9

HYDROSTATICS AND SURFACE TENSION

9.1 INTRODUCTION

In the previous lesson, you have learnt that the combination of intermolecular forces and thermal motion gives rise to three different states of matter, namely solid, liquid and gas.

You would have seen that liquids can flow on the inclined surfaces (under the effect of earth's gravity) and hence are also called fluids. *They are incapable of withstanding any shearing forces for any length of time* if they deform easily and hence are said to have negligible elasticity.

To support a solid you require only a floor; while fc~ supporting a liquid you have to use a container having side-walls. The deeper the container, the stronger have to be the side-walls of the container. Do you know why? Can you believe that you can lift an elephant by your own body weight by standing on one platform (like a pan of a balance) of a hydraulic lift, the elephant standing on the otl.er platform of the same lift? Can you walk on water? But the mosquitoes can stand and walk on still water. Similarly, When mercury falls on the flat ground, it spreads in the form of spherical globules. Do you know, why? Will it not be surprizing to see a steel needle floating on water surface?

All these amazing observations can be explained if you learn the chracteristic properties of the liquids, like hydrostatic pressure, Pascal's law and surface tension. These topics form the subject matter of present study in this lesson. In the next lesson, you will learn about the flow of liquids.

9.2 OBJECTIVES

After studying this lesson, you should be able to:

- *calculate the hydrostatic pressure at a certain depth inside the liquid containers.*
- *describe Pascal's law to explain the functioning of hydraulic press; hydraulic lift and hydraulic brakes etc.*
- *explain the property of surface tension of liquids.*
- *explain the spherical shape of liquid drops, floating of mosquitoes on water surface.*
- *derive an expression and explain the rise of water in the capillary tube.*
- *define surface tension and apply it to explain the various daily life phenomenon.*

9.3 HYDROSTATIC PRESSURE

Have you ever got a chance to see the construction of a dam? Figure (9.1) shows the walls of a high dam. They are made thicker at the base, and not like an ordinary wall of uniform thickness. Do you know why?

The liquids do exert pressure at the base of the container due to their weight like solids. However, they do exert same pressure also on the side walls of the container. **The greater is the depth below the free surface (level) of water, the greater is the pressure.** Dams have to store water to great heights and hence the pressure on the side walls of the dam at the bottom is very large. It is for this reason that to withstand such a large pressure, the side walls of the dam are made very thick. At low depths, the pressure being small, lesser thickness of wall will be sufficient to withstand the side pressure. *The pressure exerted by the stationary liquid* (filled in a container) *at any point inside the liquid is called 'hydrostatic pressure'. and the study of liquids at rest is called 'hydrostatics'.*

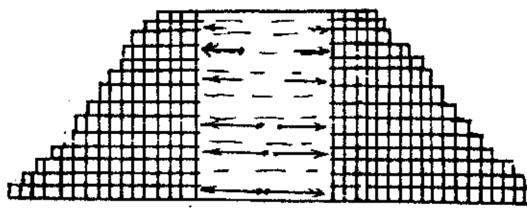

Fig. 9.1: *The structure of side-walls of a dam (length of the arrows at different depths are indicative of the magnitude of the water-pressure on the side wall.*

Since pressure (P) is defined as the force per unit area

$$P = \frac{\text{Force}}{\text{Area}} = \frac{\text{Newton}}{\text{metre}^2} \qquad \dots (9.1)$$

the pressure is measured in Nm^{-2}. which is also called ***Pascal*** in honour of the French Scientist Blaise Pascal (1623-1662) who did a lot of work on fluid pressure. In short, Pascal is represented as **Pa**.

Let us now obtain an expression for the hydrostatic pressure.

9.3.1 Hydrostatic Pressure at a point within a liquid

Let us consider a small object (A) at a depth 'h' below the free surface (level) of the liquid in the container. The liquid exerts compression of pressure on all of its sides as shown in the figure (9.2). The pressure P at the point A, which acts vertically downwards can be calculated as being due to the weight per unit area of the liquid above the point A.

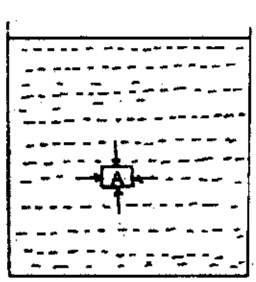

Fig. 9.2: *Compressional Pressure due to liquid acting on all sides of an immersed body.*

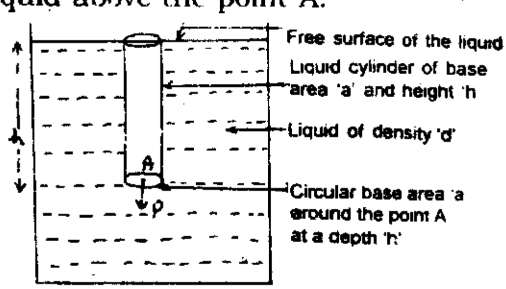

Fig. 9.3:

Suppose the point A is at a depth 'h' below the free surface of the liquid contained in the vessel. See Figure (9.3)

Imagine a liquid in a cylinder of circular base area are 'a' and height 'h' (i.e. extending upto the free surface) above the point 'A'. The weight of the liquid cylinder

= mass × acceleration due to gravity

= (volume of the cylinder) × (density of the liquid) × (acc. due to gravity)

$$W = (a \times h) \times (d) \times g$$

This weight acts vertically downwards on area 'a' at A.

$$\therefore \text{ Hydrostatic pressure at } A = \frac{\text{weight}}{\text{area}}$$

$$\Rightarrow P = \frac{a \times h \times d \times g}{a} = hdg \qquad \text{... (9.2)}$$

$$\Rightarrow \boxed{P = \text{depth} \times \text{density} \times \text{acc. to gravity}}$$

It is important to note that area 'a' does not appear in the final expression for the hydrostatic pressure.

Example 9.1: *A cemented wall of thickness 1 metre can withstand a side pressure of 10^5 Nm^{-2}. What should be the thickness of the side wall at the bottom of a water dam of depth 100 metres? Take density of water = 10^3 kgm^{-3} and $g = 9.5$ ms^{-2}.*

Solution: The pressure on the side wall of the dam at its bottom at a depth 100 metres is given by

$$P = hdg$$

$$P = 100 \times 10^3 \times 9.8 \text{ Nm}^{-2}$$

$$= 9.8 \times 10^5 \text{ Nm}^{-2}$$

$$\therefore \text{Thickness of the wall required} = \frac{9.8 \times 10^5}{10^5} \text{ m}$$

$$= 9.8\text{m}$$

9.3.2 Calculation of Atmospheric Pressure

Torisili made use of the formula for hytrostatic pressure to determine the value of atmopheric pressure as follow:

He took a long narrow (not a capillary) tube of about 1 m long; filled it with mercury of density 13,600 kgm^{-3} and then after closing its open mouth with the thumb, inverted it and placed vertically in a mercury trough as shown in the figure. Some mercury fell into the trough while a column of about 76 cm of mercury above the free surface of mercury in the mercury trough remained filled in the tube.

Since the pressure at the point A = Atmospheric pressure = P, the pressure at the point B in horizontal line with A is also = P

But hydrostatic pressure at B = $h\,d\,g$

$\therefore$ Atmospheric pressure = $P = h\,d\,g = 0.76 \times 13{,}600 \times 9.8\ \text{Nm}^{-2}$

$$P = 1.013 \times 10^5\ \text{Nm}^{-2}$$

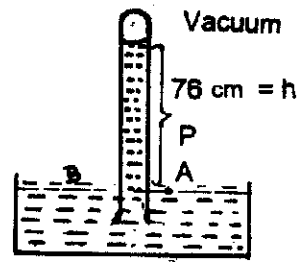

Fig. 9.4

9.3.3 Pascal's Law

Have you ever seen a hydraulic jack? Visit any motor-workshop where they clean the dirt of the car, trucks etc. There, the vehicle is lifted up to a height of about 5 feet or more with the help of a hydraulic jack and then a man cleans the lower side of the vehicle by pouring a strong stream of water with the help of a water pipe. You must have also seen the packing of cotton bales. That is also done with the help of hydraulic press. The hydraulic jack and hydraulic press both work on a principle known as ***Pascal's principle*** or law.

Pascal's law, also known as the ***law of transmission of liquid pressure*** can be stated as follows:

When a pressure is applied anywhere on the surface of given mass of an enclosed liquid at rest, an equal uniform pressure is transmitted over the whole liquid. It gets transmitted through out the liquid and acts in a direction at right angles to the surface of the liquid every where.

On any surface imagined inside the fluid or on the boundary, the liquid molecules are constantly impinging and rebouncing. The momentum transferred per unit area per second is the **Pressure** due to the liquid on the boundary.

Pascal's law, in terms of the molecules means that the momentum transferred by them per unit time to a unit area is the same throughout the fluid.

The liquid pressure depends only on its density and temperature provided there are no external forces such as gravity.

9.3.4 Applications of Pascal's law

A recent application of Pascal's law in medical treatment is the water mattress (bed) used to cut down be-sores by distributing the weight of the body uniformly.

Some of the important applications of Pasacal's law are, (i) Hydraulic Press (or Hydraulic Lift), (ii) Hydraulic Brakes; and (iii) Hydraulic Jack.

(i) Hydraulic Press

This is a simple device in which a small force is magnified many times. Since pressure is transmitted equally throughout the liquid, a small pressure can be made to act on a larger area and so produces a larger (magnified) force on that area. Fig. (9.5) shows a principle diagram of such a device.

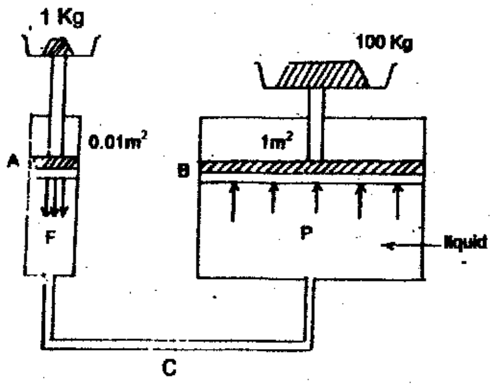

Fig. 9.5: *Principle diagram showing the working of Hydraulic lift*

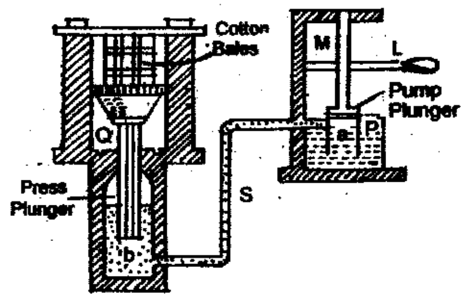

Fig. 9.6: *Hydraulic Press.*

Suppose the cylinder A has a small cross-sectional area of 0.01m^2 and cylinder B has larger area 1m^2. The two cylinders are connected by a narrow tube C. The whole apparatus is filled with some liquid or oil. If a force F_1 = 9.8 N (equal to the weight of 1 kg) is applied on the piston of cylinder A, the corresponding pressure

$$P_A = \frac{\text{Force}}{\text{Area}} = \frac{9.8}{0.01}\text{Nm}^{-2}$$
$$= 9.8\times10^2\ \text{Nm}^{-2}$$

This pressure is transmitted to the cylinder B.and the force acting on the piston of cylinder B is

$$F_B = P_B \times \text{Area of B} = 9.8 \times 10^2 \times 1 = 9.8 \times 10^2\ \text{N}.$$

Thus, a force of 9.8 N magnifies to 9.8×10^2 N

i.e (= 100 kg wt) is 100 times which is equal to the ratio of area of B to the area of A. In short since

$$\because\ F_B = P_B \times A_B \text{ and } F_A = P_A \times A_A$$

$$\therefore\quad \frac{F_B}{F_A} = \frac{P_B\cdot A_B}{P_A\cdot A_A} = \frac{A_B}{A_A}$$

$$[\because P_B = P_A]$$

This is called the ***mechanical advantage*** of the hydraulic press.

This principle is applied in the working of the hydraulic press with which bags of cotton or wood, oil seeds, newly printed books etc. are pressed very firmly together by applying a little force. Fig. (9.5)

(ii) Hydraulic Brakes

Another important use of the Pascal's law is in the design of hydraulic brakes in motor cars. Here also, when a little force is applied by the foot on the brake-plate, the pressure so applied gets transmitted through the brake oil to act on longer area where pistons are made to move the brake shoes against the brake drums. Fig. (9.7)

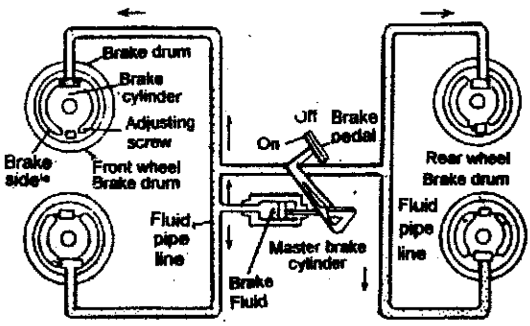

Fig. 9.7: *Hydraulic Brakes*

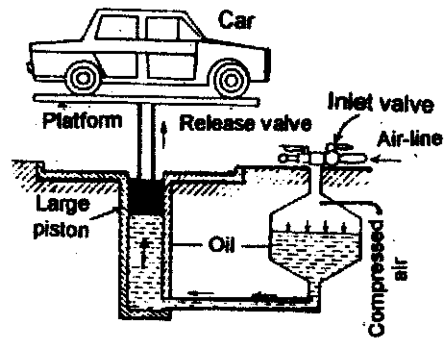

Fig. 9.8: *Hydraulic Jack*

(iii) Hydraulic Jack

Have you ever visited a service station for motor cars? You must have seen cars and large heavy trucks being raised to convenient heights so that the mechanic can work under them Fig. (9.8). Here also a slight pressure is transmitted through a liquid to act on a large surface, thus producing sufficient force to lift up the vehicle. Such a machine is known as ***hydraulic jack.***

Now, stop and try to solve the following questions to check your progress.

INTEXT QUESTIONS 9.1

1. *Two cylindrical containers A and B of base area $0.2m^2$ and $0.3m^2$ are filled with liquids of densities 1500 kg m^{-3} and 2000 kg m^{-3} respectively. If the container A is filled to a heigh 0.4 m and the container B to the height 0.31 m, which container is subjected to more pressure at its bottom? What are these pressures? Given $g = 9.8$ ms^{-2}*

   ....

2. *A coffee cup of base area 12×10^{-4} m^2 and height 0.07 m can bear a weight of 0.25 kg of any liquid filled in it. If it is to contain a liquid of density 3000 kgm^{-3}, to what height it can be filled without being turned?*

   ....

3. *What is the mechanical advantage of a hyraulic press?*

   ....

4. *A weight of 50 kg wt is put on the smaller cylinder of area 0.1 m^2 of a big hydraulic lift. How much maximum weight can be balanced on the*

bigger cylinder of area 10m² of this hydraulic lift?

....

5. *An elephant of weight 5000 kg wt. is standing on the bigger piston of area 10 m^2 of a hydraulic lift. Can a boy of weight 25 kg wt standing on the smaller piston of area 0.05 m^2 balance or lift the elephant?*

....

9.4 SURFACE TENSION

Take small amount of mercury. Drop it from about a foot on to a flat plate. You would find that the mercury gets sprayed into small spherical globules.Why? Have you seen dew drops (water-drops) on the leaves of some plant in the early morning during winter days? Here also small water drops appear spherical. Why do the liquids in small amounts gather together into a spherical drop? Also in the rainy season, when rain drops fall in a pool of water, air bubbles are formed on the water surface.

You must have enjoyed soap-bubble-making game in your childhood.

Activity (9.1): 1. Prepare a soap solution.

2. Add small amount of glycerine to it.
3. Take a narrow hand plastic tube or glass tube or wooden tube. Dip its one end in the soap-solution so that some solution fills in it.
4. Take it out and blow air into the other end with your mouth.
5. Large size soap bubble will be formed.
6. Give a jerk to the tube to detach the bubble which then floats in the air.

Do you know, why it is easier to form soap bubbles and not pure water-bubbles by the above technique?

All the above life experiences i.e. spherical shapes of the liquid-drops and soap bubbles etc. are due to the property of ***surface tension*** of the liquids.

Before, studying about this characteristic property of liquids, let us first revise our knowledge of molecular forces.

Every substance is made up of small particles called atoms. The compounds are made up of molecules which are a chemically combined group of atoms.

When liquids are contained in any open vessel, they always have a horizontal surface. According to molecular theory, all molecules do attract each other. ***The force of attraction between two similar molecules i.e. of the same substance (in a given sample) is called force of cohession.*** the liquid is in contact with the molecules of the container at the boundary of the vessel. The ***force of attraction between two dissimilar molecules (i.e. a molecule of the liquid and a molecule of***

the solid vessel) is called force of adhession. The distance upto which these forces of cohersion or adhession are effective to are called ***range of molecular attraction***. It is of the order of 10^{-9} m i.e. of the order of the size of the molecules.

9.4.1 Surface Energy

A thin layer of the surface of the liquid of thickness equal to the molecular range of attraction is called *surface layer*, or *surface film*.

See, fig. (9.9). The molecule P lying well within the liquid is attracted in all directions by molecules lying within its sphere of influence (which is the imaginary sphere of radius equal to the range of moleculer attraction drawn with molecule P at its centre; Hence the resultant cohessive force acting on P's zero. However for the molecules Q, R etc. which lie inside the surface-layer, the sphere of influence is partially outside the liquid surface where there are no liquid molecules. The molecules Q,R, therefore, experience a resultant downward force of cohession, because the number of molecules in the upper half of sphere of influence attracting the molecule Q or R is less than the number of molecules attracting Q or R in the lower half of sphere of influences.

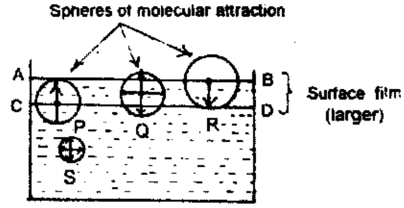

Fig. 9.9 : *The molecule P&S do not experience any resultant force, but the molecules Q & R experience aresultant vertically downward force of cohession.*

Thus, all molecules lying within the surface layer ABCD experience a resultant downward cohessive force which increases in magnitude as the position of the molecule shifts from the layer CD towards the top surface AB. Therefore, if any liquid molecule is brought from within the liquid (below CD) to this surface ABCD, some work is done against the downward cohessive force, which increases the potential energy of these molecules in the surface layer.

Now, since any system in equilibrium always tries to have the lowest possible potential energy, the number of molecules in the surface should be as small as possible i.e. The area of the surface must be the minimum or least. ***Thus liquid contained in a vessel has planer surface because a planer surface having a definite boundary depending upon the shape and size of the vessel has the minimum surface area.***

> *The sum of the energy of all the liquid molecules present in the surface is called the Surface Energy.*

Obviously a surface with lower area will have lower surface energy. Surface energy is a sort of potential energy.

9.4.3 Surface Tension and Surface Energy

To keep the surface area minimum, the surface of the liquid becomes like a stretched membrane giving rise to *surface tension* which acts normally at all points in all directions, tangential to the surface.

The tangential force per unit length acting perpendicular to any imaginary line supposed to be drawn on the liquid surface is defined as the surface Tension of that liquid, Fig. (9.10). It is measured in Nm^{-1} and is denoted by 'T. Its dimensional formuls is $[MT^{-2}]$.

At the boundaries, i.e. at the line where the liquid touches the vessel-walls, the direction of T is normal to the walls and tangential to the liquid surface.

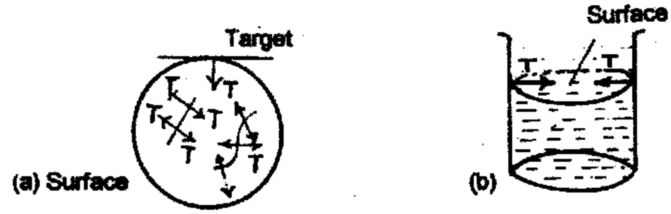

Fig. 9.10: *At the boundary the surface Tension is normal to the wall of the container.*

The value of surface tension for a certain liquid is a function of the resultant cohessive force on the liquid molecules in the surface whose magnitude depends upon the intermolecular separation which is a function of temperature. Hence surface tension also varies with the temperature of the liquid. It decreases with increase in temperature (due to increase in inter-molecular separation).

Force of surface tension tend to reduce the surface area of the liquid. Therefore, if the surface area of the liquid is to be increased, it can be done by doing work against the force of surface tension, which then gets steered in the form of extra or increased surface energy.

When many tiny drops coalepse together to form a bigger drop, there is no decrease in the surface area. The surface energy, therefore, reduces. The balance of energy appears in the form of heat and the drop gets heated up.

Similarly, if a bigger drop is sprayed into many tiny drops, there is a net increase in the surface area. The surface energy, therefore, increases. This extra energy is derived from the thermal energy of liquid drops which, therefore cool-down.

Have you seen cooling of circulating water by spraying it in the airconditioning plants of big buildings. Can you now explain why this is done?

Example 9.2 : *A water drop of radius 2 mm is sprayed into 1000 tiny drops of equal volume. Calculate the rise or fall in the temperature of each drop. Given density of water = 1000 kgm^{-3}. Surface tension 0.72 Nm^{-1}; specific heat of water $S = 4.2 \times 10^3\ J\ kg^{-1}\ {}^{\circ}C^{-1}$*

Solution :

Volume of the big drop of radius R is $V = \frac{4}{3}\pi R^3$

Volume of one tiny drop of radius r is $= \frac{4}{3}\pi r^3 = \frac{1}{1000}\left(\frac{4}{3}\pi R^3\right)$

∴ radius of tiny drop is given by

$$r^3 = \frac{R^3}{1000} \Rightarrow r = \frac{R}{10}$$

∴ gain in area $\Delta A = 4\pi\left(1000\ r^2 - R^2\right) = 4\pi\left(1000\ \frac{R^2}{100} - R^2\right)$

$$\Delta A = 4\pi \cdot 9R^2$$

∴ Extra surface energy gained $= T \cdot \Delta A = T_1\left(4\pi \cdot 9R^2\right)$

This is derived from the thermal energy of the 1000 drops which therefore, cool down by temp $\Delta\theta$, given by $1000 ms\Delta\theta = T \cdot 4\pi \cdot 9R^2$

$$\text{or} \quad 1000\left(\frac{4}{3}\pi r^3\right)s\rho\Delta\theta = T \cdot 4\pi \cdot 9 \times 100 r^2$$

$$\boxed{\Delta\theta = \frac{2.7T}{\rho r s}}$$

On substitution of the given values $\Delta\theta = 23.1 \times 10^{-6}\ °C$

If the boundary line of length 'l' is displaced by a distance 'b' against the forces of surface tension of magnitude $T \times l$, the work done for this increase in the surface area of magnitude $(l \times b)$ is = Force × distance

or Increase in surface energy $= (T \times l) \times b$

or $E = T \times (l \times b)$

= Surface Tension of the liquid × Increase in area

$$\therefore\ T = \frac{E}{(l \times b)} = \frac{\text{increase in surface energy}}{\text{increase in area}} = \frac{\text{work done}}{\text{increase in area}}$$

Hence, *Surface tension may also be defined as the work done per unit increase in area of the liquid surface.* *This is then measured in Joules per metre square i.e* Jm^{-2}.

However, the dimensional formula is still the same i.e. $\frac{ML^2T^{-2}}{L^2} = \left[MT^{-2}\right]$

If S = Total Surface Area of the liquid

T = Surface Tension

Then, total surface energy = $T \times S$ Joules.

Small drops of liquids acquire spherical shape because the surface area of a spherical surface for a given volume is minimum and hence gives minimum potential energy (surface energy) to the drop.

Example of Surface Tension

The liquid surface is horizontal. Dip your finger in the liquid. The liquid gives it the way; the surface gets curved near the line of contact of the finger. If now, you take out your finger, the surface again becomes horizontal. This shows that the liquid surface is under tension like a stretched membrane, which gets changed to concave at the point of touch of the finger and becomes straight or planes, the moment the deforming force is removed. The spherical shape of small liquid drops is due to the forces of surface tension.

ACTIVITY:

Take a circular thin wire with a handle. Dip it in a soap solution and take it out. A thin film of soap solution is enclosed inside the circular wire. Now make a small circular loop of thin cotton thread; put it gently on the horizontal soap film. It will rest on it without breaking the film. Now take an alpin, heat it in a flame and touch the film in side the thread loop by this hot pin. What do you observe? Fig. (9.11).

The film part which was within the thread gets burst and the thread is pulled into a circular loop as if pulled by some radially outward forces acting all along its circumference. It shows the presence of tangential force of surface tension. Initially, there was soap film on both sides i.e. the inside of closed thread loop and outside of closed thread loop, the forces of tension cancelling each others effect. On bursting the inner soap film, the outside film pulled the length of the thread (closed loop) normal to the length of the thread and tengentially to the film surface, which sets the closed loop into a circular shape. [The normal to the circumference of a circle is the radial direction].

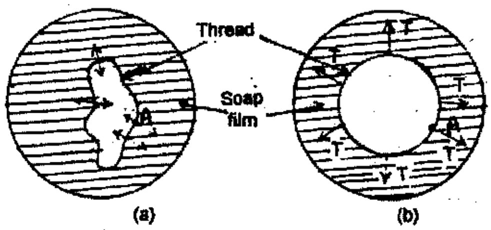

Fig. 9.11: *(a) A soap film with a closed loop of thread on it.*
(b) The shape of the thread, after the inner soap film is broken.

9.4.3 Application of Surface Tension

The water level in a glass capillary tube (fine bore tube) appears concave rather than planner-horizontal. Also the surface of mercury in a fine glass capillary tube appears to have a convex meniscus. These are due the surface tension effects. The rise of water in capillary tube above the level of water in the container is also due to surface tension forces. Fig. (9.12)

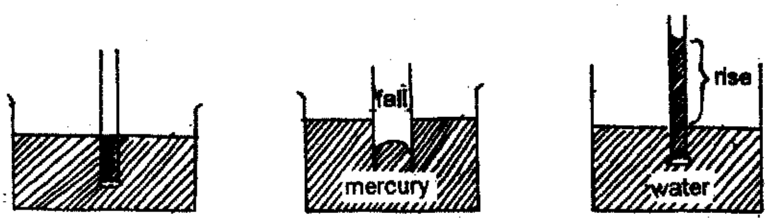

Fig. 9.12: *(a) Plane Meniscus (No rise or fall) b) Fall of level in capillary convex Meniscus*
(c) Concave Meniscus rice in capillary

In addition to it, the surface tension has wide application in our daily life. If few of them are described below:

(a) Mosquitoes Sitting on Water

Have you seen mosquitoes sitting on water surfaces. They do not sink in water. Why? This is due to the force of surface tension, which supports the weight of the mosquitoe. At the point where the legs of the mosquitoe towards the liquid surface, the surface becomes concave due to the dip. The force of surface tension acting tengentially to the surface, therefore acts at certain angle to the horizontal. Its vertical component acts upwards. The total force acting vertically upwards all along the line of contact of certain length is able to balance the vertically downward acting weight of the small mosquioes which, therefore, floats on water. Fig. (9.13).

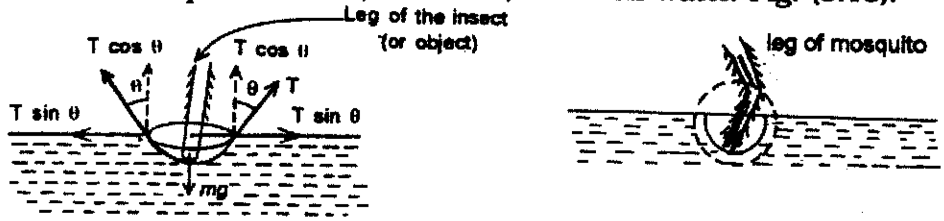

Fig. 9.13: *The weight of the insect is balanced by the force of surface tension = $2\pi r . T \cos \theta$ (a) Dip in the level to form concave surface (b) Magnified image*

(b) Excess of Pressure Inside a Spherical Surface

Consider a small surface element with a line PQ of unit length on it. Fig. (9.14). If the surface is plane i.e. θ = 90°, the forces of PQ and due to surface tension acting on the two sides tangential to the surface are equal and opposite in magnitude and hence the resultant tangential force is zero. Fig. 9.14.(a). If, however, the surface is convex, fig. 9.14 (b)., or concave Fig. 9.14 (c), the forces due to surface tension acting across the sides of the line PQ will have a resultant force **R** towards the centre of cuvature of the surface.

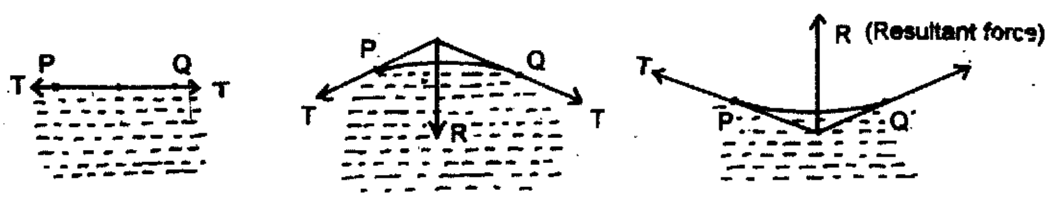

Fig. 9.14: *(a) Plane surface, R = 0; (b) Convex surface R acts towards the concave side; (c) Concave surface R acts towards the concave side.*

Thus, whenever the surface is curved (this happens near the boundary in contact with the walls of the container) the surface tension gives rise to a pressure directed towards the centre of curvature of the surface and this pressure is balanced by an equal and opposite pressure acting on the surface. Therefore (As the figure (9.14) shows), ***there is always an excess of pressure on the concave side of the curved liquid surfaces.***

(i) Spherical drop

A liquid drop has only one surface i.e. the outer surface [The liquid area in contact with air is called the surface fo the liquied]

Let r = radius of the small spherical liquid drop and p = excess of pressure inside the drop (which is concave on the inner side, but convex on the outerside)

$$= (p_i - p_0) \text{ (say)}$$

Where p_i and p_0 are the inside and outside pressures of the drop respectively Fig 9.15(a).

If we assume a small increase in the radius of the drop by Δr due to this constant excess pressure p in the spherical drop of radius r, then

Increase in surface area of the spherical drop = $4\pi(r+\Delta r)^2 - 4\pi r^2$

Fig. 9.15 (a): *Spherical drop*

or $$\Delta A = 8\pi r\Delta r + (\Delta r)^2$$
$$\approx 8\pi r\,\Delta r$$

Let T = surface tension of the liquid of the drop

= Work done by per unit increase in area (by definition)

then work done to increase this area $8\pi r\,\Delta r$ is given by

$$W = T\cdot(8\pi r\,\Delta r)$$

But the work done due to the excess pressure p

$$W' = p \times \Delta V$$

where ΔV = increase in volume = $\frac{4}{3}\pi(r+\Delta r)^3 - \frac{4}{3}\pi r^3$

$$= \frac{4}{3}\pi\left[3r^2\Delta r + 3r(\Delta r)^2 + (\Delta r)^3\right]$$

Since Δr is small, its higher powers are of still smaller value and hence can be neglected, therefore,

$$\Delta V = \frac{4}{3}\pi\left[3r^2\Delta r\right] = 4\pi r^2\,\Delta r$$

$\therefore$ $$W' = p \times 4\pi r^2\,\Delta r$$

But $$W' = W$$

$\therefore$ $$p4\pi r^2\Delta r = T\,8\pi r\Delta r$$

or $$p = \frac{2T}{r}$$

i.e., excess of pressure inside a spherical drop of radius 'r' of liquid of surface tension T is given by

$$\boxed{p = \frac{2T}{r}}$$

(ii) Air Bubble in Water

This also has a single surface, which is the inner surface, Fig. 9.15 (b).

Hence the excess of pressure 'p' inside an air bubble of radius r in water of surface tension T is also given by

$$\boxed{p=\frac{2T}{r}}$$

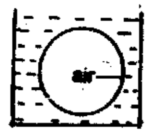

Fig. 9.15 (b): *Air bubble*

(iii) Soap Bubble Floating in Air

The soap bubble has two surfaces of equal surface areas - i.e. the outer and the inner Fig. (9.15) (c).

Therefore, its increase in surface area when the radius is increased by Δr will also be double

i.e.

$$\Delta A = 2\left[4\pi(r+\Delta r)^2\right] - 2\left[4\pi r^2\right]$$
$$= 2\cdot 8\pi r\cdot\Delta r = 16\pi r.\Delta r$$
$$\text{Work done} = W = T\cdot(6\pi r\cdot\Delta r)$$

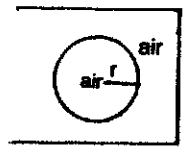

Fig. 9.15 (c): *Soap bubble*

If p = Excess inside pressure then; change in volume remaining the same i.e. $\Delta V = 4\pi r^2\cdot\Delta r$, we get work done

$W' = p\Delta V = p4\pi r^2\Delta r$

Therefore, equating W' to W, we get

$$p4\pi r^2\Delta r = T16\pi r\Delta r,\ \text{where } T = \text{Surface Tension of soap solution}$$

which gives $p=\dfrac{4T}{r}$

hence the excess of pressure inside a soap bubble floating in air =

$\boxed{p=\dfrac{4T}{r}}$ Which is twice that inside a spherical drop of same radius or an air bubble in water

Example 9.3: *What is the difference of pressure between inside and outside of a (i) spherical soap bubble in air, (ii) air bubble in water, and (iii) spherical drop of water, each of radius 1mm? Given surface tension of water = $7.2\times10^{-2}\ Nm^{-1}$ and surface tension of soap solution = $2.5\times10^{-2}\ Nm^{-1}$.*

Solution: (i) Excess of pressure inside a soap bubble of radius r is

$$=\frac{4T}{r}$$

$$=\frac{4\times2.5\times10^{-2}}{1\times10^{-3}}\ Nm^{-2} = 100\ Nm^{-2}$$

(ii) Excess of pressure inside an air bubble in water

$$=\frac{2T'}{r}$$
$$=\frac{2\times7.2\times10^{-2}}{1\times10^{-3}}\ Nm^{-2} = 144\ Nm^{-2}$$

(iii) Excess of pressure inside spherical drop of water

$$= \frac{2T'}{r}$$
$$= \frac{2 \times 7.2 \times 10^{-2}}{1 \times 10^{-3}} \text{Nm}^{-2} = 144\,\text{Nm}^{-2}$$

Example 9.4: *A rectangular thin disc of edge length 20 cm is rested vertically on the surface of a liquid of surface tension 2.5×10^{-2} Nm^{-1} and then raised up. What is the pull required to lift the disc from the liquid surface. Given weight of the disc = 1000 N.*

Solution: Here a liquid film is formed when the plate is raised and hence a downward force F due to surface tension acts on it besides its weight W acting downwards.

Hence F = total length of the boundary of the rectangular film (= $2L$) × surface tension (T) = $2LT$

∴ Net pull required = $W + 2LT$

= $(1000 + (2 \times 20 \times 10^{-2} \times 2.5 \times 10^{-2}))$ N

= $(1000 + .01)$ N = 1000.01 N

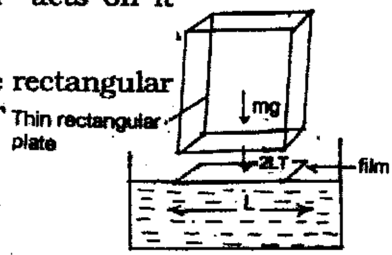

Fig. 9.15 (d):

(c) Detergents and Surface Tension

Detergents can remove the stains of oil on clothes. Water is used as cleaning agent. Soap and detergents have the effect of lowering the surface tension of water. This is desirable for washing and cleaning since the high surface tension of pure water protects it from penetrating easily between the fibres of materials where dirt particles or oil molecules are held up.

You know the surface tens n of soap solution is smaller than that of pure water, but the surface tension of detergent-solutions is still smaller and hence the detergents are more effective than soap. Using a detergent dissolved in water makes the catch of dirt particles to the clothe fibres weak, which, therefore, get easily detached on squeezing the clothe.

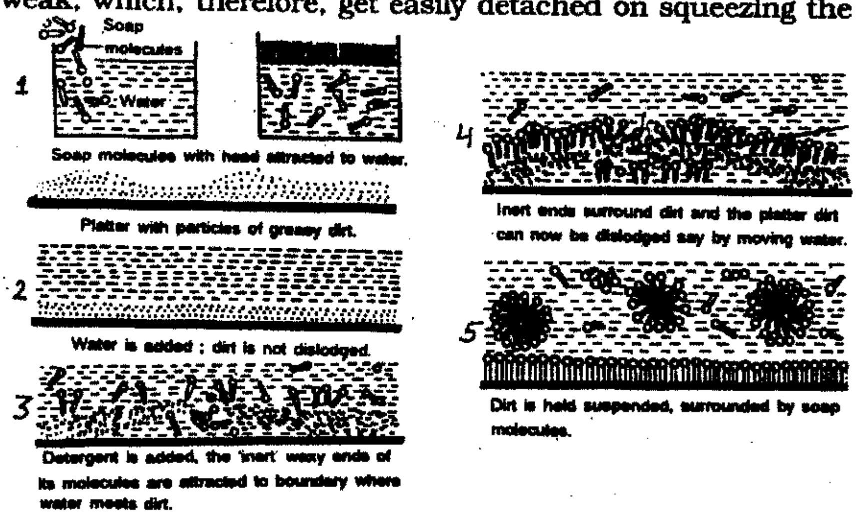

Fig. 9.16: *Detergent action in terms of what detergent molecules do.*

The addition of detergent whose molecules attract water at one end and oil (say) on the other, reduce drastically the surface tension (T) of *water-oil.* It may even become favourable to form such interfaces i.e., globes of dirt surrounded by detergent and then by water. This kind of process using surface active detergents or ***surfactants*** is important not only for cleaning the clothes but also in recovering of oil, mineral ores etc.

(d) Wax-duck Floating in Water

It is important that the surface tension of liquids decreases due to dissolved impurities If you stick a tablet of camphor to the bottom of a wax-duck and float it on still water surface, it starts moving this way and that way after a minute or two.

Fig. 9.17: *Motion of duck due to surface tension effect*

The camphor dissolves in water. Thus the surface tension of water just below the duck becomes smaller than the surrounding. The water, thus causes motion of the duck towards the pure water due to the net difference of force of surface tension causing the duck to move.

Now, it is time to work how much you have learnt. Solve the following questions then go ahead.

INTEXT QUESTIONS 9.2

1. *What is the difference between force of cohesion and force of adhesion?*

   ....

2. *What is the thickness of a surface layer? On what factors does the value of surface energy depend?*

   ....

3. *Do the solids also show the property of surface tension? Why?*

   ....

4. *Why does the mercury collect into globules when poured on plane surface?*

   ....

5. *Which has more excess pressure inside it —*

   (i) An air bubble in water of radius 2 cm. Surface tension of water is 727×10^{-3} Nm^{-1}; or

   (ii) A soap bubble in air of radius 4 cm. Surface tension of soap solution is = 25×10^{-3} Nm^{-1}

   ....

9.5 ANGLE OF CONTACT

It has been observed that though the liquid surfaces of all the liquids contained in the wide mouth vessels appear to be plane and horizontal, their surfaces at the point of contact of the liquid and the container are mostly curved i.e., concave-spherical or convex-spherical. For example, when water is filled in the glass jar, the surface is concave spherical at the boundary, and when mercury is filled in glass jar, the surface at the boundary is convex spherical. If, however, the water is filled in a container of parraffine wax, the surface of water appears convex spherical at the boundary. ***It is thus clear that the shape of the liquid surface at the boundary depends both; upon the material of the container, and the nature of the liquid.***

> *The angle which the tangent to the liquid surface at the boundary makes with the wall of the container into the liquid is called angle of contact θ. Refer Fig. 9.12(a).*

Obviously, for concave spherical meniscuses (surfaces of small area as in a capillary tube) the angle of contact is *acute* (i.e., less than 90°) and for convex spherical meniscuses, the angle of contact is **obtuse** (i.e., greater than 90°). For example for water in contact with glass angle of contact = 8°, and for mercury in contact with glass $\theta = 130°$

Fig. 9.12 shows the various forces acting on a molecule in the surface of a liquid near the boundary contained in a vessel. Due to the liquid being present only in the lower quadrant, the resultant cohesive force F_c acting on the molecule at P acts in a symmetrical direction as shown in the fig. 9.18. Similarly due to symmetry, the resultant adhesive force F_a acts outwards at right angles to the walls of the container vessel. The force F_c can be resolved into two mutually perpendicular components $F_c \cos\theta$ acting vertically downwards and $F_c \sin\theta$ and F_a acting at right angled to the boundary depends upon the relative values of F_c and F_a.

Case. 1: If $F_a > F_c \sin\theta$, the net horizontal force is acting outward and then the resultant of $(F_a - F_c \sin\theta)$ and $F_c \cos\theta$ lies outside the wall. Since liquids cannot sustain constant shear, the liquid surface and hence all the molecules in it near the boundary adjusts itself at right angles to F_R so that no component of F_R acts tangential to the liquid surface. Obviously such a surface at the boundary is concave spherical [since radius of a circle is perpendicular to the circumference at every point.] This is true in the case of water filled in a glass tube.

Case 2: If $F_a < F_c \sin\theta$, the resultant F_R of $(F_c \sin\theta - F_a)$ acting horizontally and $F_c \cos\theta$ acting vertically downwards is in the lower quadrant acting into the liquid. The liquid surface at the boundary, therefore, adjusts itself at right angles to this F_R and hence becomes convex spherical. This is true for the case of mercury filled in the glass tube.

Case 3: If, however $F_a = F_c \sin\theta$, the resultant F_R is $= F_c \cos\theta$ acting vertically downards and hence the liquid surface near the boundary becomes horizontal or plane.

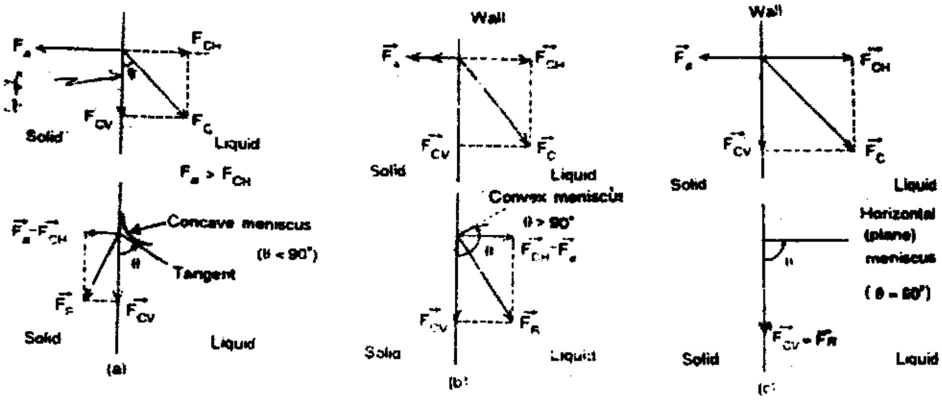

Fig. 9.18: *Different shapes of the liquid meniscuses*

9.6 CAPILLARY ACTION

You woul noticed that the walls of some old houses develop moisture to some height above the ground during rainy season. The water from the ground seeps in and rises up along the narrow lanes (capillaries) of air in the wall. Similarly you must be using blotting paper to absorb extra ink which your ink pen sometimes spils over your notebook. The ink rises into the narrow airgaps in the blotting paper and thus gets absorbed completely.

This phenomenon of rising up of liquid against gravity by itself into the capillary tubes i.e., narroes tubes is called capillary action. A tube with fine bore of diameter ≈ 1 mm is called a capillary tube.

Such an important phenomenon of the *elevation of a liquid in an open tube* of small cross-section *i.e.*, capillary tube is basically due to surface tension. This happens in the case of concave liquid meniscus only. However, in case of liquids having convex meniscus, the depression of liquid in capillary tube is observed.

Thus the action of rise or fall of liquid level in a capillary tube above or below the level in t liquid container when the capillary is dipped in the container is called ***capillary action*** or phenomenon of capillarity. Fig. 9.19.

Let us take a capillary tube dipped in any liquid and the meniscus of liquid inside it to be concave. Further suppose that the level of liquid inside the capillary tube remains at the same level as in the outer vessel, as is observed in case of wide bore tubes. We have to check whether, it is the situation of stable equilibrium.

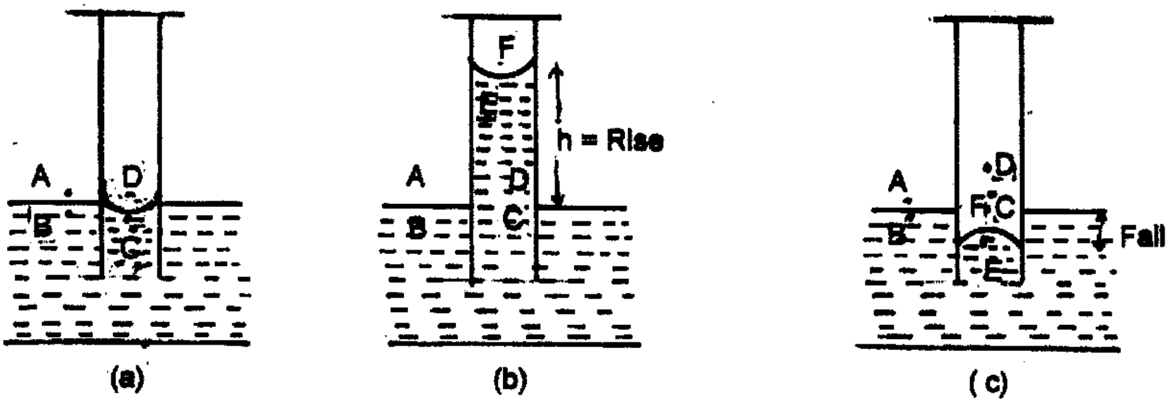

Fig. 9.19: *Rise and fall in capillary tube due to concave and convex meniscus respectively inside the capillary*

Consider the points A, B, C & D just near the liquid surface. The point D and A being exposed to air.

The pressure at A and D = atmospheric pressure = P

i.e., $P_A + P_D = P$ (say)

Since the pressure at the concave side of the liquid meniscus has to be greater than that on the other side by $\frac{2T}{r}$, we can write, pressure at C

$$= P_c = P_D - \frac{2T}{r} = P - \frac{2T}{r};$$

where r = radius of the concave surface. But pressure at A = P_A = Pressure at B = P_B = P. Thus, there exists a pressure difference between the points B, outside the capillary tube and the point C, inside the capillary tube at the same horizontal level. Therefore, the liquid would rush from the region of point B to the region of point C causing a rise of liquid in the capillary tube till the pressure at C becomes equal to the pressure at the point B. Fig. 9.20 (b). On the same arguments it can be proved that if the liquid meniscus in the capillary tube is convex, there will be a fall in the liquid level in the capillary Fig. 9.20 (c).

9.6.1 Expression for rise in capillary tube

Let h = the height to which the liquid rises in the capillary tube to achieve $P_C = P_B$, (The condition necessary to achieve stable equilibrium.)

Now, let us consider two more points E & F as shown in the figure (9.20) (b). The point F is exposed to atmosphere and is on the concave side of the liquid surface; therefore

$$P_F - P_E = \frac{2T}{r}$$

and $P_F = P$ = atmospheric pressure

$$P_E = P_F - \frac{2T}{r} = P - \frac{2T}{r}$$

Also, $P_D = P_E + hdg$; where d = density of the liquid

$$= \left(P - \frac{2T}{r}\right) + hdg \qquad \text{...(i)}$$

But $P_D = P_C$ (very close together)

$= P_B$ (in the same horizontal plane)

$= P_A$ (very close together

or $P_D = P$ = the atmospheric pressure ...(ii)

Therefore, comparing expression (i) and (ii)

$$P = P - \frac{2T}{r} + hdg$$

which gives,

$$hdg = \frac{2T}{r}$$

or

$$h = \frac{2T}{rd \cdot g} \qquad \text{...(iii)}$$

Now from the geomoetry of the figure (9.21),

If R = radius of the capillary tube and

θ = Angle of contact of the liquid in contact with the material of the capillary tube

and r = radius of the concave spherical meniscus,

$$r = \frac{R}{\cos\theta}$$

$\therefore$ Rise in capillary tube $\boxed{= h = \dfrac{2T\cos\theta}{R \cdot d \cdot g}}$ ...(iv)

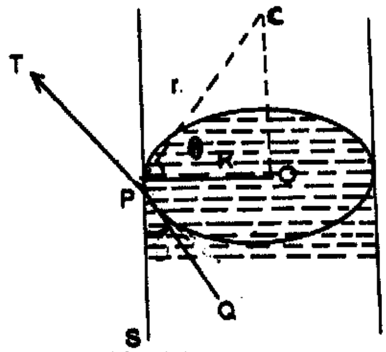

Fig. 9.21

However, since the liquid surface in the capillary tube is curved *i.e.*, not plane and h = height to the lowest point of the curved surface, a connection should be applied for the excess of water present in the tube forming the surface concave. The rigorous mathematical treatment suggests that h should be replaced by $\left(h + \frac{R}{3}\right)$; hence from (iv)

$$h + \frac{R}{3} = \frac{2T\cos\theta}{Rdg}$$

which gives $$T = \frac{R\left(h + \frac{R}{3}\right)d \cdot g}{2\cos\theta}$$ ...(v)

Same expression can be obtained for fall of liquid in case of convex meniscus in the capillary. For water, since θ is very very small $\approx 8^\circ$, which gives

$\cos\theta \Rightarrow \cos 8^\circ \to 1$ and R being very very small in comparison to h, the equations (iv), and (v) can be approximated to

$$h = \frac{2T}{Rdg} \quad and \quad T = \frac{Rhdg}{2}$$ ...(vi)

Example 9.3: *Water rises to a height of 8 cm in a certain capillary tube. In the same tube, the level of mercury is seen to fall by 3.45 cm. Compare the surface tension of water and mercury. Give specific gravity of mercury 13.6, and angles of contact of water and mercury as 0° and 135° respectively.*

Solution: The rise or fall in a capillary is given by

$$h = \frac{2T\cos\theta}{Rdg}; \text{ where } R = \text{radius of capillary tube}$$

For water rise $= (h_1) = \dfrac{2T_1\cos\theta_1}{Rd_1 g}$

For mercury, fall $= (h_2) = \dfrac{2T_2\cos\theta_2}{Rd_2 g}$

which gives $\dfrac{h_1}{h_2} = \left(\dfrac{T_1}{T_2}\right)\left(\dfrac{\cos\theta_1}{\cos\theta_2}\right)\left(\dfrac{d_2}{d_1}\right)$

or $\dfrac{T_1}{T_2} = \left(\dfrac{h_1}{h_2}\right)\left(\dfrac{\cos\theta_2}{\cos\theta_1}\right)\left(\dfrac{d_1}{d_2}\right)$

We are given, $\dfrac{h_1}{h_2} = \dfrac{8}{-3.45}; \dfrac{\cos q_2}{\cos q_1} = \dfrac{\cos 135^\circ}{\cos 0} = \dfrac{-\frac{1}{\sqrt{2}}}{1} = -\dfrac{1}{1.41}$

and

$\dfrac{d_1}{d_2} = \dfrac{1}{13.6}; \left(\text{specific gravity of mercury} = \dfrac{\text{density of mercury}}{\text{density of water}}\right)$

$\therefore \quad \dfrac{T_1}{T_2} = \dfrac{8}{(-3.45)} \times \left(-\dfrac{1}{1.41}\right) \times \left(\dfrac{1}{13.6}\right)$

$$= \frac{8}{66.15} = 0.12$$

or $\boxed{T_1 = 0.12\ T_2}$

Table (9.1) given at the end of this lesson gives surface tensions of some common liquids at 20°C, and also angles of contact of some liquids. The value of surface tension decreases with increase in tempearture and due to dissolved impurities.

INTEXT QUESTION 9.3

1. *Does the value of angle of contact depend on the value of surface tension of a liquid?*

   ....

2. *Water has concave meniscus in a glass capillary, because of which water rises to certain height in the capillary. Why then the water is not transferred from the ground floor to the first floor by using a capillary of appropriate radius without using any water pump?*

   ....

3. *Why is it difficult to enter mercury in a capillary tube by simply dipping it in a trough containing mercury while designing a thermometer?*

   ....

4. *We can form soap bubbles floating in air by blowing soap solution in air, with the help of a glass tube, but not water bubbles. Why?*

   ....

5. *Calculate the radius of a capillary to have a rise of 3 m when dipped in a vessel containing water of surface tension 7.2×10^{-2} Nm^{-1}. Given density of water = 1000 kgm^{-3}; Angle of contact = zero; g = 10 ms^{-2}.*

   ....

9.7 WHAT HAVE YOU LEARNT

- Liquids are incapable of withstanding any shearing forces for any length of time.
- Liquids do exert pressure on the side walls of the container.
- Hydrostatic pressure '*P*' at a depth '*h*' below the free surface of a liquid of density *d* inside it is given by $P = hdg$
- According to Pascal's law of transmission of liquid pressure.

  'when a pressure is applied anywhere on the surface of a given mass of an enclosed liquid at rest, an equal uniform pressure is transmitted over the whole liquid. It gets transmitted throughout the whole liquid of the containing vessel and acts in a direction at right angles to the surface of liquid there.'
- Hydraulic press, hydraulic brakes and hydraulic jack work on the principle of the Pascal's law.
- A thin layer of the surface of the liquid of thickness equal to the molecular range of attraction is called surface layer or surface film.
- The liquid molecules in the liquid surface have extra potential energy called surface energy.

- The liquid contained in a vessel has planer surface because a planer surface having a definite boundary has the minimum surface area.
- Surface tension of any liquid is a property by virtue of which the liquid-surfaces behave like a stretched membrane.
- The surface tension T of a liquid may be defined as force per unit length acting on an imaginary line supposed to be drawn in the surface. It is measured in Nm^{-1}.
- Angle of contact is defined as the angle between the tangent to the liquid surface and the wall of the container into the liquid.
- Surface tension (T) may also be defined as the work done per unit increase in area of the liquid surface and is measured in Jm^{-2}.
- The liquid surfaces in capillary tube are observed to be concave spherical or convex spherical. This curvature is due to surface tension effect. The rise in capillary = $h = \frac{2T}{r\rho g}$
- There exists an excess pressure 'p' on the concave side of radius r of the liquid surface given by :

$$\left.\begin{array}{l} \textit{for spherical water drop } p = \frac{2T}{r} \\ \textit{for air bubble in water } p = \frac{2T}{r} \\ \textit{for soap bubble in air } p = \frac{4T'}{r} \end{array}\right\} \begin{array}{l} ; \textit{where } T = \textit{surface tension of the water} \\ \\ T' = \textit{surface tension of soap solution.} \end{array}$$

- The surface tension finds its important application in clearing of woven clothes. Detergents are considered better cleaner of oily clothes because they reduce the surface tension of water-oil.

9.8 TERMINAL QUESTIONS

1. What is peculiar about liquid pressure?
2. Derive an expression for hydrostatic pressure due to a column of liquid.
3. State Pascal's law. Explain the working of hydraulic press.
4. Define surface tension. Find its dimensional formula.
5. Describe an experiment to show that liquid surfaces behave like a stretched membrance.
6. The hydrostatic paressure due to a liquid filled in a vessel at a depth 0.9m is $3Nm^{-2}$. What will be the hydrostatic pressure at a hole in the side wall of the same vessel at a depth of 0.6 m?
7. In a hydraulic press how much weight is needed to lift a heavy stone of mass 1000 kg? Given the ratio of the areas of cross-sections of the two pistons is = 5. Is the work output greater than work input? Explain.
8. A liquid filled in a capillary tube has *convex* meniscus. If F_a = Force of adhesion; F_c = Force of cohesion and θ = angle of contact, then which one of the following relations should hold good?

   (a) $F_a > F_c \sin\theta$; (b) $F_a < F_c \sin\theta$; (c) $F_a \cos\theta = F_c$; (a) $F_a \sin\theta > F_c$
9. 100 drops of water of some radius coalise to form a larger drop of water. What happens to the temperature of the water drop? Why?
10. What happens to the temperature of liquid when a bigger drop is sprayed into many drops? What is its importance in daily use?

11. What is capillary action? What are the factors upon which the value of rise or fall of a liquid in a capillary tube depends?

12. Calculate the approximate rise of liquid level in the capillary tube of length 0.05 m and radius 0.2×10^{-3} m, when dipped slightly in a liquid of density 1000 kg m^{-3}. Given surface tension of that liquid for the material of that capillary as 7.27×10^{-2} Nm^{-1}.

13. What is the angle of contact for a plane liquid surface at the boundaries of the container is

14. Why is it difficult to blow water bubbles in air while it is easier to blow soap bubble in air?

15. Why the detergents have replaced soaps to clean oily clothes?

16. Show that the rise in temp ($\Delta\theta$) of a liquid drop formed by the coalising of 1000 drops each of radius r, density ρ, specific heat s in Joules per kg per °C and sur face tension T is given by $\Delta\theta = 2.7\left(\frac{T}{r\rho s}\right)$

17. Two spherical balloons have been inflated with air to different sizes. They are now connected together with a hollow leakproof tube. What do you expect out of the following observations:

    (i) The air from smaller balloon will rush into the bigger balloon till whole of its air flows into the later.

    (ii) The air from the bigger balloon will rush into the smaller balloon till the sizes of the two become equal.

18. Which process involves more pressure to blow a soap bubble of radius 3 cm inside the sopa solution, or outside the soap solution in air? Why?

ANSWERS TO INTEXT QUESTIONS

Intext Questions 9.1

1. Container B ; $P_A = 0.4 \times 1500 \times 9.8 = 5880\,Nm^{-2}$
   $P_B = 0.31 \times 2000 \times 9.8 = 6076\,Nm^{-2}$

2. $\frac{5}{72}$ m

3. Consult the text.

$$\text{Mechanical advantage} = \frac{\text{Output Force}}{\text{Input Force}} = \frac{P \times A_2}{P \times A_1} = \frac{A_2}{A_1}$$

= Ratio of the area of the large cylinder to the area of small cylinder

4. $\frac{50}{0.1} = \frac{W}{10} \Rightarrow W = 5000\,\text{kg wt.}$

5. Pascal or Nm^{-2} in SI.

   1 Nm^{-1} = 1 Pa

6. Pressure applied by the weight of the boy $= \frac{25}{0.05} = 500\,Nm^{-2}$

   Pressure due to the weight of the elephant $= \frac{5000}{10} = 500\,Nm^{-2}$

Hence the boy can balance the weight of elephant.

Intext Questions 9.2

1. Force between molecules of the same substance is called force of cohesion and the force between molecules of different substances is called force of adhesion.

2. For definition consult the text.

   Dimensional formula of surface tension $= \frac{\text{Force}}{\text{Length}} = \frac{MLT^{-2}}{L} = [MT^{-2}]$

3. A layer of thickness equal to the range of molecular of attraction is called surface layer.

   The value of surface energy depends upon the area of the surface.

4. No, they have lightly bound molecules.

5. Due to surface tension forces.

   p for air bubble in water $= \frac{2T}{r} = \frac{2\times727\times10^{-3}}{2\times10^{-2}} = 727\times10^{-1}\ \text{Nm}^{-2}$

   p for soap bubble in air $= \frac{4T'}{r'} = \frac{4\times25\times10^{-3}}{4\times10^{-2}} = 25\times10^{-1}\ \text{Nm}^{-2}$

   Obviously air bubble in water has more excess pressure inside it.

7. (i).

8. Outside the solution in air. Because two surface are to be produced for which excess pressure $= \frac{4T}{r}$ (while excess inside pressure for blowing a bubble in solution is only $\frac{2T}{r}$)

Intext Questions 9.3

(i) No.

(ii) The radius of the capillary required for such a high rise is very very small also the radius of the meniscus increases after reaching the other end so that water does not come out of the capillary tube of insufficient length (*i.e.*, smaller length than the rise).

(iii) Mercury has a convex meniscus and there is a fall in level of mercury in a capillary which makes it difficult to enter.

(iv) The excess pressure inside air bubble being more due to large surface tension — the water film breaks down.

(v) $r = \frac{2T}{h\rho g} = \frac{2\times7.2\times10^{-2}}{3\times1000\times10}\ \text{m} = 4.8\times10^{-6}\ \text{m}$

TABLE 9.1: SURFACE TENSION OF SOME LIQUIDS AT 20°C

S.No.	Liquids in contact with air	Surface Tension Nm^{-1}	wall of	Angle of contact degrees
1.	Water	7.27×10^{-2}	i) glass ii) silver iii) paraffin	8° 0° 107°
2.	Mercury*	43.5×10^{-2}	soda lime glass	140°
3.	Soap solution	2.5×10^{-2}		
4.	Olive Oil	3.2×10^{-2}		
5.	Benzene	2.89×10^{-2}		
6.	Glycerine	6.4×10^{-2}		
7.	Turpentine	2.73×10^{-2}		
8.	Carbon tetra chloride	2.68×10^{-2}		
9.	Ethanol	2.27×10^{-2}		
10.	Methyle Iodide		i) Soda lime glass ii) Pyrex glass iii) Lead glass iv) Fused Quartz	29° 29° 30° 33°

* Decreases with age.