

Module 3 Surface Tension

This module is designed to help you to:

- explain the concept of surface tension;
- relate various concepts and applications of surface tension;
- perform activities to explain the concept of surface tension;
- explain the concept of capillarity and rise in level of a liquid in capillaries.

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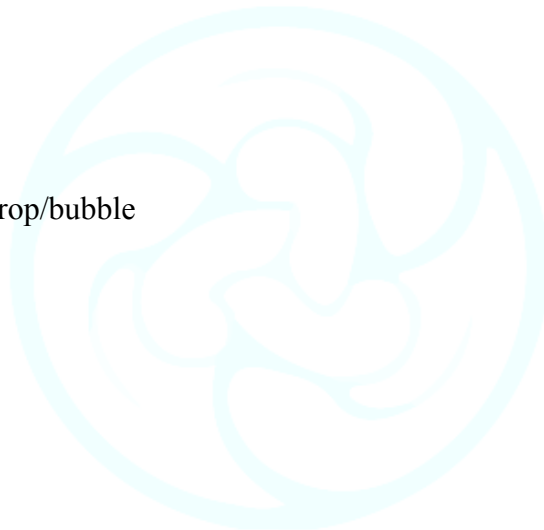
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10.3.1 Introduction

The phenomena of surface tension touches our daily lives and we make use of it in various everyday applications. Surface tension relates to the behavior of liquids when they come in contact with other surfaces or other liquids. We observe that oil and water do not mix. We see that oil forms a film or droplets on the water surface. Similarly, we see that when water droplets or mist fall on rose petals, they remain as droplets and do not wet the petals. However, these droplets wet the plants, stems and trunks. Other common phenomena related to surface tension are capillary action, rise of sap in plants and trees, rise of oil up the cotton wick of an oil lamp, action of detergents when mixed with water for washing purposes, insects moving on water surfaces etc.

In the present module, we discuss the phenomenon associated with surface tension.

10.3.2 Surface tension

Surface tension is the property of the free surface of a liquid to acquire minimum surface area. Liquids have a definite volume but no definite shape. They take the shape of the container in which they are kept. This ability of the liquid to take the shape of the container leads to liquids possessing free surfaces like the top surface of the liquid. Gases do not have free surfaces and therefore do not exhibit surface tension. Let us now discuss the phenomenon of surface tension.

Consider a molecule in the interior of a liquid [Fig.10.3.1 (a)]. It is equally attracted in all directions by the surrounding molecules. The net force on the molecule is zero.

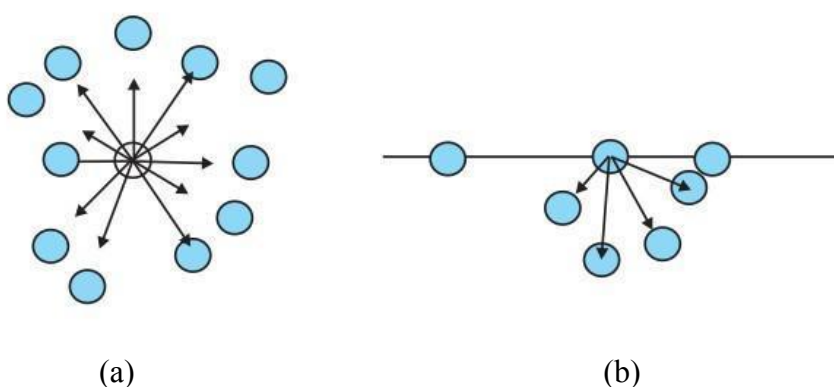


Fig. 10.3.1: Schematic picture of molecule (a) inside liquid (b) on the surface

Let us now consider a molecule on the surface [Fig. 10.3.1 (b)]. Only the lower half side of the molecule is surrounded by liquid molecules. It, therefore, experiences a net downward force. The molecules in the interior of the liquid tend to pull the molecules of the surface inwards, imparting the surface molecules some energy. Therefore, molecules on the surface of a liquid have some extra energy in comparison to molecules in the interior. The free surface of a liquid possesses some additional energy referred to as surface energy. This surface energy helps us in defining the concept of surface tension:

- The surface energy per unit area possessed by the surface molecules is a measure of surface tension.
- Surface tension is also equal to force per unit length acting at right angle to any arbitrary line drawn on the liquid surface. It acts tangentially to the liquid surface.
- Surface tension arises due to excess (potential) energy of the molecules on the surface, in comparison to their (potential) energy in the interior

10.3.3. Surface tension – a scalar

Surface tension is defined as the force per unit length, acting at right angle to an imaginary line drawn on the liquid surface. The (imaginary) line may be arbitrarily drawn on the surface. Fig 10.3.2 shows two lines drawn in arbitrary directions and both can be used to define surface tension. Hence the idea of a specific direction cannot be associated with surface tension. So we consider surface tension as a scalar quantity.

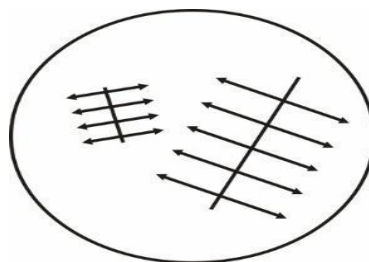
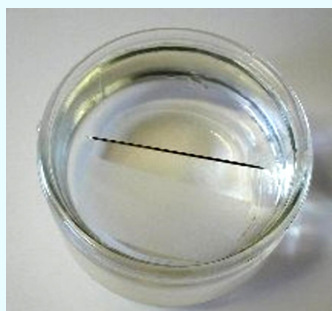


Fig. 10.3.2: *Surface tension: a scalar*

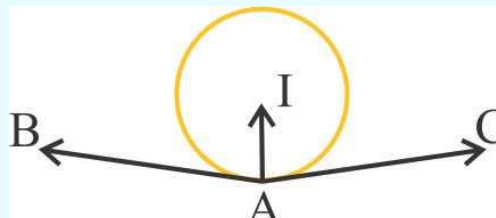
Further, surface tension of a liquid also equals the work done to increase its surface area by a unit amount (surface tension = W/A). This further justifies that surface tension has to be taken as a scalar quantity.

Activity 10.3.1

Can a metallic paper pin float on water? Let us explore.



(a)



(b)

Fig. 10.3.3: *Iron pin floating on water*

- Put a metallic paper pin on a small piece of tissue paper.
- Place the tissue paper along with the pin gently over the surface of the water kept tumbler.
- Observe carefully.
- Slowly, the tissue paper sinks and the metallic pin floats over the water surface (Fig. 10.3.3).

When the pin is placed over the water surface, it pushes the water and water in the surroundings tends to rise. However, the cohesive forces acting between water molecules do not allow the surface to rise. So it again pushes the water that is below the paper pin in an upward direction. An equilibrium is maintained and the paper pin floats on the water.

Activity 10.3.2

- Make a rectangular frame ABCD of a wire as shown in Fig. 10.3.4.
- Make a small loop(irregular) of a light thread [Fig. 10.3.4 (a)].
- Tie the loop to the frame using two thread pieces as shown.
- Prepare a soap solution in a container.
- Dip the frame along with the thread in the soap solution.

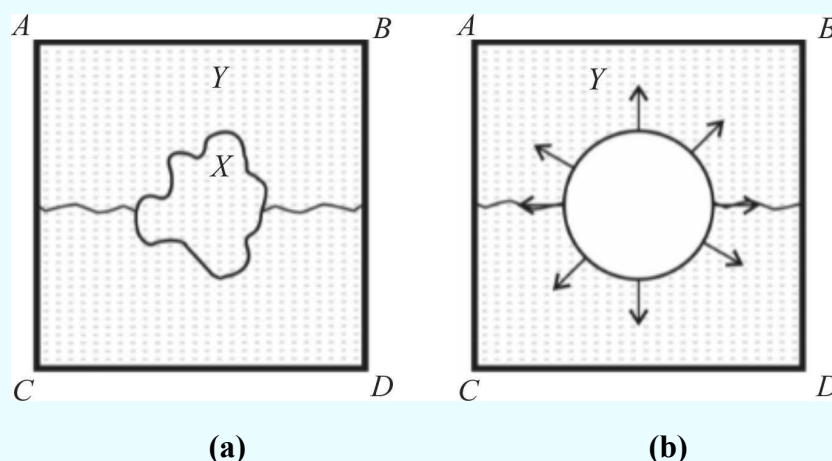


Fig. 10.3.4: *Surface tension: an illustration*

- Lift the arrangement. A soap film will be formed in the frame.
- Observe the film carefully. The thread loop still has an irregular shape.
- Prick the part X (inside the thread loop) of the film. The soap film inside the loop bursts.
- The loop acquires the shape of a perfect circle as shown in Fig. 10.3.4 (b).

Why does the thread loop acquire a circular shape?

This is so because the remaining part Y of the film tends to shrink to minimize its surface area. **For a given periphery the area enclosed by a circle is maximum.** When thread acquires a circular shape the remaining film (Y) has a minimum area.



Let Us Reflect

Q.10.3.1 W is the work done in forming a liquid drop of radius r . The work done in blowing a bubble of radius $\sqrt{2} r$ of the same liquid is

- (A) $\sqrt{2} W$
- (B) $2 W$
- (C) $2\sqrt{2} W$

(D) 4 W



Answers

A.10.3.1 (D)

Hint: The drop has only one free surface whereas the bubble has two free surfaces.

10.3.4 Angle of contact

At the interface of the free surface of the liquid with another medium, the unbalanced forces acting on the surface molecules due to the surrounding molecules of the liquid and the medium cause the free surface of the liquid to become curved. The angle that the tangent to the curved surface of the liquid at the point of contact, makes with the surface of the other medium, measured inside the liquid, at the interface is referred to as angle of contact (denoted by θ). The curvature of the free surface is a property of the liquid and the surface in contact. Therefore, it is different for different pairs of liquids and solids.

The value of θ gives information about the physical properties of the liquid and the shape of the curved surfaces. For θ exceeding 90° , the liquid will form droplets on the surface of the medium as water on the lotus leaf [Fig. 10.3.5 (a)].

For θ less than 90° , the liquid spreads on the solid surface, like water on glass [Fig. 10.3.5 (b)].

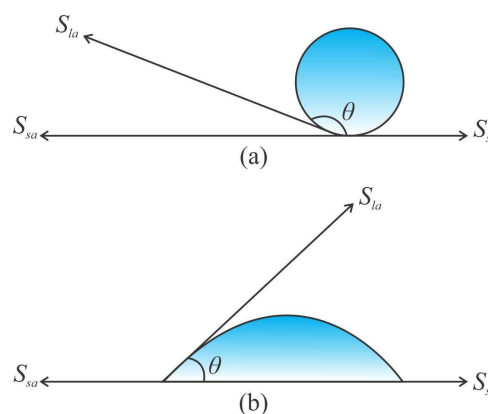


Fig. 10.3.5: Different shapes of water drops with interfacial tensions (a) on a lotus leaf (b) on a clean glass plate

From the above Fig. 10.3.5 (a) and (b), it is clear that there are three interfaces: liquid-air, solid-air and solid-liquid. Accordingly, there are three interfacial tensions at the three interfaces denoted by S_{la} , S_{sa} and

S_{sl} respectively. The forces acting between the surfaces of the three media must be in equilibrium at the point of contact. We get,

$$S_{la}\cos\theta + S_{sl} = S_{sa}$$

In Fig. 10.3.5 (a), depicting the case of water drop on a leaf, the angle of contact is an obtuse angle and $\cos\theta$ is a negative number. Therefore, $S_{sl} > S_{sa}$ imply that the liquid molecules are strongly attracted to themselves and weakly to those of solids.

For such combinations of solids and liquids, the liquid does not wet the surface of the solid.

Water on oil, water on wax coated surfaces and mercury on glass are examples of such combinations. To prevent the rusting of the metal body of a vehicle, it is painted and coated with wax or teflon.

In Fig. 10.3.5 (b), depicting water on glass, the angle of contact is an acute angle. Therefore,

$S_{sl} < S_{sa}$, implying that the liquid molecules are attracted weakly to the other liquid molecules and strongly to the solid molecules. Such liquids wet the surface of the solid as in the case of water on glass.

An important application of the concept of surface tension is the cleaning up of oil slick on water bodies. Use of sorbents, surface dispersants, oil absorbent and oil containment booms and gelling agents use the principle of surface tension to clean up the oil spill. Adding or spraying the surface of the oil with the sorbent makes the angle of contact between oil and the sorbent acute for effective cleaning of the oil spill.

The above discussion is summed up in Table 10.3.1.

Table 10.3.1: *Angle of contact*

Angle of contact	Surface tension at the interface of solid-liquid/liquid-air	Example	Molecules attraction
Obtuse	$S_{sl} > S_{sa}$	Liquid does not wet the solid. Example water-leaf interface. Mercury on the glass surface.	Molecules of liquids are attracted strongly to themselves and weakly to those of solid surfaces.
Acute	$S_{sl} < S_{sa}$	Liquid wets the solid. Example water on a glass plate.	Molecules of the liquid are more strongly attracted to those of solids than to themselves.

10.3.5 Drops and bubbles

It is a common observation that small raindrops are spherical in shape. When liquids are sprayed (as in the case of perfumes and deodorants), the droplets formed are spherical. Such spherical shapes are also observed when we blow soap bubbles. The air bubbles trapped in liquids are also spherical.

Why do drops and bubbles acquire spherical shape?

Small liquid drops and bubbles are spherical in shape. Large drops deviate from spherical shape due to the effect of gravity. The drops acquire and retain their spherical shape due to surface tension. We have learnt that the molecules on the surface of a liquid have an additional energy called surface energy.

Every system in the universe tries to attain the state of the minimum possible potential energy. The energy of the liquid will become minimum if the minimum number of molecules remain on the surface. So, the molecules of a liquid tend to leave the surface and move to the interior of the liquid. Therefore, the free surface of the liquid attains the minimum possible area. For a given volume; the surface area is the minimum for spherical shape. Therefore, the free surface of the liquid tends to be spherical in shape.

10.3.6 Excess pressure inside a drop/bubble

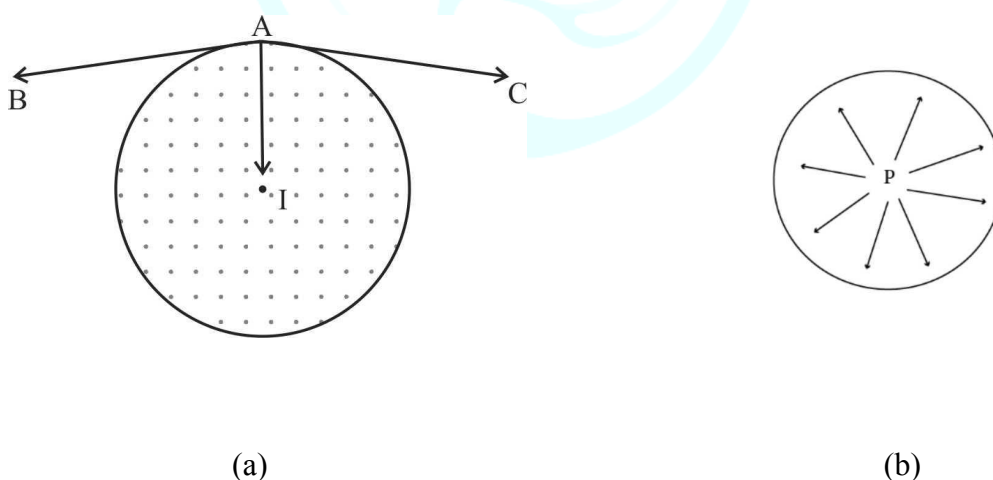


Fig. 10.3.6: (a) and (b) *Excess pressure inside a drop/bubble*

Consider a spherical drop of a liquid. For a molecule A on the surface of the drop, forces due to surface tension act along AB and AC. These forces have a net inward resultant force acting along AI [Fig. 10.3.6 (a)]. Hence, the spherical drops tend to shrink due to intermolecular forces. The drops however do not collapse due to this inward force. This is due to an excess pressure inside the drop [Fig. 10.3.6 (b)].

Expression for excess pressure:

Consider a spherical drop of radius r . The radius of the drop is increased by a small amount Δr (Fig. 10.3.7).

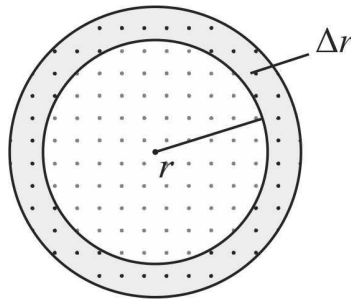


Fig. 10.3.7: Expression for excess pressure

The increase in surface energy (work done for expansion) is given by

$$W = (\text{Surface tension}) \cdot (\text{increase in area})$$

$$= S \left[4\pi(r + \Delta r)^2 - 4\pi r^2 \right] = S \cdot (8\pi r \cdot \Delta r) \quad \{\text{Neglecting } (\Delta r)^2 \text{ as it is very small}\}.$$

The work W can also be calculated in terms of the pressure difference $(P_i - P_o)$ inside and outside the bubble. We get,

$$W = F \cdot \Delta r = (P_i - P_o) 4\pi r^2 \Delta r$$

From the above expressions for the work W ,

$$W = (P_i - P_o) 4\pi r^2 \Delta r = S \cdot (8\pi r \Delta r)$$

Therefore, excess pressure

$$(P_i - P_o) = 2S/r$$

In general, for a liquid-gas interface, the concave side has a higher pressure than the convex side. For example an air bubble in a liquid would have higher pressure inside it.

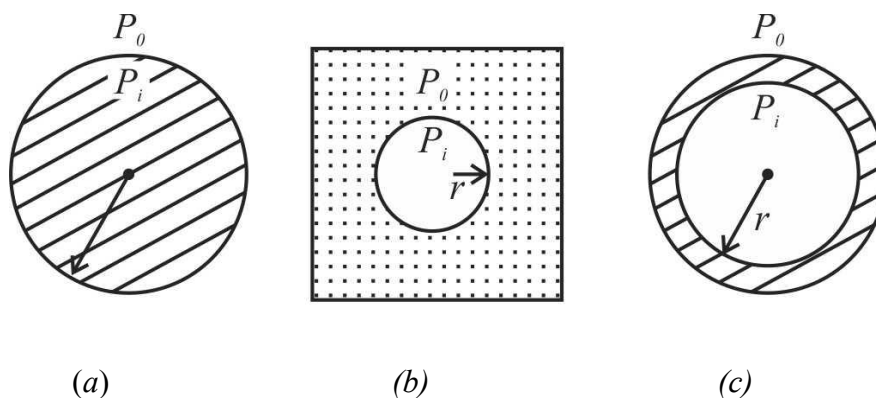


Fig. 10.3.8: (a) Liquid drop, (b) air bubble in a liquid, (c) soap bubble

A bubble differs from a drop and a cavity. It has two interfaces [Fig. 10.3.8 (a),(b)]. Proceeding as above, the excess pressure inside a bubble is $(P_i - P_o) = 4S/r$.

This is why you have to blow hard, but not too hard, to form a soap bubble. A little extra air pressure is needed inside [Fig. 10.3.8 (c)].



Let Us Reflect

Q.10.3.2 The excess pressure inside a liquid bubble of radius 20 mm is 14 N m^{-2} .

Surface tension of the liquid is

- (A) $3.5 \times 10^{-2} \text{ N cm}^{-1}$
- (B) $3.5 \times 10^{-2} \text{ N m}^{-1}$
- (C) $7 \times 10^{-2} \text{ N cm}^{-1}$
- (D) $7 \times 10^{-2} \text{ N m}^{-1}$

Q.10.3.3 Which of the following statement(s) is (are) correct ?

- (A) There is an excess pressure inside a liquid drop
- (B) Excess pressure inside a liquid drop increases as its radius increases.
- (C) Excess pressure inside a liquid drop decreases as its radius increases.
- (D) Excess pressure inside a liquid drop is independent of the liquid forming the drop.



Answers

A.10.3.2 (D)

A.10.3.3 (A) and (C)

10.3.7 Capillarity

The phenomenon of rise or fall of a liquid in a tube of narrow bore is called capillarity. Capillary rise is widely used in nature and in daily life. In nature, the trees and plants fulfill their requirement for water and nutrients by pulling up water from under the soil through capillaries. In daily life, the rise of oil in the wick of a lamp is an example of capillary rise. Interestingly, capillary rise occurs against gravity.

For a capillary dipped in a liquid which wets the tube (water in glass), the level of the liquid in the capillary is above its level in the container. The angle of contact for such liquids in the capillary is acute. On the other hand, if a capillary is dipped in a liquid which does not wet the tube (mercury in glass), the level of the liquid in the capillary is below its level in the container. The angle of contact for such liquids in the capillary is obtuse. The phenomenon is due to the pressure difference across curved liquid-air interfaces.

Expression for rise in level of a liquid in capillary

Consider a tube of small radius r (a capillary) dipped in a liquid of surface tension S and density ρ . Let θ be the angle of contact between the solid and the liquid. The surface of the liquid in the capillary is assumed to be spherical.

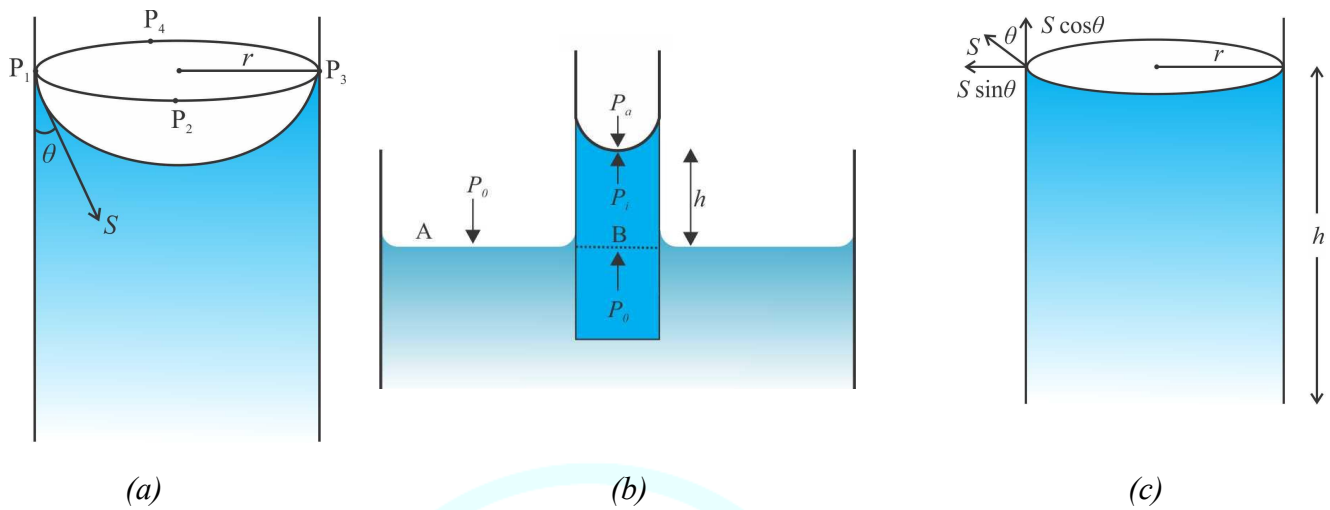


Fig 10.3.9: Capillary rise: (a) Enlarged picture of a capillary near interface, (b) Schematic picture of capillary rise in a narrow tube immersed in water, (c) The reaction force to surface tension S and its components

At a point P_1 , the surface tension acts on the solid along the tangent to the liquid surface

at the point P_1 inside the liquid [Fig. 10.3.9 (a)]. By Newton's third law of motion, an equal and opposite reaction is exerted on the liquid by the solid [Fig. 10.3.9 (b)]. This is so at all points P_2 , P_3 and P_4 , etc. on the liquid meniscus.

The component $S \cos \theta$ of the reaction force acts vertically upwards and pulls the liquid up in the capillary [10.3.9 (c)]. This force acts along the wall of the capillary in contact with the liquid all along a circle of radius r (radius of the capillary). By definition of surface tension $S = F/L$,

the net upward force on the liquid = $(S \cos \theta) \cdot 2\pi r$

The liquid rises to a height of h till the upward force on the liquid balances the weight of the liquid inside the capillary. Therefore,

$$\begin{aligned} (S \cos \theta) \cdot 2\pi r &= \text{Weight of the liquid inside the capillary} \\ &= (\text{Volume of the liquid inside the capillary}) (\text{density}) g \\ &= (\pi r^2 h) \rho g \end{aligned}$$

$$\text{Therefore, } h = \frac{2S \cos \theta}{r \rho g}$$

The expression implies that the rise h of the liquid in the capillary varies

- a) directly as surface tension S
- b) inversely as radius r of the capillary
- c) inversely as the density ρ of the liquid.

Hence, the capillary rise is larger in tubes with a smaller radius.

Note that for liquids like mercury in glass, the surface of the liquid is convex; the angle of contact is obtuse; $\cos \theta$ is negative and the liquid falls inside the capillary.

Example 10.3.1 A given liquid rises to a height h in a given capillary tube of radius r . Would the liquid overflow if this capillary tube were cut-down to have a total length l , less than h ?

Solution: No, the liquid would not overflow even if the capillary tube were a tube of insufficient length. This is so because an overflow, if it were to happen, would violate the principle of conservation of energy. One could then raise a liquid to a height (i.e. transfer it from a container, at a lower level to one at a higher level without any explicit input of energy). We could then get, so to say, energy ‘out of nothing’.

How does the situation manage itself then? We know that the formula for height, h , to which the liquid rises in a capillary tube, is

$$h = \frac{(2 \cos \theta) S}{r \rho g}$$

All the other terms being constants, under the given conditions, it is the angle of contact (usually taken as zero for rise of water in a glass capillary tube) that readjusts itself. The angle of contact, θ' , in case of a tube of insufficient length takes a new value such that

$$\cos \theta' = \frac{(r \rho g) l}{2S}$$

$$\text{i.e. } \theta' = \cos^{-1} \left[\frac{(r \rho g) l}{2S} \right]$$

It is this readjustment, in the value of θ (i.e. the shape of the liquid meniscus) which ensures that the relation between the height, and other parameters, remains valid even for a tube of insufficient length.

Explanation of surface tension concepts with the help of a numerical example

Surface tension is exhibited by liquids due to the force of attraction between molecules of the liquid. The surface tension decreases with increase in temperature and vanishes at boiling point.

Example 10.3.2 Given: Latent heat of vaporization for water $L_v = 540$ kcal/kg, Mechanical equivalent of heat $J = 4.2$ J/Cal, density of water $\rho_w = 10^3$ kg m⁻³, Avogadro's number $N_A = 6.0 \times 10^{26}$ (k mol)⁻¹ and the molecular weight of water = 18.

- Estimate the energy required for one molecule of water to evaporate.
- Show that the intermolecular distance for water is $\left(\frac{M_A}{N_A} \times \frac{1}{\rho_w} \right)^{1/3}$ and find its value.
- 1 g of water vapors at 100 °C and 1 atm occupies a volume of 1601 cm³. Estimate the intermolecular distance at boiling point in vapor state.
During vaporization, a molecule overcomes a force F (assumed constant) to go from an intermolecular distance d to d' . Estimate the value of F .
- Calculate F/d (a measure of the surface tension).

Solution:

Molecular weight of water = 18. Therefore,

mass of 1k mole of water = $M_A = 18$ kg

(a) As M_A kg contains N_A molecules, mass of 1 molecule = M_A/N_A .

Energy for one molecule to escape

$$= \frac{L_v M_A}{N_A} = 6.8 \times 10^{-20} \text{ J}$$

(b) If intermolecular distance is d , then volume per molecule

$$d^3 = \frac{M_A}{\rho N_A} = 3 \times 10^{-29} \text{ m}$$

Therefore, $d = 3.1072 \times 10^{-10} \text{ m}$.

(c) Intermolecular distance in vapor state

$$d' = (1601)^{1/3} d = 36.35 \times 10^{-10} \text{ m}$$

(d) Work done for a molecule to escape = $F(d' - d)$. Therefore,

$$F = \frac{\text{energy per molecule}}{(d' - d)} = 2.045 \times 10^{-11} \text{ N}$$

$$\therefore \frac{F}{d} = 0.0658 \text{ N/m.}$$



Let Us Reflect

Q. 10.3.4. A liquid X of surface tension S , density d and angle of contact 0° rises to a vertical height h in a capillary tube. The same tube is immersed in another liquid Y of surface tension $S\sqrt{\frac{3}{2}}$, density $d/\sqrt{2}$ and angle of contact 30° . The vertical height H to which the liquid Y rises in the tube is

- (A) $3h$
- (B) $2h$
- (C) $1.5h$
- (D) h

Q. 10.3.5. S , d and 0° are the surface tension; density and angle of contact of a liquid A. The corresponding values for another liquid B are $\sqrt{3}S$, d' and 60° . In the same capillary tube the ratio of rise of A and B are $2:3$. $\frac{d}{d'}$ is

- (A) $\frac{1}{\sqrt{3}}$
- (B) $\frac{2}{\sqrt{3}}$
- (C) $\sqrt{3}$
- (D) $\frac{\sqrt{3}}{2}$



Answers

A.10.3.4 (C)

A.10.3.5 (C)

10.3.8 Summary

- Surface tension is the property of the free surface of a liquid to acquire minimum surface area. It is equal to the force per unit length acting at a right angle to any arbitrary line drawn on the liquid surface. It acts tangentially to the liquid surface.
- Surface tension is a scalar quantity.
- Angle of contact can have any value between 0° and 180° .
- Acute angle of contact between a liquid and a solid indicates that the liquid will spread over the surface of the solid, or wets the solid.
- Obtuse angle of contact between a liquid and a solid indicates that the liquid will not spread over the surface of the solid. The liquid does not wet the solid.
- An excess pressure exists inside liquid drops and bubbles due to which they do collapse. Smaller the drop/bubble, the greater the excess pressure.
- Surface tension results in the rise/fall of liquids in capillary tubes. Capillarity is responsible for the rise of sap in plants. The vertical distance through which a liquid rises/falls in a capillary is

$$h = \frac{2S \cos \theta}{r\rho g}$$

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