta L)}{\text{Original length } (L_o)} \quad \ldots\ldots\ldots \quad (5.2)$$

Since strain is the ratio of lengths, it is dimensionless and therefore, has no units. If strain ε is due to tensile stress σ, it is called tensile strain, and if it is produced as a result of compressive stress σ, it is termed as compressive strain.

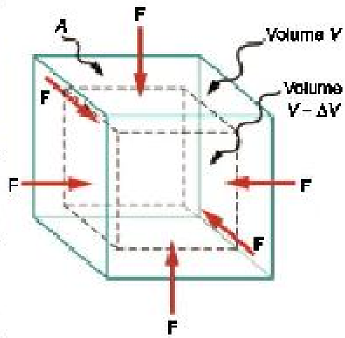


Fig. 5.3(b): Volumatric strain

In case when the applied stress changes the volume, the change in volume per unit volume is known as volumetric strain as shown in Fig. 5.3 (b), thus

$$\text{Volumetric strain } (\varepsilon_v) = \frac{\Delta V}{V_o} \quad \ldots\ldots\ldots \quad (5.3)$$

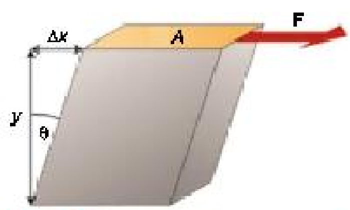


Fig. 5.3(c): Shear strain

Let y be the distance between two opposite faces of a rigid body (Fig. 5.3-c), which are subjected to shear stress one of its face slides through a distance Δx, then shear strain is produced which is is given by

$$\text{Shear strain } (\gamma) = \frac{\Delta x}{y} = \tan\theta \quad \ldots\ldots\ldots \quad (5.4)$$

However, for small value of angle θ, measured in radian $\tan\theta \cong \theta$, so that

$$\gamma = \theta \quad \ldots\ldots\ldots\ldots\ldots\ldots(5.5)$$

For your information

Although it is named after the 19th century British Scientist Thames Young, the concept was developed in 1727 by Leonhard Euller.

Young's Modulus

The stress applied per unit strain is called Young's modulus

i.e. $$Y = \frac{\text{Tensile stress}}{\text{Tensile strain}}$$

$$Y = \frac{F/A}{\Delta L / L_o} \quad \ldots\ldots\ldots \quad (5.6)$$

It has the same unit as that of stress i.e., N m^{-2}. The value of Young's modulus of different material is given in Table 5.1.

There are various methods to determine the Young's modulus of a wire. One of the method is Searle's method.

Table 5.1: Elastic constants for some materials

Material	Young's Modulus 10^9 N m^{-2}	Bulk Modulus 10^9 N m^{-2}	Shear Modulus 10^9 N m^{-2}
Aluminium	70	70	30
Bone	15	-	80
Brass	91	61	36
Concrete	25	-	-
Copper	110	140	44
Diamond	1120	540	450
Glass	55	31	23
Ice	14	8	3
Lead	15	7.7	5.6
Mercury	0	27	0
Steel	200	160	84
Tungsten	390	200	150
Water	0	2.2	0

5.4 DETERMINATION OF YOUNG'S MODULUS OF A WIRE

Experimentally, the magnitude of Young's modulus for a material in the form of wire can be found out mostly with the help of Searle's apparatus as shown in Fig. 5.4.

It consists of two wires, reference wire and test wire of equal lengths of same material having same diameters attached to a rigid support. Both wires are connected to horizontal bars (frames F_1 and F_2) at the other ends. Hang a constant weight to the hook of horizontal bar of reference wire and hanger on test wire so that wire remains stretched and free from kinks.

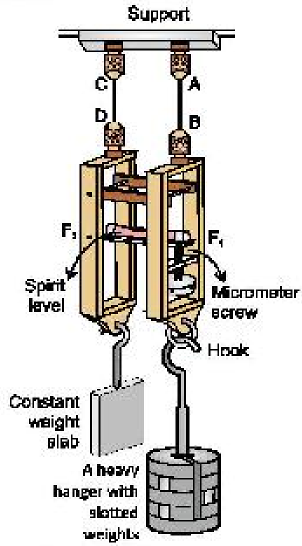


Fig. 5.4: Searle's apparatus

Procedure

The following procedure is adopted for finding Young's modulus of a wire experimentally.

1. Measure the initial length L_o of the wire using a metre scale.
2. Measure the diameter 'd' of the wire using a screw guage. The diameter should be measured at several

different points along the wire and take average.

3. Adjust the spirit level so that it is in horizontal position by turning the micrometer. Record the micrometer reading to use it as the reference reading.
4. Load the test wire with a further weight, the spirit level tilts due to elongation of the test wire.
5. Adjust the micrometer screw to restore the spirit level in the horizontal position. Subtract the first micrometer reading from the second micrometer reading to obtain the extension of the test wire.
6. Calculate stress and strain from the following formula:

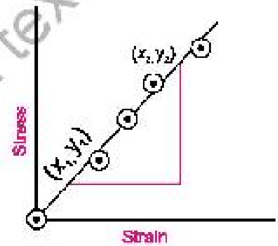
$$\text{Stress} = \frac{\text{Weight}}{\text{Area of wire}} = \frac{F}{A} = \frac{mg}{\pi r^2}$$

$$\text{Strain} = \frac{\Delta L}{L_o} = \frac{\text{Change in length}}{\text{Original length}}$$

Brain teaser

A steel rod and a rubber band are subjected to a same force. Which one will be stretched more?

7. Repeat the above steps by increasing load on test wire to obtain more values of stresses and strains.
8. Plot the above values on stress strain graph, it should be straight line. Now determine the value of slope Y. The value of slope is equal to Young's modulus of wire.



5.5 ELASTIC DEFORMATION, PLASTIC DEFORMATION AND ELASTIC LIMIT

In a tensile test machine, metal wire is extended at a specified deformation rate, and stresses generated in the wire during deformation are continuously measured by a suitable electronic device fitted in the mechanical testing machine. Force-elongation diagram or stress-strain curve is plotted automatically on X-Y chart recorder. A typical stress-strain curve for a ductile material is shown in Fig. 5.5.

In the initial stage of deformation, stress is increased linearly with the strain till we reach point A on the stress-strain curve. This is called proportional limit (σ_p). It is defined as the greatest stress that a material can withstand without losing straight line proportionality between stress and strain. Hooke's law which states that the strain (deformation) is directly proportional to stress (force or load) is obeyed in the region OA. From A to B, stress and strain are not proportional.

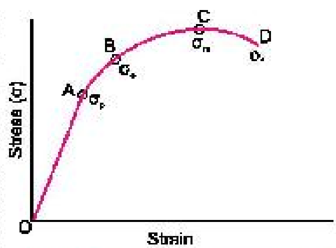


Fig. 5.5: Stress-strain curve of a typical ductile material.

Elastic limit

If the load is removed at any point between O and B, the curve will be retraced and the material will return to its original state. In the region OB, the material is said to be elastic. The point B is called the yield point. The value of stress at B is known as elastic limit σ_e.

Plastic Deformation

If the stress is increased beyond the yield stress or elastic limit of the material, the specimen becomes permanently changed and does not recover its original shape or dimension after the stress is removed. This kind of behaviour is called plasticity. The region of plasticity is represented by the portion of the curve from B to C, the point C in Fig. 5.5 represents the ultimate tensile strength (UTS) σ_m of the material. The UTS is defined as the maximum stress that a material can withstand, and can be regarded as the nominal strength of the material. Once point C corresponding to UTS is crossed, the material breaks at point D, responding the fracture stress (σ_f).

Ductile substances

Substances which undergo plastic deformation until they break, are known as ductile substances. For example, Lead, copper and wrought iron are ductile substances.

Brittle Substances

The substances which break just after the elastic limit is reached, are known as brittle substances. For example, glass and high carbon steel are brittle. Moreover, Beryllium, Bismuth, Chromium are also brittle metals.

Example 5.1 A steel wire 12 mm in diameter is fastened to a log and is then pulled by a tractor. The length of steel wire between the log and the tractor is 11 m. A force of 10,000 N is required to pull the log. Calculate: (a) the stress and strain in the wire. (b) how much does the wire stretch when the log is pulled? ($E = 200 \times 10^9$ N m^{-2})

Solution (a) Tensile stress $\sigma = \dfrac{F}{A} = \dfrac{10{,}000\ \text{N}}{3.14(6\times10^{-3}\ \text{m})^2} = 88.46\times10^6\ \text{N m}^{-2}$

Tensile strain $\varepsilon = \dfrac{\Delta L}{L_o}$, also $E = \dfrac{\text{Stress}}{\text{Strain}} = \dfrac{88.46\times10^6\ \text{N m}^{-2}}{\text{Strain}} = 200\times10^9\ \text{N m}^{-2}$

$$\text{Strain} = \frac{88.46\times10^6\ \text{N m}^{-2}}{200\times10^9\ \text{N m}^{-2}} = 4.4\times10^{-4}$$

(b) Using the relation; Strain $= \dfrac{\Delta L}{L_o}$ or $\Delta L = \text{Strain}\times L_o = 4.4\times10^{-4}\times 11\ \text{m} = 4.84\times10^{-3}$ m

5.6 STRAIN ENERGY IN DEFORMED MATERIALS

When a body is deformed by a force, work is done against elastic restoring force. It is stored in it as its potential energy and is equal to the gain in potential energy of the molecules of a body due to the displacement of these molecules from their mean positions.

Derivation of Expression for Energy Stored in a Stretched Material

Consider a material in the form of a spring as shown in Fig. 5.6. It is stretched by a force F through extension x. As the extension is directly proportional to the stretching force within the elastic limit, therefore the force increases uniformly from zero to F as shown in Fig. 5.7. Thus, the average force that stretches the spring through x is $1/2F$. Hence work done by the stretching force will be given as:

Work done = Average force × Distance in the direction of the force

$$W = \frac{1}{2} F \times x \quad .... \quad (5.7)$$

From Hooke's law $\quad F = k(x)$

Therefore, $\quad W = (\frac{1}{2}kx).(x) \quad = \frac{1}{2}kx^2$

or $\quad W =$ Area of OPQ

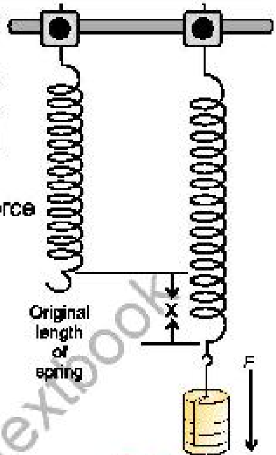


Fig. 5.6

The work done by the stretching force is stored in the spring as its strained energy and is equal to the potential energy stored in its molecules.

Strained energy stored in the body $E = \frac{1}{2}F{\cdot}x = \frac{1}{2}kx^2 \cdots (5.8)$

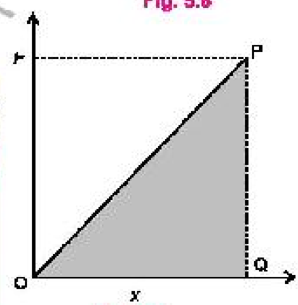


Fig. 5.7

For your information

The amount of work done in stretching a material is equal to the average force applied multiplied by the distance moved.
Therefore, the area under a force-extension graph represents the work done to stretch the material. Work done to stretch the material is also equal to elastic $P.E.$ stored in the material.

5.7 ARCHIMEDES' PRINCIPLE AND FLOATATION

An air-filled balloon immediately shoots up to the surface when released under the surface of water. The same would happen if a piece of wood is released under water. We might have noticed that a mug filled with water feels light under water but feels heavy as soon as we take it out of water.

More than two thousand years ago, the Greek scientist, Archimedes noticed that there is an upward force which acts on an object which is kept inside a liquid. As a result, an apparent reduction in weight of the object is observed. This upward force acting on the object is called the upthrust of the liquid. Archimedes' principle states that:

> When an object is totally or partially immersed in a liquid, an upthrust acts on it equal to the weight of the fluid it displaces.

Consider a solid cylinder of cross-sectional area A and height h immersed in a liquid as shown in Fig. 5.8. Let h_1 and h_2 be the depths of the top and bottom faces of the cylinder respectively from the surface of the liquid. Then

$$h_2 - h_1 = h \text{ ....(5.9)}$$

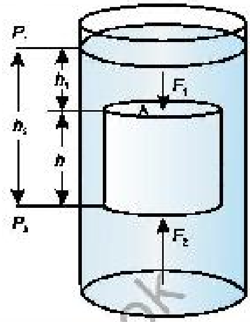


Fig. 5.8: Upthrust on a body immersed in a liquid is equal to the weight of the liquid displaced.

If P_1 and P_2 are the liquid pressures at depths h_1 and h_2 respectively and ρ is its density, then using equation $P = \rho gh$ of liquid pressure at height h:

$$P_1 = \rho g h_1$$

and $$P_2 = \rho g h_2$$

Let the force F_1 be exerted at the top of cylinder by the liquid due to pressure P_1 and the force F_2 be exerted at the bottom of the cylinder by the liquid due to P_2.

Then $F_1 = P_1 A = \rho g h_1 A$

and $F_2 = P_2 A = \rho g h_2 A$

F_1 and F_2 are the forces acting on the opposite faces of the cylinder. Therefore, the net force F will be equal to the difference of these forces. This net force F on the cylinder is called the upthrust of the liquid. Hence

$$F_2 - F_1 = \rho g h_2 A - \rho g h_1 A$$

$$= \rho g A (h_2 - h_1) \text{ ....(5.10)}$$

or Upthrust of liquid = $\rho g A h$

$$\text{Upthrust} = \rho g V \text{ ....(5.11)}$$

For your information

Archimedes was born about 287 BC, in Syracuse on the Island of Sicily. He was killed by a Roman soldier after he refused to leave his mathematical work.

Here Ah is the volume V of the cylinder and is equal to the volume of the liquid displaced by the cylinder, therefore, $\rho g V$ is the weight of the liquid displaced. This equation shows that an upthrust acts on a body immersed in a liquid and is equal to the weight of liquid displaced, which is Archimede's principle.

Example 5.2 A wooden cube of sides 10 cm each has been dipped completely in water. Calculate the upthurst of water acting on it.

Solution **Given**

Length of side $L = 10 \text{ cm} = 0.1 \text{ m}$

Volume $V = L^2 = (0.1 \text{ m})^3 = 1 \times 10^{-3} \text{ m}^3$

Density of water $\rho = 1000 \text{ kg m}^{-3}$

Upthrust $F = ?$

Using Archimede's principle

Upthrust of water $= \rho g V$

$= 1000 \text{ kg m}^{-3} \times 9.8 \text{ m s}^{-2} \times 1 \times 10^{-3} \text{ m}^3 = 9.8 \text{ N}$

Thus, upthrust of water acting on the wooden cube is 9.8 N.

Brain teaser

Why does a ship made of heavy steel float on water, while a small rock sink?

Floatation

An object sinks into a fluid if its weight is greater than the upthrust acting on it. However, an object floats if its weight is equal or less than the upthrust. When an object floats in a fluid, the upthrust acting on it is equal to the weight of the object. In case of floating object, the object may be partially immersed. The upthrust is always equal to the weight of the fluid displaced by the object. This is the principle of floatation. It states that:

A floating object displaces a fluid having weight equal to the weight of the object.

Archimedes' principle is applicable on liquids as well as on gases. We find numerous applications of this principle in our daily life.

Applications

Following are some important applications of Archimedes' principle.

1. Hot-air balloon

Fig. 5.9

The reason why hot-air balloons (Fig. 5.9) rise and float in mid-air is because of the density of the hot-air balloon is less than the surrounding air. When the upthrust of the surrounded air is more, it starts to rise. This is done by varying the quantity of hot air in the balloon.

2. Wooden block floating on water

A wooden block floats on water. It is because the weight of an equal volume of water is greater than the weight of the block. According to the principle of floatation, a body floats if its displaced water is equal to the weight of the body when it is partially or completely immersed in water.

Fig.5.10 (a): A ship floating over water

3. Ships and boats

Ships and boats are designed on the same principle of floatation. They carry passengers and goods over water. It would sink in water if its total weight becomes greater than the upthrust of water.

4. Submarine

Fig.5.10 (b): Submarine

A submarine can travel over as well as under water using the same principle of floatation.

It floats over water when the weight of water equal to its volume is greater than its weight. Under this condition, it is similar to a ship and remains partially above water level. It has a system of tanks which can be filled with and emptied from seawater. When these tanks are filled with seawater, the weight of the submarine increases. As soon as its weight becomes greater than the upthrust, it dives into water and remains under water. To come up on the surface, the tanks are made empty from seawater.

Example 5.3 An empty meteorological balloon weighs 80 N. It is filled with 10 cubic metres of hydrogen. How much maximum contents the balloon can lift besides its own weight? The density of hydrogen is 0.09 kg m^{-3} and the density of air is 1.3 kg m^{-3}.

Solution **Given:**

Weight of the balloon	w	=	80 N
Volume of hydrogen	V	=	10 m^3
Density of hydrogen	ρ_1	=	0.09 kg m^{-3}
Density of air	ρ_2	=	1.3 kg m^{-3}
Weight of hydrogen	w_1	=	?
Weight of the contents	w_2	=	?

Upthrust F = Weight of air displaced

$= \rho_2 gV$

$= 1.3\ \text{kg m}^{-3} \times 9.8\ \text{m s}^{-2} \times 10\ \text{m}^3$

$= 127.4$ N

Weight of hydrogen $w_1 = \rho_1 Vg$

$= 0.09\ \text{kg m}^{-3} \times 10\ \text{m}^3 \times 9.8\ \text{m s}^{-2}$

$= 8.82$ N

Total weight lifted $F = w + w_1 + w_2$

To lift the contents, the total weight of the balloon should not exceed F.

Thus $w + w_1 + w_2 = F$

$80\ \text{N} + 8.82\ \text{N} + w_2 = 127.4\ \text{N}$

or $w_2 = 38.58$ N

Thus, the maximum weight of 38.58 N can be lifted by the balloon in addition to its own weight.

5.8 STEADY, NON-VISCOUS AND IDEAL FLUID

Moving fluids have great importance. In order to find the behaviour of the fluid in motion, we consider their flow through the pipes. When a fluid is in motion, its flow can take place in two ways, either streamline or turbulent.

Streamline or Laminar Flow

The flow is said to be streamline or laminar flow.

If every particle that passes a particular point, moves along exactly the same path, as followed by particles which passed that points earlier.

In a steady flow of a fluid, the motion of the particles is smooth and regular, as shown in Fig. 5.11. The smooth path followed by fluid particles in laminar flow is called a streamline. The streamline may be the straight or curved and tangent to any point gives the direction of flow of a fluid. The different streamlines cannot cross each other.

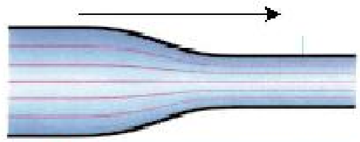


Fig. 5.11: Streamlines (laminar flow)

Example: A fluid flowing in a pipe as shown in Fig. 5.12 will have certain velocity v_1 at P, a velocity v_2 at Q and so on. If the velocity of a particle of the fluid at P, Q and R does not change with the passage of time, then the flow is said to be steady flow or streamline flow.

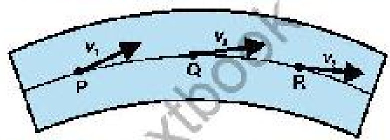


Fig. 5.12: The velocities of the particles at different points on streamline.

The line PQR which represents the path followed by the particle is called a streamline. It represents the fixed path followed by orderly processing particles. In streamline flow, all the particles passing through P also pass through Q and R. It means that two streamlines cannot cross each other.

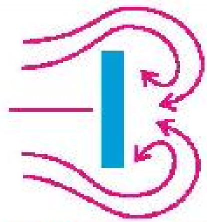


Fig. 5.13: Turbulent flow

Turbulent Flow

The irregular or unsteady flow of the fluid is called turbulent flow.

Above a certain velocity of the fluid flow, the motion of the fluid becomes unsteady and irregular. Under this condition, the velocity of the fluid changes abruptly as shown in the Fig. 5.13. In this case, the exact path of the particles cannot be considered.

If two streamlines cross each other, then the particles will go in one or in the other directions and flow will not be a steady flow. Such a flow is a turbulent flow. When the flow is unsteady or turbulent, there are eddies and whirlpools in the motion and the paths of the particles are continuously changing.

For your information

Formula One racing cars have a streamlined design.

Dolphins have streamlined bodies to assist their movement in water.

Ideal Fluid

The behaviour of the fluid which satisfies the following conditions is called ideal fluid:

1. The fluid is non-viscous i.e., there is no frictional force between adjacent layers of the fluid.

2. The fluid is incompressible i.e., its density is constant.
3. The fluid motion is steady.

Rate of Flow

The rate of flow of a fluid through a pipe is the volume of the fluid passing through any section of pipe per unit time.

Formula For Rate of Flow

Consider a fluid flowing through a pipe of area of cross-section A as shown in Fig. 5.14. Let the velocity of the fluid be v and it flows through the pipe for time t, then the distance covered by the fluid in time is:

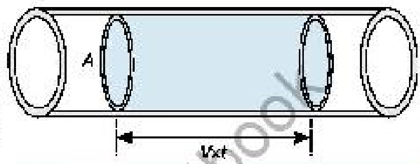


Fig. 5.14: Rate of flow of a liquid

$$\ell = vt$$

where ℓ is the length of the pipe through which the fluid passes in time t. Volume of the fluid passing through the pipe in time t, is:

$$A \times \ell = Avt$$

Thus The rate of flow of the liquid $= \dfrac{\text{Volume}}{\text{Time}}$

$$= \frac{Avt}{t} = Av$$

$$\text{Rate of flow} = Av \quad \text{.................(5.12)}$$

In SI units, it is measured in cubic metre per second ($m^3\,s^{-1}$). Sometimes, it is also measured in litres per second ($L\,s^{-1}$).

Steady Flow

If the overall flow pattern does not change with time, the flow is called steady flow.

In steady flow, every particle of the fluid follows the same flow line as its previous particle.

5.9 EQUATION OF CONTINUITY

Statement

The product of cross-sectional area of the pipe and the fluid speed (i.e., Av) at any point along the pipe is a constant. This constant is equal to the volume flow per second of the fluid or simply the flow rate.

Thus $$Av = \text{Constant} = \frac{\text{Volume}}{\text{Time}}$$

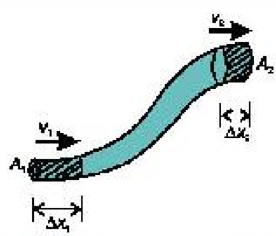


Fig. 5.15: Steady flow of a fluid

Consider a fluid flowing through a pipe of non-uniform size.

The particles in the fluid move along the same lines in a steady state flow as shown in Fig 5.15.

If we consider the flow for a short interval of time Δt, the fluid at the lower end of the tube covers a distance Δx, with a velocity v_1, then distance covered by the fluid is:

$$\Delta x_1 = v_1 \Delta t \quad \text{.................(5.13)}$$

Scientific Fact

Euler obtained the continuity equation for a incompressible fluid with a large number of terms in 1752. Later, it was translated by C. Truesdell from English in 1954.

Let A_1 be the area of cross-section of the lower end, then volume of the fluid that flows into the tube at A_1 is:

$$V = A_1 \Delta x_1$$

or $$V = A_1 v_1 \Delta t$$

If ρ_1 is the density of the fluid, then the mass of the fluid contained in the shaded region (through A_1) is:

$$\Delta m_1 = \text{Volume} \times \text{Density}$$

or $$\Delta m_1 = A_1 v_1 \Delta t \times \rho_1$$

Similarly, the mass of the fluid that moves with velocity v_2 through the upper end of the pipe having cross-sectional area A_2 in the same time Δt is given by

$$\Delta m_2 = A_2 v_2 \Delta t \times \rho_2$$

where ρ_2 is the density of the fluid flowing out through A_2 and Δm_2 indicates small mass.

If the fluid is incompressible and the flow is steady, the mass of the fluid is conserved. That is the mass flowing into the bottom of the pipe through A_1 in a time Δt must be equal to the fluid flowing out though A_2 in the same time. Therefore,

$$\Delta m_1 = \Delta m_2 \quad \text{............................(5.14)}$$

So $$A_1 v_1 \Delta t \times \rho_1 = A_2 v_2 \Delta t \times \rho_2$$

or $$A_1 v_1 \rho_1 = A_2 v_2 \rho_2 \quad \text{.........................(5.15)}$$

Equation (5.15) is called the equation of continuity. Since density is constant for the steady flow of incompressible fluid, therefore, the equation of continuity becomes:

$$A_1 v_1 = A_2 v_2 \quad \text{............................(5.16)}$$

Equation (5.16) states that in steady flow, the rate of flow of the fluid inward is equal to the rate of flow of the fluid outward.

This equation justifies the conservation of mass of the fluid which is flowing through a pipe.

Example 5.4 A water hose with an internal diameter of 20 mm at the outlet discharge 30 kg of water in 60 s. Calculate the water speed at the outlet. Assume the density of water is 1000 kg m^{-3} and its flow is steady.

Solution Internal diameter of water hose $D = 20\text{ mm} = 0.02\text{ m}$

Radius $$r = \frac{D}{2} = \frac{0.02\text{ m}}{2} = 0.01\text{m}$$

Mass of water $m = 30\ kg$

Time taken $t = 60\ s$

Density of water $\rho = 1000\ kg\ m^{-3}$

Speed of water $v = ?$

Mass flow per second $m/t = 30\ kg / 60\ s$

$= 0.5\ kg\ s^{-1}$

Cross-sectional area $A = \pi r^2$

$= 3.14 \times (0.01\ m)^2$

$= 3.14 \times 10^{-4}\ m^2$

From equation of continuity, the mass of water discharging per second through area A is:

$$\rho A v = \text{Mass / Second}$$

$$v = \frac{\text{Mass / Second}}{\rho A}$$

$$v = \frac{0.5\ kg\ s^{-1}}{1000\ kg\ m^{-3} \times 3.14 \times 10^{-4}\ m^2}$$

$$= 1.6\ m\ s^{-1}$$

Tidbits

As the water falls, its speed increases and so its cross sectional area decreases as mandated by the continuity equation.

For your information

The equation of continuity is applied to:

(i) blood flow in arteries and veins

(ii) water flow in rivers and pipes

(iii) air flow in duct and ventilation systems.

5.10 INCREASE IN FLOW VELOCITY

We can increase the flow velocity of water in a rubber pipe by squeezing it. When we squeeze the rubber pipe, we decrease the cross-sectional area through which the water flows. According to the equation of continuity,

$$A_1 v_1 = A_2 v_2$$

where A is the cross-sectional area and v is the flow velocity. By decreasing the cross-sectional area $(A_2 < A_1)$, the velocity of the water (v_2) must increase to maintain the same flow rate. Therefore, squeezing the rubber pipe increases the flow velocity of fluid.

5.11 BERNOULLI'S EQUATION

The sum of pressure, K.E. per unit volume and P.E. per unit volume of an ideal fluid throughout its steady flow remains constant.

As the fluid moves through a pipe of varying cross-section and height, the pressure will change along the pipe. Bernoulli's equation is the fundamental equation in fluid dynamics that relates pressure to fluid speed and height.

Fig. 5.16: The speed of water spraying from the end of a garden hose increases as the hose is squeezed with the thumb.

In deriving Bernoulli's equation, we assume that the fluid is incompressible, non-viscous and flows in a steady state manner. Let us consider the flow of the fluid through the pipe in time t, as shown in Fig. 5.17.

The force on the upper end of the fluid is P_1A_1 where P_1 is the pressure and A_1 is the area of cross-section at the upper end. The work done on the fluid, by the fluid behind it, in moving it through a distance Δx_1, will be:

$$W_1 = F_1\Delta x_1 = P_1A_1\Delta x_1$$

Similarly, the work done on the fluid at the lower end is:

$$W_2 = -F_2\Delta x_2 = -P_2A_2\Delta x_2$$

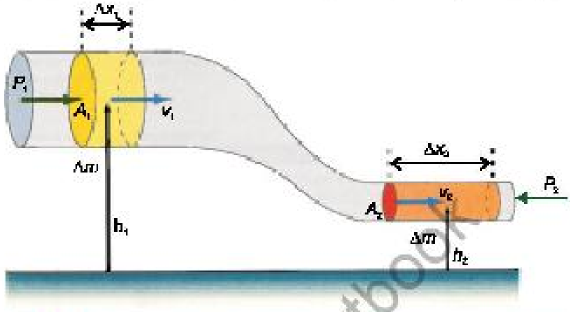


Fig. 5.17: An ideal flow of fluid through a non-uniform cross-section pip at different heights.

where P_2 is the pressure, A_2 is the area of cross-section of lower end and Δx_2 is the distance moved by the fluid in same time interval t. The work W_2 is taken to be –ve as this work is done against the fluid force. The net work done will be:

$$W = W_1 + W_2$$

or $$W = P_1A_1\Delta x_1 - P_2A_2\Delta x_2 \quad \text{..........(5.17)}$$

If v_1 and v_2 are the velocities at the upper and lower ends respectively, then

$$W = P_1A_1v_1t - P_2A_2v_2t$$

Brain teaser

How does the shape of a curveball in baseball relate to Bernoulli's principle?

From equation of continuity;

$$A_1v_1 = A_2v_2$$

Hence $$A_1v_1t = A_2v_2t = V \text{ (volume)}$$

So $$W = (P_1 - P_2)V \quad \text{..............................(5.18)}$$

If m is the mass and ρ is the density, then $V = \dfrac{m}{\rho}$. So, Eq. (5.18) becomes:

$$W = (P_1 - P_2)\frac{m}{\rho} \quad \text{.............................. (5.19)}$$

A part of this work is utilized by the fluid in changing its $K.E.$ and a part is used in changing its gravitational $P.E.$

$$\text{Change in } K.E. = \Delta K.E. = \frac{1}{2}mv_2^2 - \frac{1}{2}mv_1^2 \quad \text{..........................(5.20)}$$

$$\text{Change in } P.E. = \Delta P.E = mgh_2 - mgh_1 \quad \text{..........................(5.21)}$$

where h_1 and h_2 are the heights of the upper and lower ends respectively.

Applying the law of conservation of energy to this volume of the fluid, we have

$$(P_1 - P_2)\frac{m}{\rho} = \frac{1}{2}mv_2^2 - \frac{1}{2}mv_1^2 + mgh_2 - mgh_1 \quad ......(5.22)$$

Rearranging Eq. (5.22), we have

$$P_1 + \frac{1}{2}\rho v_1^2 + \rho g h_1 = P_2 + \frac{1}{2}\rho v_2^2 + \rho g h_2$$

This is Bernoulli's equation and is often expressed as:

$$P + \frac{1}{2}\rho v^2 + \rho g h = \text{constant}$$

5.12 USES OF BERNOULLI'S EQUATION

A number of devices operate by means of pressure difference that results from changes in the speed of the fluid.

1. Aeroplane Wings

Uplifting of an aeroplane is due to the designing of its wings, which deflect the air so that streamlines are closer together above the wing than below it as illustrated in Fig.5.18. We have seen that where the streamlines are forced closer together, the speed is faster. Thus, air is travelling faster on the upper side of the wing than on the lower. The pressure will be lower at the top of the wing, and the wing will be forced upward and the lift of an aeroplane is due to this effect.

Fig. 5.18: Lift of an aeroplane

2. Swing of a Ball

When a ball is thrown or kicked with spin or the ball is made smoother on one side by the bowler and remains rough on the other side, the air moves faster over rough side and slows over the smoother (Fig. 5.19). According to Bernoulli's equation, the faster moving air creates lower pressure, while the slower moving air creates higher pressure, this pressure difference generates a sideways force, known as Magnus effect which causes the ball to curves in the air.

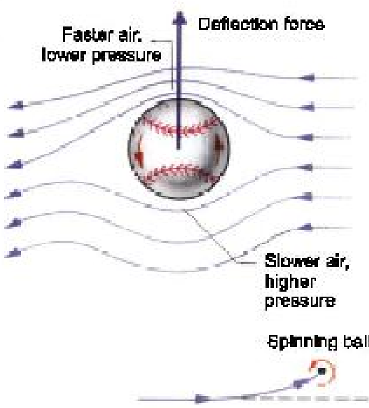


Fig. 5.19: Turbulent flow

3. Filter Pump

A filter pump has a constriction in the centre, so that a jet of water from the tap flows faster here. This causes a drop in pressure near it and air, therefore, flows in from the side tube. The air and water together are expelled through the lower part of the pump (Fig. 5.20).

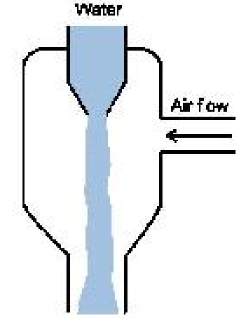


Fig. 5.20: Turbulent flow

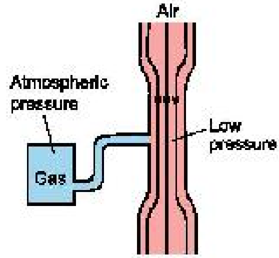


Fig. 5.21: Carburetor of an engine

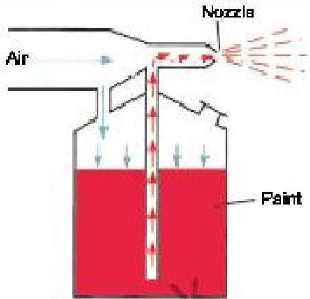


Fig. 5.22: A stream of air passing over a tube dipped in a liquid.

4. Carburetor

The carburetor of a car engine uses a Venturi duct to feed the correct mixture of air and petrol to the cylinders. Air is drawn through the duct and along a pipe to the cylinders (Fig. 5.21). A tiny inlet at the side of duct is fed with petrol.

The air through the duct moves very fast, creating low pressure in the duct, which draws petrol vapours into the air stream.

5. Paint Sprayer

A stream of air passing over a tube dipped in a liquid will cause the liquid to rise in the tube as shown in Fig. 5.22. This effect is used in perfume bottles and paint sprayers. Actually when the rubber ball of atomizer is squeezed, the air is blown through tube and it rushes out through the narrow aperture with high speed and it causes fall of pressure. So, the atmospheric pressure pushes the perfume up leading to the narrow aperture.

6. Venturi Relation

Consider a pipe within which a fluid of density ρ is flowing through different areas of cross-section as shown in the Fig. 5.23.

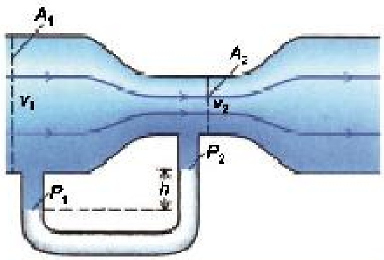


Fig. 5.23: Venturi meter

Let A_1 be the cross-sectional area at wide end and A_2 be the cross-sectional area at narrow portion.

Suppose that v_1 and v_2 be the flow speeds at the wide and narrow portions respectively. Pressure P_1 and P_2 indicate the liquid pressure at both the portions by connecting the limbs of the manometer.

As the pipe is placed horizontally, therefore, we consider that average potential energy is the same at both places while using Bernoulli's equation.

Thus, Bernoulli's equation can be written as:

$$P_1 + \frac{1}{2}\rho v_1^2 = P_2 - \frac{1}{2}\rho v_2^2$$

or $$P_1 - P_2 = \frac{1}{2}\rho v_2^2 - \frac{1}{2}\rho v_1^2$$

or $$P_1 - P_2 = \frac{1}{2}\rho\left(v_2^2 - v_1^2\right) \quad \text{..................(5.23)}$$

From the equation of continuity:

$$A_1 v_1 = A_2 v_2$$

or $$v_1 = \frac{A_2 v_2}{A_1}$$

As the cross-sectional area A_2 is small as compared to the area A_1 as is clear from the figure, i.e. $A_2 < A_1$. So, v_1 will be small as compared to v_2. Thus, the speed of the fluid is very slow in wider portion of the pipe as compared to the narrow portion, So, we can neglect v_1 on the right-hand side of Eq.(5.23). Hence

$$P_1 - P_2 = \frac{1}{2}\rho v_2^2 \quad \text{.................. (5.24)}$$

This is known as Venturi relation, which is used in venturi meter, a device used to measure speed of liquid flow.

Interesting Information

It is clear from the result of Bernoulli's Equation for horizontal pipe that "where speed is high, the pressure will be low". Mathematically,

$$P + \frac{1}{2}\rho v^2 = \text{constant}$$

7. Torricelli's Theorem

A simple application of Bernoulli's equation is shown in Fig. 5.24. Suppose a large tank of fluid has two small orifices A and B on it. Let us find the speed with which the water flows from the orifice A.

Since the orifices are so small, the efflux speeds v_2 and v_3 will be much larger than the speed v_1 of the top surface of water. We can therefore, take v_1 as approximately zero. Hence, Bernoulli's equation can be written as:

$$P_1 + \rho g h_1 = P_2 + \frac{1}{2}\rho v_2^2 + \rho g h_2$$

But $$P_1 = P_2 = \text{Atmospheric pressure}$$

Therefore, the above equation becomes:

$$v_2 = \sqrt{2g(h_1 - h_2)} \quad \text{....................(5.25)}$$

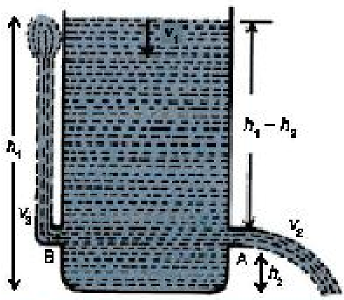


Fig.5.24:
A tank containing fluid with a orifice.

This is Torricelli's theorem which states that:

> The speed of efflux is equal to the velocity gained by the fluid in falling through the distance $(h_1 - h_2)$ under the action of gravity.

Notice that the speed of the efflux of liquid is the same as the speed of a ball that falls through a height (h_1 - h_2). The top level of the tank has moved down a little and the *P.E.* has been transferred into *K.E.* of the efflux of fluid. If the orifice had been pointed upward at B as shown in Fig.6.4, this *K.E.* would allow the liquid to rise to the level of water tank. In practice, viscous-energy losses would alter the result to some extent.

5.13 VISCOUS DRAG AND STOKES' LAW

The frictional effect between different layers of a flowing fluid is described in terms of viscosity of the fluid. Viscosity measures, how much force is required to slide one layer of the liquid over another layer. Substances that do not flow easily, such as thick tar and honey, etc., have large coefficients of viscosity, usually denoted by Greek letter 'η'. Substances which flow easily, like water, have small coefficient of viscosities. Since liquids and gases have non zero viscosity, therefore, a force is required if an object is to be moved through them. Even the small viscosity of the air causes a large retarding force on a car as it travels at high speed. If you stick out your hand out of the window of a fast moving car, you can easily recognize that considerable force has to be exerted on your hand to move it through the air. These are typical examples of the following fact.

For Your Information

Viscosities of Liquids and Gases at 30°C

Material	Viscosity 10^{-3} (N s m^{-2})
Air	0.019
Acetone	0.295
Methanol	0.510
Benzene	0.564
Water	0.801
Ethanol	1.000
Plasma	1.6
Glycerin	6.29

An object moving through a fluid experiences a retarding force called a drag force. The drag force increases as the speed of the object increases.

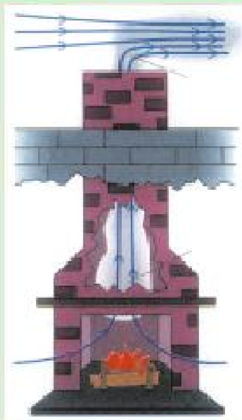
Even in the simplest cases, the exact value of the drag force is difficult to calculate. However, the case of a sphere moving through a fluid is of great importance.

The drag force F on a sphere of radius r moving slowly with speed v through a fluid of viscosity η is given by Stokes' law as under:

$$F = 6\pi\eta r v \text{ .... } (5.26)$$

However, at high speeds the force is no longer simply proportional to speed.

Do you know?



A chimney works best when it is tall and exposed to air currents, which reduces the pressure at the top and forces the upward flow of smoke.

5.14 TERMINAL VELOCITY

Consider a water droplet having radius r such as that of fog falling vertically, the air drag on the water droplet increases with speed. The droplet accelerates rapidly under the over powering force of gravity which pulls the droplet rapidly downward due to force of gravity. However, the upward drag force on it increases as the speed of the droplet increases. The net force on the droplet is

$$\text{Net force} = \text{Weight} - \text{Drag force} \quad \ldots\ldots\ldots\ldots \quad (5.27)$$

As the speed of the droplet continues to increase, the drag force eventually approaches the weight in the magnitude. Finally, when the magnitude of the drag force becomes equal to the weight, the net force acting on the droplet is zero. Then the droplet will fall with constant speed called terminal velocity.

To find the terminal velocity v_t in this case, we use Stokes' law for the drag force. Equating it to the weight of the drop, we have

$$0 = mg - 6\pi\eta r v_t$$

$$v_t = \frac{mg}{6\pi\eta r} \quad \ldots\ldots\ldots\ldots \quad (5.28)$$

The mass of the droplet is ρV, where $V = \frac{4}{3}\pi r^3$ is the volume of the sphere.

Substituting above values in the Eq. (5.28), we have

$$v_t = \frac{2gr^2\rho}{9\eta} \quad \ldots\ldots\ldots\ldots \quad (5.29)$$

Example 5.5 A tiny water droplet of radius 0.010 cm descends through air from a high building. Calculate its terminal velocity. Given that η for air = 19×10^{-6} kg m^{-1} s^{-1} and density of water $\rho = 1000$ kg m^{-3}.

Solution

$$r = 1.0 \times 10^{-4}\,\text{m}, \quad \rho = 1000\,\text{kg m}^{-3}, \quad \eta = 19 \times 10^{-6}\,\text{kg m}^{-1}\,\text{s}^{-1}$$

Putting the above values in Eq. (5.29)

$$v_t = \frac{2 \times 9.8\,\text{m s}^{-2} \times (1.0 \times 10^{-4}\,\text{m})^2 \times 1000\,\text{kg m}^{-3}}{9 \times 19 \times 10^{-6}\,\text{kg m}^{-1}\,\text{s}^{-1}}$$

Terminal velocity = 1.1 m s^{-1}.

5.15 REAL FLUIDS ARE VISCOUS FLUIDS

Ideal fluid

It is a fluid that does not have viscosity and cannot be compressed. This type of fluid cannot exist practically.

Real fluid

All types of fluids that possess viscosity are termed as real fluids.

Examples: Kerosene oil, castor oil and honey etc.

Comparison of Ideal and Real Fluids

An example of ideal fluid cannot be provided because it does not exist in the real world.

However, every fluid that we see around us like water, diesel, petrol, honey, etc. are real fluids. Moreover, differences in viscosity can be found in real life, for example, honey is more viscous than water. Bernoulli's equation states that the speed of fluid flow is increased as a result of a simultaneous decrease in the potential energy of the fluid or a decrease in the static pressure on the fluid. When a fluid is viscous, it essentially refers to the thickness of the fluid or the friction, the fluid faces while fluid flows. Therefore, ideal fluids do not face the opposing force and have a non-viscous flow, while real fluids have a viscous flow. Ideal fluids are incompressible. It is not also subjected to surface tension.

5.16 SUPERFLUIDS

Superfluidity is the characteristic property of fluids with zero viscosity i.e., flow is frictionless. A substance exhibiting this property is a superfluid. Superfluids flow without loss of kinetic energy. They can flow through incredibly narrow spaces without any friction.

Superfluidity is achieved in some substances at extremely low temperature. For example, in fluid dynamics, a vortex is region in a fluid in which the flow revolves around an axial line, which may be straight or curved. The vortices are generally created at a moving boundary due to frictionless conditions. Vortices move with the fluid and dispersed by the action of viscosity.

Tidbit

Parachutes increase air resistance (drag) by creating a large surface area, which counteracts the force of gravity. This slows down the persons fall, allowing them to land safely.

Superfluid helium-4 is the most studied example of superfluidity. It changes from a liquid to a superfluids just a few degree below its boiling point of –452°F (-269°C or 4 K). Superfluids helium-4 moving as a normal clear liquid, but it has no viscosity. This means that once it starts to flow, it keeps moving past any obstacles.

Tidbit

Superfluids can "climb" up walls and over edges of containers because they do not experience friction like normal fluids do.

Superfluidity Applications

Currently, there are few practical uses for superfluids. Superfluid helium-4 serves as a coolant for high-field magnets. Both helium-3 and helium-4 are utilized in advanced particle detectors. Researching superfluidity also helps us learn more about superconductivity.

Liquid helium is recognized for its great thermal conductivity and is used in cryogenic applications, including cooling superconducting magnets, scientific research, and medical uses. Additionally, it is employed in industry for leak testing and in the production of electronic and optical products.

QUESTIONS

Multiple Choice Questions

Tick (✓) the correct answer.

5.1 The region of stress-strain curve which obeys Hooke's law is:
(a) proportional limit (b) elastic region (c) plastic region (d) yield limit

5.2 Which of the following is more elastic?
(a) Rubber (b) Wood (c) Sponge (d) Steel

5.3 Which of the following is polymer solid?
(a) Wool (b) Glass (c) Sodium chloride (d) Copper

5.4 The effect of decrease of pressure with the increase in speed of a fluid in horizontal pipe is:
(a) Torricelli's effect (b) Bernoulli's effect (c) Venture's effect (d) Doppler's effect

5.5 The pressure will be low when speed of a fluid is:
(a) zero (b) high (c) low (d) constant

5.6 As per law of fluid friction for steady streamline flow, the friction:
(a) varies proportionally to velocity of fluid
(b) varies inversely proportional to pressure
(c) does not depend on pressure
(d) first increases then decreases

5.7 If a stone is submerged in water and it weighs less in water than in air, this phenomenon is due to:
(a) the reduction of mass in water (b) increase of density in water
(c) buoyant force acting upwards (d) the gravitational force acting upward

5.8 The principle of floatation is a direct application of:
(a) Pascal's law (b) Bernoulli's principle
(c) Archimedes' principle (d) Newton's third law

5.9 An ideal flow of any fluid must satisfy:
(a) Pascal law (b) Bernoulli's equation
(c) Continuity equation only (d) Both (b) and (c)

5.10 The lift force experienced by an aeroplane wings is primarily due to:
(a) viscosity of air (b) density of air
(c) pressure difference above and below the wing (d) gravitational force

5.11 In medical field, a venture mask, used to deliver a known oxygen concentration to patients operates is based on:

(a) Newton's third law
(b) Archimedes' principle
(c) Pascal's law
(d) Bernoulli's principle

5.12 Which of the following is a defining characteristic of a superfluid?

(a) Zero viscosity
(b) Infinite density
(c) Zero temperature
(d) Infinite thermal conductivity

Short Answer Questions

5.1 What is meant by (i) cohesive force (ii) viscosity?

5.2 Differentiate between streamline and turbulent flow of a fluid.

5.3 How does pressure changes with depth in fluids?

5.4 How is variation in pressure related to speed of a fluid?

5.5 How is the flow rate related to the cross-sectional area and velocity of the fluid?

5.6 How do you study the variation in velocity of a fluid at different points in a hose with varying diameter?

5.7 How does an object float or sink according to Archimedes Principle?

5.8 How does Archimedes reportedly discover the principle that bears his name?

5.9 Why standing near fast moving train is dangerous? Explain briefly.

5.10 What are some potential applications of superfluidity?

5.11 Differentiate between stress, strain and Young's modulus. Write down their SI units.

Constructed Response Questions

5.1 The ratio stress/strain remains constant for small deformation. What will be effect on this ratio when the deformation made is very large?

5.2 When pure water falls on a flat glass plate, it spreads on the plate while the mercury, when falls on the same plate gets converted into small globules. Why?

5.3 According to Bernoulli's theorem, the pressure of a fluid should remain uniform in a pipe of uniform radius. But actually, it goes on decreasing. Why is it so?

5.4 Why wings of an aeroplane are rounded outward while flattened inward?

5.5 What is the difference in real fluid, ideal fluid and superfluid? Which of these really exits in the world? Explain.

5.6 Why is the study of superfluids important for advancing our knowledge of low temperature physics?

Comprehensive Questions

5.1 Explain in detail the classification of solids with respect to atomic arrangements.

5.2 What is Archimedes' principle? Explain it in detail for finding upthrust.

5.3 Justify that mass remains conserved when a fluid flows through a pipe.

5.4 Explain the term superfluidity.

5.5 State and derive equation of continuity.

5.6 State and prove Bernoulli's equation.

5.7 Give some practical applications of Bernoulli's equation.

5.8 Define terminal velocity of a body and show that terminal velocity is directly proportional to the square of radius of the body.

Numerical Problems

5.1 A steel wire of length 2 metres and cross-sectional area of 2×10^{-4} m^2 is stretched by a force of 400 N. If the Young's modulus of steel is 2×10^{11} N m^{-2}, calculate the extension of the wire. (Ans: 0.002 m)

5.2 A spring with a spring constant 200 N m^{-1} is stretched by 0.5 m. Find the elastic *P.E.* stored in the spring. (Ans: 25 J)

5.3 A copper wire of length 3 metres and cross-sectional area of 1×10^{-6} m^2 is subjected to a force of 500 N. Calculate the stress and strain produced in the wire. (Young's modulus of copper $Y = 1.1 \times 10^{11}$ N m^{-2}) (Ans: 5×10^{8} N m^{-2}, 0.00455)

5.4 A block of wood of mass 10 kg and density of 600 kg m^{-3} is floating in water. Calculate the buoyant force acting on the block. (Density of water = 1000 kg m^{-3}.)

(Ans: 98 N)

5.5 Water flows through a pipe with a diameter of 0.05 m at a velocity of 2 m s^{-1}. If the pipe narrows to a diameter of 0.03 m, calculate the velocity of water at narrow section. (Ans: 5.56 m s^{-1})

5.6 Water flows through a horizontal pipe with a velocity of 3 m s^{-1} and pressure of 200,000 Pa at point 1. At the nozzle (point 2), the pressure decreases to atmospheric pressure 101,300 Pa and the velocity increases to 14 m s^{-1}. Calculate the velocity of the water exiting the nozzle. (Density of water = 1000 kg m^{-3})

(Ans: 14.37 m s^{-1})

5.7 A tank filled with water has a hole at a depth of 5 m from the water surface. Calculate the velocity of water flowing out of the hole. (Ans: 9.9 m s^{-1})

5.8 Calculate the terminal velocity of a spherical raindrop with a radius 0.5 mm falling through the air. (η for air = 19×10^{-6} kg m^{-1} s^{-1}, ρ = 1000 kg m^{-3} for water)

(Ans: 28.65 m s^{-1})