UNIT 5 VISCOSITY OF LIQUIDS

Structure

5.1 INTRODUCTION

In the previous unit, you studied about the surface tension. a property which arises due to intermolecular forces of attraction operating between the molecules of the liquid. In this unit, in the light of the intermolecular forces, you will study another important property of liquids i.e. the **viscosity**. Viscosity is a property of fluids, i.e., both gases and liquids have viscosity; but here we will focus our attention only on the liquids. As you know the liquids are mobile and have general property to flow, known as **fluidity**. When the molecules of a liquid move forward, the surrounding molecules due to intermolecular forces of attraction develop a relative tendency to oppose this movement. Such internal resisting forces that restrain the molecules of a liquid from flowing past each other are, indeed, responsible for what is known as the **viscosity** of liquids. In this unit, you will study about the measurement of the coefficient of viscosity of aqueous solution of cane sugar.

Objectives

After studying this unit and performing the experiments, you should be able to:

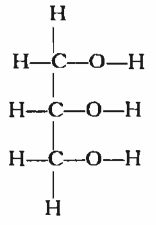
- distinguish between the fluidity and the viscosity of liquids and correlate them,
- define the coefficient of viscosity of a liquid,
- derive the units of coefficient of viscosity,
- predict the effect of temperature and the molecular forces of attraction on the coefficient of viscosity of a liquid, and
- explain the principles involved in the measurement of the coefficient of viscosity of a liquid.

5.2 VISCOSITY OF LIQUIDS

Coefficient of viscosity is represented by the Greek letter η (eta).

Liquids, in general, have an inherent tendency to flow. But this tendency to flow is not always the same for all liquids. It is a common experience that water flows more easily than honey. Therefore, water is said to have lower fluidity. On the other hand, honey is said to have lower fluidity. Those liquids which have lower fluidity are said to be viscous. The examples being honey, caster oil and glycerol. **The viscosity, therefore, measures the resistance of a liquid to flow, while the fluidity measures the ease with which a liquid can flow.** The two quantities, the **viscosity** and the **fluidity**, are essentially reciprocal to each other. Thus, we can say that

$\eta = \frac{1}{\phi}$, where η is the coefficient of viscosity and ϕ is the fluidity.



$CH_2OH-CHOH-CH_2OH$

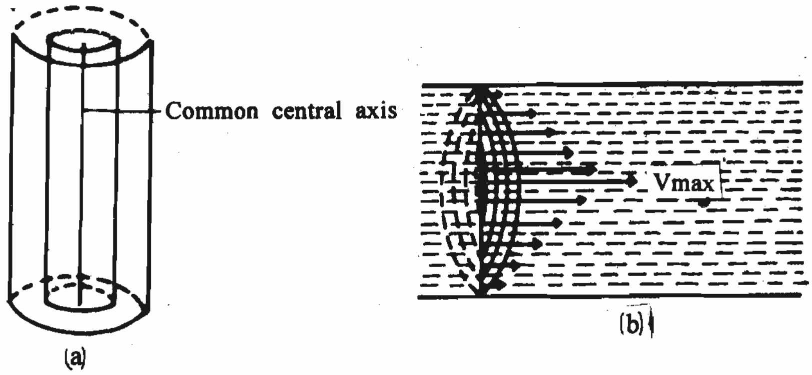
Glycerol

The viscosity is very much influenced by the shape, size and the chemical nature of the liquid molecules. The **greater** the size of the molecules and the **higher** the molar mass, the **higher** will be the viscosity because the **greater** will be the intermolecular interactions. The hydrogen bonds also enhance the coefficient of viscosity to a large extent. It is, indeed, the presence of a network of hydrogen bonds which accounts for the very high viscosity of glycerol. Incidentally, the larger the number of hydroxyl groups in a molecule, the more complex will be the network of hydrogen bonds and the greater will be the resistance of a liquid to flow. In long chain hydrocarbons or polymeric compounds the viscosity increases with the increase in the length of the molecular chain. Due to this reason, heavy hydrocarbon oil and grease (which are used as lubricants) have fairly high viscosity values. Similar to the surface tension, you would expect the viscosity to decrease with the increase in temperature. This is due to the decrease in intermolecular forces of attraction with increase in temperature. At higher temperature, the number of hydrogen bonds in a liquid also diminishes and the viscosity is expected to decrease.

5.2.1 The Coefficient of Viscosity

Parallel concentric cylindrical layers: cylindrical layers of liquids which have common central axis as shown in Fig. 5.1(a).

To define the coefficient of viscosity, let us consider a liquid flowing through a narrow circular tube. The flowing liquid can be viewed as being composed of parallel concentric cylindrical layers, See Fig. 5.1*(a)*. It is assumed that the layer of liquid in contact of the wall is stationary and each successive layer starting from the wall towards the centre, moves faster than the previous one. In other words, the velocity increases to a maximum at the middle of the tube. Such a flow in which one layer slides smoothly relative to another, with regular gradation of velocity is called **laminar flow** and is shown in Fig. 5.1. *(b)*.



(a) (b)

Fig. 5.1: (a) Parallel concentric cylindrical layers (b) Laminar Flow.

For such flow, if, at a given temperature dv (m s^{-1}) is the velocity difference between two successive layers each of area A(m^2) which are at a distance dx (m), then the net resisting force F operating between two successive layers will be directly proportional to the area A and velocity difference dv, and inversely proportional to the distance dx, such that

$$F \alpha A \cdot \frac{dv}{dx}$$

or

$$F = \eta \cdot A \cdot \frac{dv}{dx} \qquad \text{... (5.1)}$$

where, η is the proportionality constant and is also called the coefficient of viscosity of the liquid at the given temperature. Therefore, from Eq. 5.1, we can write

$$\eta = \frac{F}{A \cdot \frac{dv}{dx}} \qquad \text{... (5.2)}$$

$\frac{dv}{dx}$ is called the velocity gradient.

Unit of $\frac{dv}{dx} = \frac{ms^{-1}}{m}$

$= s^{-1}$

If A is $1 m^2$ and $\frac{dv}{dx}$ is $1 s^{-1}$, then $\eta = F$.

Thus, the coefficient of viscosity of a liquid, η, at a given temperature may be defined as, **the force per unit area required to maintain a unit difference of velocity between two parallel layers at unit distance apart.** This is also obvious from the Eq. 5.2. For convenience, at times, the coefficient of viscosity is often called the viscosity of liquids. Having defined the coefficient of viscosity, let us now study its units.

5.2.2 Units

In SI system, from Eq. 5.2, we can say that

$$\text{Unit of } \eta = \frac{\text{Unit of } F}{\text{Unit of } \left(A \cdot \frac{dv}{dx}\right)} = \frac{\text{N}}{\text{m}^2 \cdot \frac{\cancel{\text{m}}\,\text{s}^{-1}}{\cancel{\text{m}}}} = \text{N m}^{-2}\,\text{s}$$

Since N m^{-2} = Pa (Pascal, unit of pressure)

η = Pa s

1N = 1 kg m s^{-2}

Hence, 1 Pa s = 1 N m^{-2} s

= 1 (kg m s^{-2}) m^{-2} s

= 1 kg m^{-1} s^{-1}

In c.g.s. system, the unit of coefficient of viscosity is **poise**. A liquid has a coefficient of viscosity of one poise if a force of 1 dyne (1 g cm s^{-2}) is required to move a plane of 1 cm^2 at a velocity of 1 cm s^{-1} with respect to a plane 1 cm away and parallel with it.

A liquid has a viscosity of 1 Pa s if a force of 1N is required to move a plane of 1 m^2 at a velocity of 1 m s^{-1} with respect to a plane surface 1 m away and parallel with it.

$$\begin{aligned}
\text{Unit of } \eta &= \frac{\text{Unit of } F}{\text{Unit of } \left(\text{A} . \frac{dv}{dx}\right)} \\
&= \frac{\text{dyne}}{\text{cm}^2 \, \frac{\cancel{\text{cm}}\,\text{s}^{-1}}{\cancel{\text{cm}}}} \\
&= \frac{\text{g cm s}^{-2}}{\text{cm}^2\,\text{s}^{-1}} \\
&= \text{g cm}^{-1}\,\text{s}^{-1} \\
&= \text{poise}
\end{aligned}$$

In other words, 1 poise = 1 g cm^{-1} s^{-1}

If you are interested in knowing the conversion from c.g.s. to SI units, go through the following steps:

$$\begin{aligned}
1 \text{ poise} = 1 \text{ g cm}^{-1}\,\text{s}^{-1} &= 1(10^{-3}\text{ kg})\ (10^{-2}\text{ m})^{-1}\,\text{s}^{-1} \\
&= 10^{-3}\text{ kg} \times 10^{2}\text{ m}^{-1}\,\text{s}^{-1} \\
&= 10^{-1}\text{ kg m}^{-1}\,\text{s}^{-1} \\
&= 10^{-1}\ \text{Pa s}
\end{aligned}$$

Hence, 10 poise = 1 Pa. s

At this stage, it will be beneficial for you to answer the SAQ given below:

SAQ 1

i) How are the viscosity and the fluidity of a liquid related to each other?

....

ii) What does the viscosity of a liquid measure?

....

iii) Fill in the blanks with correct words.
Liquids having high .... are said to have ....
.... viscosity and the liquids with the high ....
.... are said to have low ....

iv) What are the units of the coefficient of viscosity in the c.g.s. and SI systems?

....

Let us now study the effect of temperature on viscosity.

5.3 EFFECT OF TEMPERATURE

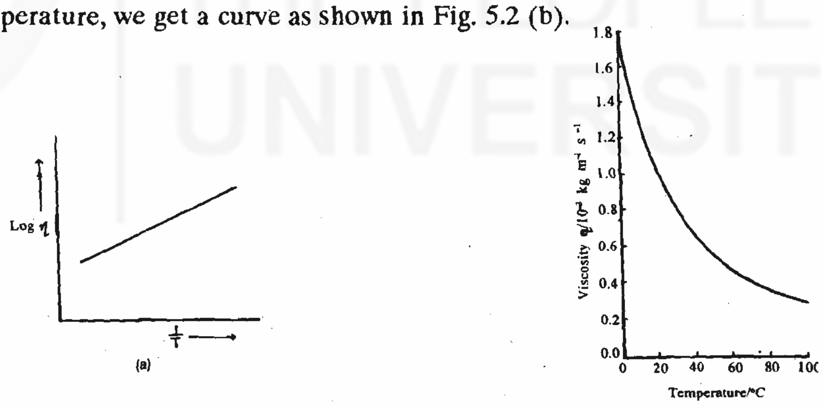
In liquids, as the temperature rises, the kinetic energy of the molecules increases and the intermolecular forces of attraction become weak, resulting in the subsequent decrease in the viscosity. **The value of the coefficient of viscosity appreciably drops as the temperature of liquid increases** such that for each degree rise in temperature there is about two percent decrease in the viscosity. The viscosity and temperature are related to each other by the following expression:

$$\log \eta = \frac{A}{T} + B \qquad \text{... (5.3)}$$

where A and B are constants for a given liquid and T is the absolute temperature.

The plot of log η against $\frac{1}{T}$, therefore, gives a straight line, demonstrating the fact that the viscosity of a liquid rapidly decreases with the rise in temperature, see Fig. 5.2. (a).

On the other hand, if we plot a graph between coefficient of viscosity and temperature, we get a curve as shown in Fig. 5.2 (b).



(a)

(b)

Fig. 5.2 : Temperature dependence of viscosity of water.

The viscosities of some liquids are shown in Table 5.1.

Table 5.1 : Coefficient of Viscosity of different substances

Substance	Temperature °C	Coefficient of Viscosity (η /10^{-3} Pa s)
Acetic acid	20	1.314
Acetone	20	0.337
Chloroform	15	0.596
Methanol	25	0.544
Mercury	20	1.552

Now answer the following SAQ.

SAQ 2

Fill in the blanks with correct words.

i) With the .... in temperature, the viscosity of a liquid ....

ii) The viscosity of those liquids which have hydrogen bonds in their molecular structure, generally .... with the .... in temperature.

iii) The plot of log η against $1/T$ gives a ....

5.4 MEASUREMENT OF THE COEFFICIENT OF VISCOSITY

The coefficient of viscosity of liquids is generally determined by using the following two methods:

i) Ostwald Viscometer technique

ii) Falling Sphere Technique

We will discuss here the principles involved in the first method because in the laboratory, you will be measuring the coefficient of viscosity by this technique.

5.4.1 Ostwald Viscometer Technique

For the measurement of coefficient of viscosity of liquids having a laminar or streamlined flow, Poiseuille derived an expression, known as **Poiseuille's equation.** This expression is given below.

$$\eta = \frac{\pi p r^4 t}{8Vl} \quad .... (5.4)$$

where η = coefficient of viscosity of the liquid

V = volume of the liquid flowing out of the tube

t = time in which the volume V flows

r = radius of the tube

l = length of the tube

p = driving pressure necessary to maintain uniform rate of flow of volume V, of the liquid.

The flow of liquid through a pipe or tube of radius r, is associated with Reynolds Number (R) which is given by the following expression,

$$R = \frac{2rvd}{\eta}$$

where v is the average velocity of the liquid, d is the density and η is the coefficient of viscosity. If the value of R is less than 2100, the flow of liquid is said to be laminar or streamlined, and if R is greater than 4000, the flow is termed as turbulent.

This involves the use of Ostwald Viscometer in which a fixed volume of a liquid is allowed to fall under its own weight or the force of gravity, and the time required for a given volume of the liquid to flow is noted. Obviously the driving pressure p is replaced by $h.d.g$, where h is the height of the liquid and d is its density and g is the acceleration due to gravity. Therefore,

$$p = h.d.g$$

substituting $h.d.g.$ for p in Poiseuille's Equation (Eq. 5.4), we get,

$$\eta = \frac{\pi r^4 . h . d . g . t}{8Vl} \quad .... (5.5)$$

The relationship, $p = hdg$ can be derived as follows:

$$p = \frac{\text{Force}}{\text{Area}}$$

$$= \frac{\text{mass} \times \text{acceleration due to gravity}}{\text{Area}}$$

$$= \frac{mg}{\pi r^2} \quad \text{(cross-sectional area of a cylindrical layer is } \pi r^2\text{)}$$

$$= \frac{V.dg}{\pi r^2} \quad \text{(since mass = volume} \times \text{density)}$$

$$= \frac{\pi . r^2 . h . d . g}{\pi r^2}$$

$$= h . d . g$$

During the flow of the liquid, as the height (h) (level) of the liquid changes, there is a change in the pressure difference (p). But, for every position of the meniscus, p is proportional to density (d).

Thus, $p_1 \propto d_1$

and $p_2 \propto d_2$

or $\frac{p_1}{p_2} = \frac{d_1}{d_2}$

As a result of the change in driving pressure (p) the rate of flow of the liquid also changes all the time the flow is taking place. The rate of flow, i.e., the volume of liquid flowing per second (V) is inversely proportional to time. Thus, for the liquids, 1 and 2, we can say that

$$\frac{V_2}{V_1} = \frac{t_1}{t_2}$$

If equal volumes of the two liquids (1 and 2) are allowed to fall through the same capillary tube under identical conditions of temperature and pressure then, from Eq. 5.5 by comparison, we have

$$\frac{\eta_1}{\eta_2} = \frac{d_1 \cdot t_1}{d_2 \cdot t_2} \qquad \text{...(5.6)}$$

where η_1, d_1 and t_1 are, respectively, the coefficient of viscosity, density and time of flow for the liquid 1 under examination and η_2, d_2 and t_2 the corresponding values for the reference liquid (liquid 2). Thus, by knowing η_2, d_2, t_2 and d_1 and t_1 the coefficient of viscosity of first liquid, η_1 could be determined.

Let us now study about the experiment which you will be performing.

5.5 EXPERIMENT 2: DETERMINATION OF THE COEFFICIENT OF VISCOSITY OF 30% CANE SUGAR SOLUTION BY OSTWALD VISCOMETER

5.5.1 Principle

In this experiment, you will make use of the Ostwald viscometer. This is usually employed in the laboratory for the determination of the coefficient of viscosity of liquids. Ostwald viscometer is a simple apparatus and is shown in Fig. 5.2. It consists of a bulb A, with a mark (X) above and as mark (Y) below, attached to a capillary tube B and a storage bulb C.

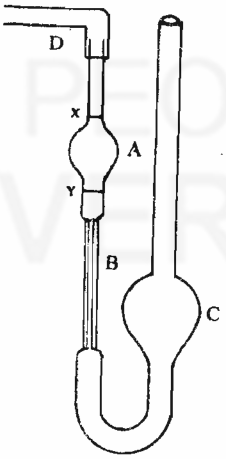


Fig. 5.3: Ostwald Viscometer.

A definite volume of a liquid say, 10 ml is introduced into bulb C. The liquid is then sucked into the bulb A through a rubber tube attached to the end, D. The liquid is allowed to flow freely from the mark X to the mark Y. Then the time t is observed for this flow of liquid. This method is very successful for comparing the viscosity coefficients of two or more liquids or liquid solutions.

In Ostwald viscometer, when a liquid is allowed to flow through the capillary under the influence of gravity, then the instant driving pressure is equal to $h.d.g$; where h is the difference in heights between the levels of the liquid in the two arms, which is constant for a particular set of the observations and g, acceleration due to gravity, is also constant. Obviously, the driving pressure is directly proportional to the density, d, of the liquid.

Since the same capillary is employed, and the same volume V of the liquid flows through it in each case, the values of r, l, V become all constant. Therefore, the Eq. 5.5 when applied to two liquids can be written as:

$$\frac{\eta_1}{\eta_0} = \frac{d_1 t_1}{d_0 t_0}$$

where, the subscripts, 1 and 0, denote the unknown and the reference liquids. Thus, if we divide the viscosity of the unknown liquid (η_1) with the viscosity of the reference liquid η_0, (say water), we can get the relative viscosity of the second liquid with respect to that of water.

Hence, the relative viscosity of second liquid $= \eta_{rel} = \frac{\eta_1}{\eta_0} = \frac{d_1 t_1}{d_0 t_0}$

To get the absolute viscosity of the liquid, multiply this relative viscosity by the absolute viscosity of the reference liquid. Thus, for absolute viscosity, the expression will be

$$\eta_{1(abs.)} = \frac{\eta_0 d_1 t_1}{d_0 t_0}$$

Now, answer the following SAQ to check your understanding of the above discussion.

SAQ 3

i) Name the two methods which can be used for the measurement of the coefficient of viscosity of liquids.

....

ii) The vertical flow of a liquid through a capillary is proportional to the .... of the liquid.

5.5.2 Requirements

Ostwald Viscometer (small)	1
Stop watch	1
Thermostat	1
Specific gravity bottle	1
10 cm^3 pippete	1
Distilled water	
30% Cane sugar solution	50 to 100 cm^3
Rubber tubing	small piece
Thermometer (110°C)	1

5.5.3 Procedure

Before use, the Ostwald Viscometer should be first cleaned with chromic acid solution ($K_2Cr_2O_7$ + Conc . H_2SO_4), and then with distilled water (twice), alcohol or acetone, respectively. Finally, it should be dried by passing the current of dust free air. Make sure that the capillary of the viscometer does not contain any dust particle or greasy material inside to pose any obstruction to the flowing liquid.

Now, introduce a definite volume of the 30% cane sugar solution (10 cm^3) into the bulb C, and suck the liquid up into the bulb A with the help of the rubber tube attached to the end D somewhere above the mark X. Make sure there is no air bubble inside the liquid. Now, allow the liquid to flow freely through the capillary upto the mark X. Start a stop watch and note the time t_1 for the flow of the liquid from mark X to mark Y. Repeat this process twice or thrice by sucking the liquid into the bulb A upto the mark X and noting the time t_1 for the flow of the liquid from mark X to mark Y. These values should be concordant. Fill the liquid again and repeat the same for second filling.

Remove the first liquid and clean and dry the viscometer again. Repeat the experiment by taking an exactly the same volume of water in bulb C and note the values of time, t_0, taken for water to flow from mark X to mark Y. Suck the water up, twice or thrice to obtain other values of t_0, as done above. Repeat the same for second filling. Determine the density of the cane sugar solution with the help of specific gravity bottle. This can be done by taking a definite volume of liquid (say, 5 cm^3) in the specific gravity bottle and determining its mass. Also note down the temperature at which the experiment was performed.

Do not forget to observe the following precautions while doing the experiment;

Precautions

1) The volume of the liquids taken in bulb C should be so much that when sucked up to mark X, it should fill the bulb A and a little should still remain in the bulb C.

2) The viscometer should be held in a vertical position during the flow of the liquids.

3) While sucking the liquids, no air bubble should be formed inside the capillary tube.

You can record your observations in the following manner.

5.5.4 Observations

Temperature of measurement = ... = t°C

Density of water at t °C = ... = d_0 (see from reference tables in the appendix)

Viscosity of water at t °C= .... = η_0 (see from Table 5.2)

Table 5.2 : Coefficient of viscosity of water at different temperatures

Temperature °C	Coefficient of Viscosity (($\eta/10^{-3}$ Pa s)
0	1.7702
5	1.5108
10	1.3039
15	1.1374
20	1.0019
21	0.9764
22	0.9532
23	0.9310
24	0.9100
25	0.8903
26	0.8703
27	0.8512
28	0.8328
29	0.8145

contd....

30	0.7973
35	0.7190
40	0.6526
45	0.5972
50	0.5468
55	0.5042
60	0.4669
65	0.4341
70	0.4050
100	0.2840

Table 5.3

Liquid	Time of flow		
	First Filling	Second Filling	
30% Cane sugar solution	(i) . . . . (ii) . . . . (iii) . . . . Average t_1=	(i) . . . . (ii) . . . . (iii) . . . . Average t_1=	Average t_1=. . . .s
Water	(i) . . . . (ii) . . . . (iii) . . . . Average t_0=	(i) . . . . (ii) . . . . (iii) . . . . Average t_0=	Average t_0=. . . .s

Weight of empty specific gravity bottle = ... = w_1 g

Weight of bottle + 30% cane sugar solution = ... = w_2 g

Weight of bottle + Same volume of water = ... = w_3 g

5.5.5 Calculations

Density of 30% cane sugar solution $= d_1 = \dfrac{w_2 - w_1}{w_3 - w_1} \times d_0$

Relative viscosity of 30% cane sugar solution $= \dfrac{\eta_1}{\eta_0} = \dfrac{d_1 \cdot t_1}{d_0 \cdot t_0}$

Absolute viscosity of 30% cane sugar solution, $\eta_{1(abs.)} = \dfrac{\eta_0 \cdot d_1 \cdot t_1}{d_0 \cdot t_0}$

5.5.6 Result

The relative viscosity of the given solution is . . . . Pa s

The absolute viscosity of the given solution is . . . . Pa s

Similarly, you can determine the coefficient of viscosity for various solutions such as that of NaCl or copper sulphate provided to you.

5.6 ANSWERS

Self Assessment Questions

1. i) They are reciprocal to each other.
   ii) Viscosity of a liquid measures its resistance to flow.
   iii) Fluidity, low, viscosity, fluidity
   iv) Poise, Pa s
2. i) Rise, decreases
   ii) Decreases, increases/rise
   iii) Straight line
3. i) Ostwald technique, Falling sphere technique
   ii) Density