7

THE LIQUID STATE

You are familiar with gases, liquids and solids in your daily life. You are aware that water can exist as a liquid, a solid (ice) or as a gas (vapour). These are called three *states of matter*. In lesson 6, you have learnt about the differences in properties of these three states of matter. The properties of gaseous state can be explained in terms of large separation of molecules and very weak intermolecular forces. In this lesson we shall study about the intermolecular forces in liquids and see how their properties can be explained in terms of these forces.

Objectives

After reading this lesson, you will be able to :

- explain the properties of liquids in terms of their structure (molecular arrangement and intermolecular forces);
- differentiate between evaporation and boiling;
- define vapour pressure of a liquid and correlate it with its boiling point;
- define surface tension and explain the effect of various factors on it;
- explain the consequences of surface tension and
- define viscosity of a liquid and correlate it with intermolecular forces.

7.1 Nature of Liquids

Look at Figure 7.1 in which the molecular arrangement has been shown in the three states of matter. What do you notice?

In figure 7.1a, you would find that the molecules are far apart. A gaseous state can be represented by this arrangement. In liquid state (figure 7.1b), molecules are closer as compared to gaseous state. You would notice that they have very little spaces between

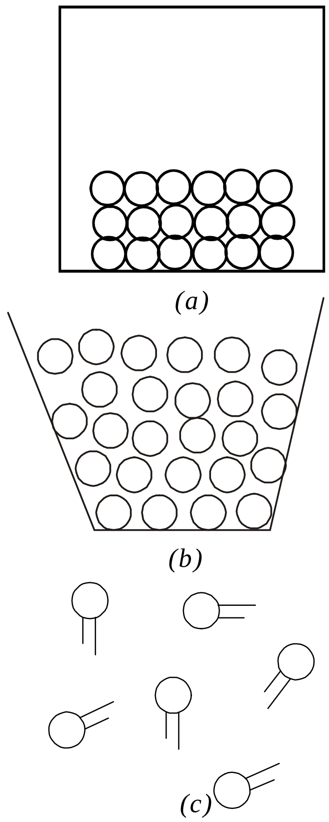


Fig. 7.1 : *Arrangement of molecuels in (a) solids; (b) liquids and (c) gases*

them. However, there is no order in arrangement of molecules. Further we say that, these molecules can move about, but with lesser speeds than those in gases. They can still collide with one another as in the gaseous state. You would recall that the molecules in gases have very little attraction between them. But in liquid state the attraction between the molecules is comparatively much stronger as compared to that in the gaseous state. The attractions are strong enough to keep the molecules in aggregation. Contrary to this, in solids (Fig. 7.1a) you notice that the molecules are arranged at the closest possible distance.

Solid state is a well ordered state and has very strong intermolecular forces. You would learn more about solids in lesson 8.

We would say, in a gas there is complete chaos due to very weak intermolecular forces, whereas in solids there is a complete order due to strong forces. Liquids falls between gases and solid state. Liquid molecules have some freedom of gases state and some order of solid state. Intermolecular forces in liquids are strong enough to keep the molecules close to one another but not strong enough to keep them in perfect order.

7.2 Properties of Liquids

In this section you would learn how the properties of liquids can be explained in terms of molecular arrangement and intermolecular forces. Let us consider a few properties of liquids as examples.

7.2.1 Volume and Shape

You would recall that the liquids (for example water) take the shape of the container in which they are kept. However, they have a definite volume. How can you explain the properties of definite volume and variable shape? In liquids, the attractive forces are strong enough to keep the molecules moving within a definite boundary. Thus, they maintain a definite volume. These intermolecular forces are not strong enough to keep them in definite positions. The molecules can, therefore, move around and take the shape of the container in which they are kept.

7.2.2 Compressibility

Compressibility of a substance is its ability to be squeezed when a force is applied on it. Let us study the compressibility of liquids with the help of the following activity.

Activity 7.1

Aim: To study the compressibility of water.

What is required?

A 5 mL syringe and water.

What to do?

(i) Take the syringe and fill it with water by pulling out the plunger.

(ii) Note the volume of water.

(iii) Press the plunger while blocking the nozzle of the syringe with a finger.

What to observe?

Observe the volume of water in the syringe while pressing the plunger. Does the volume of water change by pressing the plunger? You would observe that it does not change.

The above activity clearly shows that liquids are largely incompressible. It is because there is very little empty space between the molecules. In contrast, the gases are highly compressible because of large empty spaces between their molecules.

The large difference in the free space in gaseous and liquid states becomes evident from the fact that the volume occupied by a given amount of a substance in liquid state is *100-1000 times less* than that in the gaseous state.

7.2.3 Diffusion

Diffusion is the process of spreading of a substance from a region of higher concentration to a region of lower concentration. Let us study the phenomenon of diffusion in liquids with the help of the following activity.

Activity 7.2

Aim : To study the phenomenon of diffusion through water.

What is required?

A glass, water, blue ink and a dropper.

What to do?

(i) Take some water in the glass.

(ii) Add a few drops of blue ink into water with the help of a dropper.

What to observe?

Observe the water and ink in the beaker.
Initially the ink does not mix with water. After some time it starts spreading slowly. After a few hours the whole of water in the glass becomes coloured due to diffusion of ink through water.

The above activity demonstrates that diffusion occurs in liquids. Why does it happen? Because the molecules of both the liquids are moving and help in the diffusion process.

7.2.4 Evaporation

You know that water left in an open pan evaporates slowly until the pan becomes dry. Evaporation is the process by which a liquid changes into vapour. It occurs at all temperatures from freezing point to boiling point of the liquid.

In a liquid, at any temperature, a small fraction of the molecules is moving with relatively high velocity. Such molecules have high kinetic energy. These can overcome the intermolecular attractive forces and escape through the surface of the liquid.

Rate of evaporation of a liquid depends on a number of factors. For example, more is the surface area, faster will be the evaporation. For faster drying, we increase the surface area by spreading the wet clothes. If we supply heat to the liquid, evaporation is faster. The wet clothes dry faster in the sun. The increase in temperature increases the kinetic energy of the molecules of the liquid and the liquid evaporates at a faster rate. We feel cool after the bath. Why do we feel so? It is because during evaporation water takes the heat from our body and we feel cold.

Now let us compare the rate of evaporation of two liquids, for example, water and alcohol. Which of these two liquids evaporates faster? You must have experienced that alcohol evaporates faster. Why does this happen? The number of molecules escaping from a liquid depends upon the attractive forces. When these forces are stronger, fewer molecule escape. In alcohol, these attractive forces are weaker than those in the water. Hence, alcohol evaporates faster than water.

7.3 Vapour Pressure and Boiling Point

In the previous section you have learnt that liquids evaporate when kept in an open vessel. Different liquids evaporate to different extent under similar conditions. The extent of evaporation of a liquid is measured with the help of **vapour pressure** of a liquid. In this section, you will study about it and also about the boiling point of a liquid.

7.3.1 Vapour Pressure of a Liquid

You know that a liquid placed in an open vessel evaporates completely. If, however, the liquid is allowed to evaporate in a closed vessel say in stoppered bottle or a bell jar, evaporation occurs, but after sometime the level of the liquid does not change any further and become constant. Let us understand how does it happen. In the closed vessel, the molecules evaporating from the liquid surface are confined to a limited space. These molecules may collide among themselves or with the molecules of air and some of them may start moving towards the surface of the liquid and enter into it. This is known as condensation. In the beginning, rate of evaporation is greater than the rate of condensation. But as more and more molecules accumulate in the space above the liquid, rate of condensation gradually increases. After some time, rate of evaporation becomes equal to the rate of condensation and an equilibrium state is reached (Fig. 7.2). The number of molecules in the vapour above the liquid becomes constant. These molecules exert certain pressure over the surface of the liquid. This pressure is known as **equilibrium vapour pressure, saturated vapour pressure** or simply as **vapour pressure.** The vapour

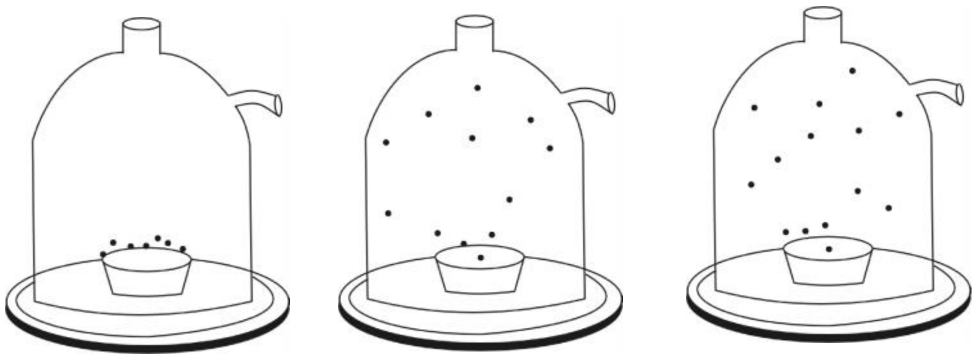


Fig. 7.2 : *Establishing (vapour liquid) equilibrium under a evacuated jar*

pressure of a liquid has a characteristic value at a given temperature. For example, vapour pressure of water is 17.5 torr and that of benzene is 75.00 torr at 20º C. The vapour pressure of a liquid increases with increase in temperature. It is so because at a higher temperature more molecules have sufficiently high energy to overcome the forces of attraction and escape to form vapour. A plot of vapour pressure as a function of temperature is called **vapour pressure curve**. Figure 7.3 depicts the vapour pressure curves of some liquids.

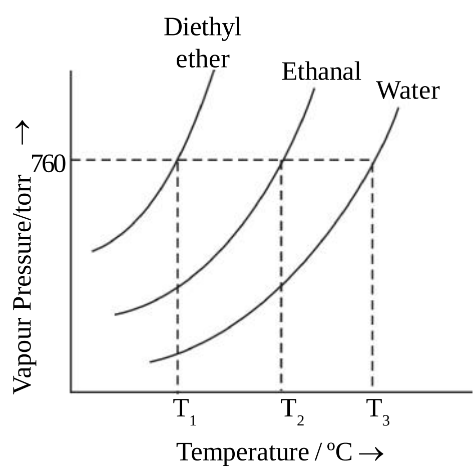


Fig. 7.3 : *Vapour pressure curves of some liquids.*

What would happen if we remove some of the vapour from the closed vessel. Would the vapour pressure of the liquid increase, decrease or remain constant? Vapour pressure of the liquid would remain constant at that temperature. In the beginning, the vapour pressure would decrease after the removal of the vapour, but soon more liquid would evaporate to maintain the equilibrium and the original vapour pressure would be restored. So the vapour pressure of a liquid has a definite value at a particular temperature.

7.3.2 Boiling

You must have seen the formation of bubbles at the base of a vessel, in which a liquid is heated. The rate of formation of bubbles increases with increse in heat supplied. What are the bubbles made up of? The first bubbles that you see are of the air, which is driven out of the liquid by increase in temperature. After some time, bubbles of the liquid are formed throughout it. These bubbles rise to the surface and break. When this happens, we say that the liquid is boiling. The bubbles of the liquid would form only if its vapour pressure is equal to the atmospheric pressure.

The temperature at which boiling occurs is called the **boiling point** of the liquid. At this temperature the vapour pressure of the liquid is equal to the atmospheric pressure. The boiling point, therefore, depends upon the atmospheric pressure. For example, water boils at 100ºC at 760 torr and at 97.7ºC at 700 torr.

The normal boiling point of a liquid is defined as the temperature at which the vapour pressure of a liquid is equal to one atmosphere or 760 torr.

The boiling point of a liquid depends upon its nature. A more volatile liquid would boil at a lower temperature than a less volatile liquid. You can again refer to figure 7.3 and note that diethyl ether boils at a much lower temperature than water, because it is highly volatile liquid. The boiling point of ethanol lies in between those of diethyl ether and water. Vapour pressures or boiling points of liquids give us an idea of the strength of attractive forces between molecules in liquids. Liquids having lower boiling points have weaker attractive forces in comparison to those having higher boiling points.

You can make a liquid boil at temperature other than normal boiling point. How? Simply alter the pressure above the liquid. If you increase this pressure, you can increase the boiling point and if you can decrease this pressure you decrease the boiling point. On the mountains, the atmospheric pressure decreases and therefore boiling point of water also decreases. People living on hills face problem in cooking their meals. They, therefore, use pressure cooker. How food is cooked faster in it? The lid of pressure cooker does not allow water vapours to escape out. On heating the water vapours accumulate and the inside pressure increases. This makes the water boil at a higher temperature and the food is cooked faster.

7.3.3 Evaporation and Boiling

Evaporation and boiling, both involve conversion of a liquid into vapour and appear to be similar. However, they differ from each other in some aspects. Evaporation occurs at all temperatures from freezing point of a liquid to its boiling point, while boiling occurs at a definite temperature only i.e, at its boiling point. Evaporation occurs slowly while boiling is a fast process. Evaporation of a liquid occurs at its surface alone while boiling occurs throughout the liquid. These differences between evaporation and boiling have been summarized in Table 7.1.

Table 7.1 : Differences between evaporation and boiling

S.No.	Evaporation	Boiling
1.	It takes place at all temperatures.	It takes place at a definite temperature.
2.	It is a slow process.	It is a fast process
3.	It occurs only at the surface of the liquid.	It occurs throughout the liquid.

Intext Questions 7.1

1. **Match the following.**

Column I	Column II
(i) Liquids have a definite volume.	(A) The molecules in a liquid can move about.
(ii) Liquids acquire the shape of their container.	(B) The molecules in liquids are close and have very little free space.
(iii) Liquids are largely incompressible.	(C) The inter molecular forces liquids strong enough to keep the molecules moving with in a definite space.

2. When a liquid is heated till it starts boiling.

   (i) What are the small bubbles that appears initially at the bottom and sides of the vessel made up of?

   ....

   (ii) What are the large bubbles that form in the boiling liquid made up of?

   ....

3. Liquids A, B and C boil at 65ºC, 120ºC and 90ºC respectively. Arrange them in the decreasing order of the strength of intermolecular forces.

   ....

7.4 Surface Tension

Liquids show the effects of inter molecular forces most dramatically in another property, namely, **surface tension**. Any molecule in the interior of liquid is equally attracted by neighbour molecules from all sides and it does not experience any 'net' force. On the other hand, any molecule at the surface of a liquid is attracted by other molecules at the surface of the liquid or below it. Due to the imbalance of forces, any molecule at the surface experiences a net inward pull (Figure 7.4). As a result the surface is under tension as if the liquid were covered with a tight skin (or stretched membrane). The phenomenon is called *surface tension*. Quantitatively, the **surface tension** *is defined as the force acting on an imaginary line of unit length drawn on the surface of the liquid and acting perpendicular to it towards the liquid side* as shown in Figure 7.5. It is represented by the Greek letter *gamma, r*. Its SI unit is newton per metre (N m^{-1}) and CGS unit is dyne per centimetre (dyne cm^{-1}). The two units are related as : 1 N m^{-1} = 10^3 dyne cm^{-1}

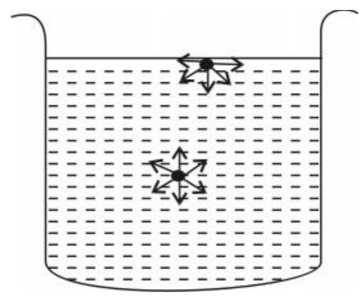


Fig. 7.4 : *Forces acting on molecules, at the surface and in bulk of liquids*

Surface molecules of a liquid experience a constant inward force. Therefore they have a higher energy than the molecules in the bulk of the liquid. Due to this reason liquids tend to have minimum number of molecules at their surface. This is achieved by *minimising the surface area.* In order to increase the *surface area* more molecules must come to the surface. This can happen only if some energy is supplied or work is done. *The energy supplied (or work done) for increasing the surface area of a liquid by a unit amount is known as its* **surface energy.** Its units are joule per square metre J m^{-2} or N m^{-1} (since 1J = 1N m). Thus dimensionally, the surface tension and surface energy are similar quantities and they have the same numerical value.

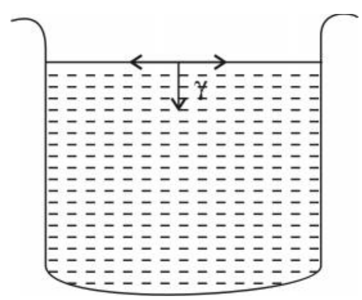


Fig. 7.5 : *Surface tension force acting on the surface of a liquid.*

Effect of Temperature

On raising the temperature surface tension of a liquid decreases. It completely vanishes at the critical temperature. This happens due to the following two factors:

(i) On heating, the liquids expand. This increases the intermolecular distances.

(ii) On heating, the average kinetic energy of molecules and hence their chaotic motion increases.

Due to both of these factors, the intermolcular forces become weak and the surface tension decreases.

Effect of Adding Surface Active Solutes

The solutes which get more concentrated on the surface of the liquid than in the bulk are called **surface active solutes** or **surfactants**. Alcohols are examples of such substances. Their addition to a liquid lowers its surface tension. The cleaning action of soaps and detergents is based on this fact.

Some Effects of Surface Tension

Surface tension results in many interesting and important properties of liquids. Let us now study some of them.

(i) Spherical Shape of liquid drops

You have already learnt that liquids tend to have a minimum surface area. For a given volume, the geometrical shape having minimum surface area is a sphere. Hence, liquids have a natural tendency to form spherical drops, when no external force acts on them. Rain drops are distorted spheres and the distortion is due to the friction of air.

(ii) Wetting and Non-wetting properties

When a drop of liquid is placed on a solid surface, the force of gravity should cause it to spread out and form a thin layer (Fig. 7.6). Such a liquid is called a **wetting liquid.** This happens in case of most of the liquids. For example, drops of water or alcohol spread out on the surface of glass. Some liquids behave differently. When a drop of mercury is placed on the surface of glass, it does not spread out (Fig. 7.6). Such liquids are called **non-wetting liquids**.

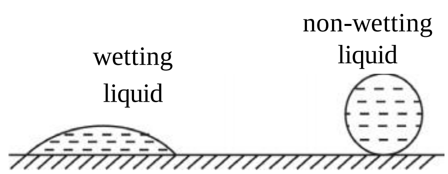


Fig. 7.6 : *Wetting and non-wetting liquids on the surface of a solid.*

Wetting or non-wetting nature of a liquid depends upon two types of forces. The intermolecular attractive forces between molecules of a liquid are called **cohesive force** while those between the molecules of the liquid and the solid (whose surface is in contact with the liquid) are called **adhesive forces**. If adhesive forces are stronger than cohesive forces, the liquid would be wetting in nature and when cohesive forces are stronger than adhesive forces it would be non-wetting in nature on the surface of a particular solid.

(iii) Capillary Action

Let us carry out the following activity.

Activity 7.3

Aim : To study the capillary action.

What is required?

Glass capillary tubes, water, mercury and two petri dishes.

What to do?

(i) Take some water in a petri dish

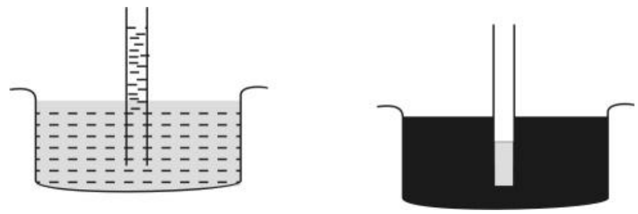
(ii) Dip one end of a 3-4 cm long capillary in it.

(iii) Take some mercury in another petri dish.

(iv) Dip one end of another 3-4 cm long capillary in it.

What to observe?

Observe the levels of water and mercury in the capillaries. Is it below or above the levels of the liquids in petri dishes.



(a) (b)

Fig. 7.7 : *Capillary Action*

You would observe that when one end of a capillary tube is dipped in water, it rises in the capillary as shown in Fig. 7.7(a). On the other hand when one end of a capillary tube is dipped in mercury, its level falls in the capillary as in Fig. 7.7(b).

The phenomenon of rise or fall of a liquid in a capillary is known as **capillary action**. The rise of water in the glass capillary is due to its wetting nature as the adhesive forces are stronger then cohesive forces. Water tends to increase the area of contact with glass wall of the capillary by rising in it. Mercury being non-wetting with respect of glass (its cohesive forces are stronger than adhesive forces) tends to minimise the area of contact by depressing inside the capillary

(iv) Curved meniscus

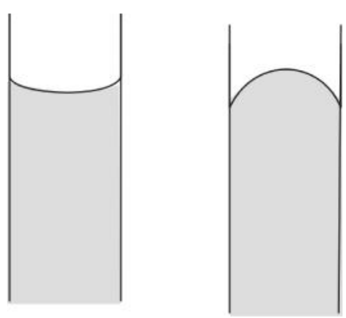


Fig. 7.8 : *Curved meniscus of liquids*
(a) Concave meniscus **(b) Convex meniscus**

When a wetting liquid such as water is taken in a glass tube, the liquid tends to rise slightly along the walls of the tube for increasing its area of contact with glass. The surface of the liquid (meniscus) becomes curved. It is concave in shape [Fig. 7.8(a)]. When a non-wetting liquid like mercury is taken a glass tube, it tends to decrease its area of contact and depresses along the walls of the glass tube. The meniscus is convex in shape in this case [Fig. 7.8(b)].

7.5 Viscosity

Every liquid has the ability to flow. It is due to the fact that molecules in a liquid move freely, although within a limited space. Water flows down a hill *under gravitational force* or through pipes when forced by a pump. Some external force is always required for a liquid to flow. Some liquids like glycerol or honey flow slowly while others like water and alcohol flow rapidly. This difference is due to the *internal resistance to flow* which is called **viscosity**. The liquids with higher viscosity flow slowly and are more viscous in nature like glycerol or honey. Water and alcohol have lower viscosity and are less viscous in nature. They flow more rapidly.

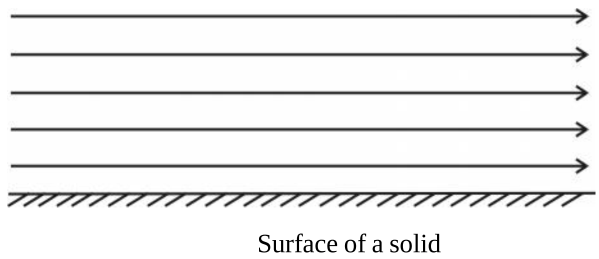


Fig. 7.9 : *Flow of different layers of a liquid*

The viscosity is related to the intermolecular forces. Stronger the intermolecular forces more viscous are the liquids. Let us understand this with the help of Figure 7.9. When a liquid flows steadily, it flows in different layers with one layer sliding over the other. Such a flow is known as **laminar flow**. Consider a liquid flowing steadily on a plane surface. The layer closest to it is almost stationary due to adhesive forces. As the distance of the layer from the surface increases, is velocity increases. Thus different layers move with different velocities. Due to intermolecular forces (cohesive forces) each layer experiences a force of friction from its adjacent layers. This force of friction, *f* between two layers depends upon:

(i) area of contact between them *A.*

(ii) distance between the layers, *dx*.

(iii) difference in velocity between the layers, *du*.

These quantities are related as

$$f = \eta A \frac{du}{dx}$$

Here η (Greek letter 'eeta') is called the coefficient of viscosity and $\frac{du}{dx}$ is the *velocity gradient* between the layers.

If A = 1 cm^2, du = 1 cm s^{-1} and dx = 1 cm, then

$$f = \eta$$

Thus, coefficient of viscosity is the force of friction between two parallel layer of the liquid which have 1cm^2 area of contact, are separated by 1cm and have a velocity difference of 1cm s^{-1}. It may be noted that *f* is also equal to the **external force** which is required to overcome the force of friction and maintain the steady flow between two parallel layers having *A* area of contact, and which are *dx* distance apart and moving with a velocity difference of *du*.

Units

CGS unit of viscosity is dyne cm^{-2} s. This unit is also known as **poise(P)**. The SI unit of viscosity is N m^{-2}s or Pas. The two units are related as :

1 Pas = 10 P

The unit paise is found to be too large and its submultiples **centipoise** (1 cP = 10^{-2} P) and **milli poise** (1 mP = 10^{-3} P) are used for liquids and micropoise (μP = 10^{-6} P) is used for gases.

Effect of Temperature

Viscosity of a liquid decreases on raising the temperature. It is due to decrease in intermolecular forces on heating as discussed in previous section (Section 7.4).

Intext Questions 7.2

1. Fill in the blanks.

   (i) A molecule at the surface of a liquid has............... energy than the one within the liquid.

   (ii) Surface tension of liquid.................... on cooling.

   (iii) Meniscus of a non-wetting liquid is .... in shape while that of a wetting liquid is..................... in shape.

   (iv) When one end of a glass capillary tube was dipped in a liquid, the level of liquid inside the capillary was observed to fall. The adhesive forces in this liquid are.................than the cohesive forces between the liquid and glass.

   (v) Liquid X is more viscous than liquid Y. The intermolecular forces in Y are .... than in X.

2. What are the SI units of

   (i) Surface tension.

   ....

   (ii) Coefficient of viscosity

   ....

3. Why do liquids have a tendency to acquire minimum surface area?

   ....

What You Have Learnt

- In liquids the intermolecular force are quite strong as compared to gases but weak enough to allow the molecules to move within a limited space and the intermolecular distance is short.
- Liquids have definite volume but no definite shape, are almost incompressible and can diffuse.
- Liquids evaporate and exert a definite vapour pressure at specified temperature.
- Boiling point is the temperature at which the vapour pressure of the liquid becomes equal to the external pressure.

- Surface tension is the force acting on an imaginary line of unit length drawn on the surface of the liquid and acting perpendicular to it towards the liquid side.
- Due to surface tension, liquids tend to have minimum surface area and show the phenomena of capillary rise or fall and curved meniscus.
- Viscosity is the internal force of friction to the flow of liquid.

Terminal Exercise

1. Explain the following properties of liquids on in basis of their structure:

   (i) Volume (ii) Shape (iii) Compressibility (iv) Ability to flow
2. Why diffusion can occur in liquids. Explain.
3. Define (i) vapour pressure and (ii) boiling point.
4. Differentiate between evaporation and boiling.
5. Explain the effect of temperature on vapour pressure of a liquid.
6. Define surface tension and give its CGS and SI units.
7. What is surface energy?
8. Why is energy required to increase the surface area of a liquid?
9. What is the effect of addition of a surface active substance on the surface tension of a liquid.
10. Why are liquid drops spherical in shape?
11. What are wetting and non-wetting liquids?
12. The cohesive forces acting in liquids A and B are C_1 and C_2 respectively and $C_1 > C_2$ Which of them would have higher surface tension.
13. Liquid A rises in glass capillary tube. If one drop of it is put on a plane glass surface, would it spread out or not. Explain.
14. A liquid forms a convex meniscus in glass tube. Comment on its nature.
15. Define viscosity.
16. What is coefficient of viscosity?
17. Give CGS and SI units of coefficient of viscosity.
18. What is the effect of temperature on (i) vapour pressure (ii) surface tension and (iii) viscosity of a liquid?

Answers to Intext Questions

7.1

1. (i) C; (ii) A; (iii) B

2. (i) Air (ii) Liquid.

3. B > C > A

7.2

1. (i) more

   (ii) increases

   (iii) convex; concave

   (iv) stronger

   (v) weaker

2. (i) N m^{-1}; (ii) N m^{-2} s

3. Molecules in the surface of a liquid have higher energy due to an inward force on them. Therefore liquids tend to have minimum number of molecules in the surface or have minimum surface area.