SEMESTER-TWO

PERIOD–IV

P10CH4

Topic 4

Thermal Physics

4.1. INTRODUCTION

We have all noticed that when you heat something up, its temperature rises. Often we think that heat and temperature are the same thing. However, this is not the case. Heat and temperature are related to each other, but are different concepts. We will study both these concepts in this unit. We will also learn to use different thermometers for measuring temperature and compare different temperature scales along with thermal expansion and gas laws.

4.2. HEAT AS A FORM OF ENERGY

In our day-to-day life, we come across a number of objects. Some of them are hot and some of them are cold. Tea is hot and ice is cold. Copy table 4.1 in your notebook. List some objects you use commonly in that table. Mark these objects as hot or cold.

Table 4.1. Hot and Cold Objects

Objects	Cold/Cool	Warm/Hot
Ice cream	✓	
Spoon in a tea cup		
Fruit juice		
Handle of a frying pan		

CAUTION !

Do not touch objects which are too hot. Be careful while handling a candle flame or a stove.

We see that some objects are cold while some are hot. You also know that some objects are hotter than others while some are colder than others.

Can you explain why one object is hotter and the other is colder. The hot object has energy in the form of **heat** stored in them. When this heat energy flows into a body, it warms the body. When it flows out of a body, it cools the body. We know that all objects are made up of atoms and molecules. Thus, ***heat** is a form of energy stored in the atoms and molecules of the hotter substances*. How would you decide which object is hotter or colder than the other?

We often do it by touching the objects. But is our sense of touch reliable? Is it safe? Let us find out.

ACTIVITY 4.1

Take three large mugs. Label them as *A*, *B* and *C*. Put cold water in mug *A* and hot water in mug *B*. Mix some cold and hot water in mug *C*. Now dip your left hand in mug *A* and the right hand in mug *B*. After keeping the hands in the two mugs for 2–3 minutes, put both the hands simultaneously in mug *C* (Fig. 4.1). Do both the hands get the same feeling?

Make sure that water is not so hot that you burn your hand.

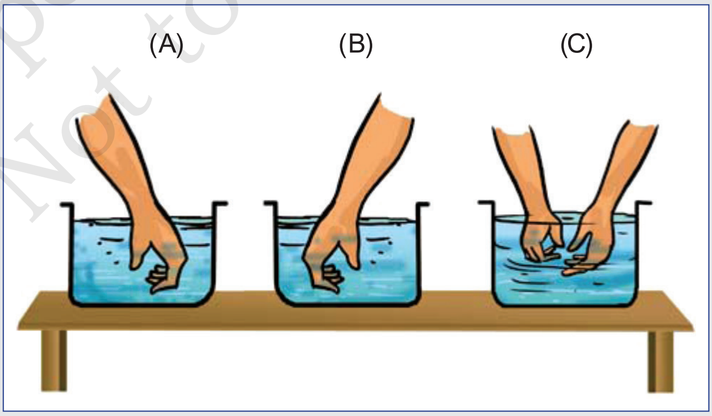

Fig. 4.1. Feeling water in three mugs

Your left hand will feel that the water in mug *C* is hot. The right hand will feel that the same water is cold. This shows that we cannot always rely on our sense of touch to decide whether an object is hot or cold. Sometimes it may deceive us.

Then, how do we find out how hot an object really is? A reliable measure of the hotness of an object is its **temperature**. Temperature is measured by a device called **thermometer**.

Difference between Heat and Temperature	
Heat	**Temperature**
1. Heat is a form of energy stored in the molecules of a substance. It flows from one body to another due to temperature difference between the two.	1. Temperature is the measure of the degree of hotness or coldness of a substance.
2. It is measured in Joules (J) or in Calories.	2. It is measured in Kelvin (K), Celsius (°C) and Fahrenheit.

4.3. DIFFERENT TYPES OF TEMPERATURE SCALES

4.3.1. Lower and Upper Fixed Point of Temperature

In all types of temperature scales, fixed reference points (temperature) are required, with respect to which all other temperatures are measured. These fixed reference points are defined as follows.

Lower fixed point (L.F.P): Melting point of pure ice at normal atmospheric pressure is regarded as the lower fixed point.

Upper fixed point (U.F.P): Boiling point of pure water at normal atmospheric pressure is regarded as the upper fixed point.

4.3.2. Types of Temperature Scales

There are four different scales used for measuring temperature.

1. **Kelvin scale of temperature:** In this scale, L.F.P. is 273 K and U.F.P. is 373 K. Its divisions are of the same size as those of Celsius scale.

2. **Fahrenheit scale:** In this scale, L.F.P. is 32 °F and U.F.P. is 212 °F. The distance between these two points is divided into 180 divisions.
3. **Celsius or centigrade scale:** In this scale, L.F.P. (ice point) is taken to be zero and U.F.P. (steam point) is taken to be 100 °C. The scale between U.F.P. and L.F.P. is divided into 100 divisions all of equal size.

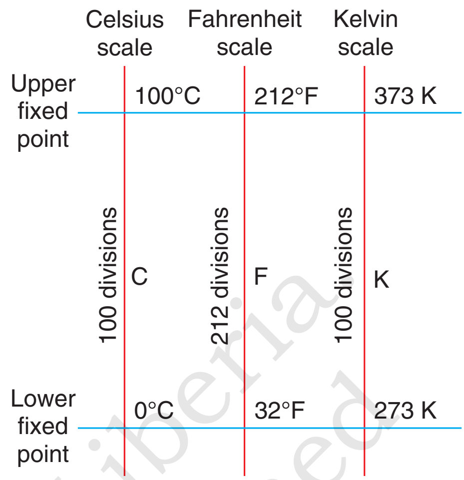

Fig. 4.2. Temperature scales

Celsius scale is used in most of the countries and is more convenient than Fahrenheit scale. Kelvin scale is very widely used for scientific work.

4.4. TYPES OF THERMOMETERS

Thermometers are of the following three types:

(i) Clinical thermometer
(ii) Laboratory thermometer
(iii) Maximum and Minimum thermometer.

4.4.1. Clinical Thermometer

The thermometer that measures our body temperature is called a clinical thermometer.

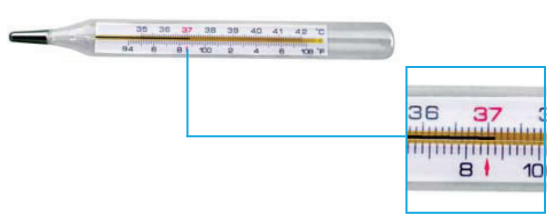

Fig. 4.3. A clinical thermometer

Hold the thermometer in your hand and examine it carefully. If you do not have a thermometer, request a friend to share it with you. A clinical thermometer looks like the one shown in figure 4.3.

A clinical thermometer consists of a long, narrow, uniform glass tube. It has a bulb at one end. This bulb contains mercury. Outside the bulb, a small shining thread of mercury can be seen.

If you do not see the mercury thread, rotate the thermometer a bit till you see it. You will also find a scale on the thermometer. The scale we use is the celsius scale, indicated by °C.

A clinical thermometer reads temperature from 35 °C to 42 °C.

Activity 4.2

Reading a Thermometer

Let us learn how to read a thermometer. First, note the temperature difference indicated between the two bigger marks. Also note down the number of divisions (shown by smaller marks) between these marks. Suppose the bigger marks read one degree and there are five divisions between them. Then, one small division can read 1/5 = 0.2 °C.

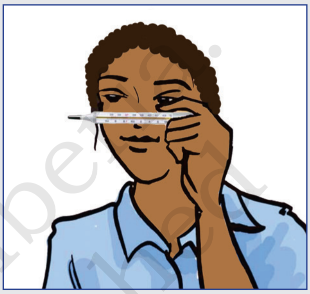

Fig. 4.4. Correct method of reading a clinical thermometer

Wash the thermometer, preferably with an antiseptic solution. Hold it firmly and give it a few jerks. The jerks will bring the level of mercury down. Ensure that it falls below 35 °C. Now place the bulb of the thermometer under your tongue. After one minute, take the thermometer out and note the reading. This is your body temperature. The temperature should always be stated with its unit, °C.

What did you record as your body temperature?

The normal temperature of human body is 37 °C. Note that the temperature is always stated with its unit.

CAUTION !

Do not use a clinical thermometer for measuring the temperature of any object other than the human body. Also avoid keeping the thermometer in the sun or near a flame. It may break.

Precautions to be observed while reading a clinical thermometer

- Thermometer should be washed before and after use, preferably with an antiseptic solution.
- Ensure that before use the mercury level is below 35 °C.

- Read the thermometer keeping the level of mercury along the line of sight. (See Fig. 4.4).
- Handle the thermometer with care. If it hits against some hard object, it can break.
- Don't hold the thermometer by the bulb while reading it.

4.4.2. Laboratory Thermometer

How do we measure the temperature of other objects? For this purpose, there are other thermometers. One such thermometer is known as the laboratory thermometer. The teacher will show you this thermometer. Look at it carefully and note the highest and the lowest temperature it can measure.

The range of a laboratory thermometer is generally from –10 °C to 110 °C. Also, as you did in the case of the clinical thermometer, find out how much a small division on this thermometer reads. You would need this information to read the thermometer correctly.

Let us now learn how this thermometer is used.

ACTIVITY 4.3

Take some tap water in a beaker or a mug. Dip the thermometer in water so that the bulb is immersed in water but does not touch the bottom or the sides of the container. Hold the thermometer vertically (Fig. 4.5). Observe the movement of mercury in the thermometer. Wait till the mercury thread becomes steady. Note the reading. This is the temperature of water at that time.

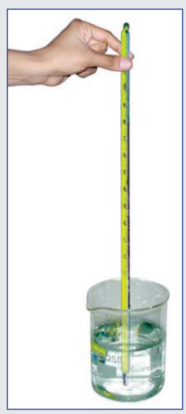

Fig. 4.5. Measuring temperature of water with a laboratory thermometer

In addition to the precautions needed while reading a clinical thermometer, the laboratory thermometer

- should be kept upright not tilted. (Fig. 4.5)
- bulb should be surrounded from all sides by the substance of which the temperature is to be measured. The bulb should not touch the surface of the container.

Activity 4.4

Take some hot water in a beaker or a mug. Dip the thermometer in water. Wait till the mercury thread becomes steady and note the temperature. Now take out the thermometer from water. Observe carefully what happens now. Do you notice that as soon as you take the thermometer out of water, the level of mercury begins to fall. This means that the temperature must be read while the thermometer is in water.

You may recall that while taking your own temperature, you have to take the thermometer out of your mouth to note the reading. Can you then use the laboratory thermometer to measure your body temperature? Obviously, it is not convenient to use the laboratory thermometer for this purpose.

Why does the mercury not fall or rise in a clinical thermometer when taken out of the mouth?

Observe a clinical thermometer again. Do you see a kink near the bulb (Fig. 4.6).

What is the use of the kink? It prevents mercury level from falling on its own.

Fig. 4.6. A clinical thermometer has a kink in it

4.4.3. Maximum and Minimum Thermometer

Maximum and Minimum thermometer is used to measure lowest and highest temperature of a day.

A maximum and minimum thermometer is made of a bent U-shaped tube. Mercury and alcohol are poured inside the tube. Then two metal indices are placed inside the tube. When the temperature rises, alcohol and mercury expand. Expansion of mercury pushes the metal index in the right limb of the tube showing maximum temperature. When the temperature falls, the mercury in the right limb of the tube comes down.

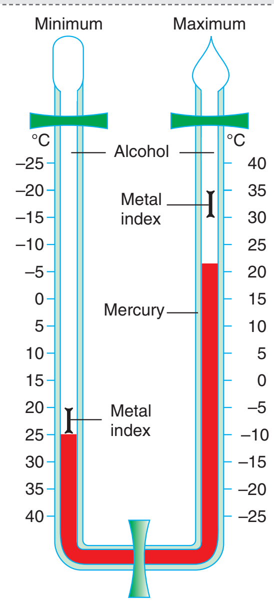

Fig. 4.7. Maximum and minimum thermometer (Six's thermometer)

It pushes the contracting alcohol up into the left limb pushing the metal index to the lowest temperature. This thermometer is used in weather stations to measure daily temperature of an area.

4.5. THERMAL EQUILIBRIUM

It is the condition in which no heat flows between two objects in physical contact with each other. When two objects are in thermal equilibrium they have the same temperature. During the process of reaching thermal equilibrium heat is transferred between the objects. Heat transfer always takes place from a hot body to a cold body.

ACTIVITY 4.5

Calibrating a Thermometer

Every thermometer must be calibrated (given a scale) before it can be used. The more accurately this is done, the more accurate will be the readings taken from it. In this activity, you will mark the scale on a blank thermometer and use it to measure some temperatures.

1. Place an unmarked thermometer in a beaker containing melting ice. When the reading has settled, mark the scale using sticky tape to indicate the position of 0 °C.
2. Place the thermometer in a beaker containing boiling water. When the reading has settled, mark the scale using sticky tape to indicate the position of 100 °C.
3. Dry the thermometer. Measure the distance between 0 °C and 100 °C along the length of thermometer. Cut a strip of paper of this length. Mark 10 equal divisions along its length and label them from 0, 10, 20, ... up to 100. Mark subdivisions to indicate steps of 1 or 2 °C.
4. Attach the scale to the thermometer. From the scale, read the value of room temperature.
5. Place the thermometer in a container of warm water. Read the temperature of the water.

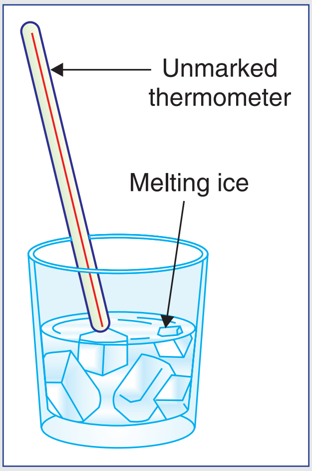

Fig. 4.8. Calibrating a thermometer

4.6. LIQUIDS FOR THERMOMETERS

The Liquid-in-Glass thermometers utilize the property of variation in volume of a liquid with change in temperature. They use the fact that most liquids expand on heating. The liquid is contained in a sealed glass bulb, and its expansion is measured using a scale etched in the stem of the thermometer.

Liquid-in-Glass thermometer have been used in science, medicine, metrology and industry for almost 300 years.

Liquids commonly used include Mercury and Alcohol. The thermometers using mercury have a range of –39 °C to 357 °C and that using alcohol have range of –200 °C to 80 °C.

4.6.1. Mercury

The advantages and disadvantages of using mercury as a thermometric liquid are as follows.

Advantages

1. Mercury is a naturally opaque liquid (Silver). This means that it can be directly utilised in its pure form.
2. Mercury does not wet glass. When it moves up and down in the capillary, strong cohesive properties of mercury do not allow it to leave any traces on the inside of the capillary.
3. Mercury is a liquid metal. As a metal it has high conductive properties. This property allow it to be more sensitive than the alcohol-in-glass thermometer.

Disadvantages

Mercury poses a potential toxic hazard if the glass tube breaks.

There is a lot of concern over the use of mercury in thermometers. Mercury is a toxic substance and is very difficult to dispose of if a thermometer breaks. These days, digital thermometers are available which do not use mercury.

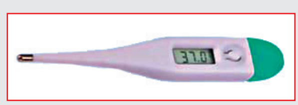

Fig. 4.9. Digital thermometer

4.6.2. Alcohol

The types of alcohol used are ethyl alcohol, toluene and technical pentane. The advantages and disadvantages of using alcohol as a thermometric liquid are as follows.

Advantages

It can measure very low temperatures.

Disadvantages

Alcohol is transparent therefore it requires a dye to make it visible. Dyes tend to add impurities that may not have the same temperature range as the alcohol. This can make alcohol thermometers less sensitive and less accurate.

4.6.3. Advantages of Mercury over Alcohol as a Thermometric Liquid

1. Mercury has a wide temperature range. It functions in the range of 234 Kelvin to 630 Kelvin, which cannot be matched by alcohol thermometer.
2. The amount that mercury expands is eight times less than alcohol. This allows mercury thermometers to be made smaller and more compact than alcohol thermometers.
3. Mercury's high boiling point allows it to be used in thermometers that are used in steaming hot liquids and other cooking foods.

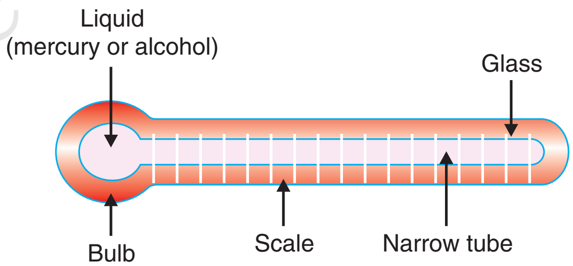

Fig. 4.10. A liquid-in-glass thermometer

4.7. TEMPERATURE CONVERSION

Relation between Different Scales. If temperature of a body measured on different scales are C on Celsius; F on Fahrenheit; K on Kelvin and X on any other scale, then the relation between them is

$$\frac{X - L.F.P.}{U.F.P. - L.F.P.} = \frac{C - 0}{100 - 0} = \frac{F - 32}{180} = \frac{K - 273}{373 - 273}$$

$$\frac{X - L.F.P.}{U.F.P. - L.F.P.} = \frac{C}{100} = \frac{F - 32}{180} = \frac{K - 273}{100}$$

Example 4.1: *Temperature of a man on Fahrenheit scale is 98.6°F, what will it be on (i) Celsius scale; (ii) Kelvin scale?*

Solution: Now,

$$\frac{C - 0}{100 - 0} = \frac{F - 32}{212 - 32}$$

or $$\frac{C}{100} = \frac{F - 32}{180}$$

or $$\frac{C}{5} = \frac{98.6 - 32}{9}$$

or $$C = \frac{5}{9} \times 66.6 = \frac{333.0}{9}$$

or $$C = 37°C$$

Example 4.2: *Change the following thermometer readings: – 273°C, – 100°C, – 40°C, 30°C, 2,000°C to Kelvin scale.*

Solution:

$$-273°C = (-273 + 273)\text{ K} = 0\text{ K}$$

$$-100°C = (-100 + 273)\text{ K} = 173\text{ K}$$

$$-40°C = (-40 + 273)\text{ K} = 233\text{ K}$$

$$30°C = (30 + 273)\text{ K} = 303\text{ K}$$

$$2{,}000°C = (2{,}000 + 273)\text{ K} = 2{,}273\text{ K}$$

Example 4.3: *Find the temperature common to Celsius and Fahrenheit scales.*

Solution: Let x be the common temperature on both the scales.

$$\therefore \quad \frac{C}{100} = \frac{F - 32}{180}$$

or $$\frac{x}{100} = \frac{x - 32}{180}$$

or $$180x = 100x - 3200$$

or $$80x = -3200$$

or $$x = -40$$

$$\therefore \quad -40\ °C = -40\ °F$$

4.8. THERMAL EXPANSION

The expansion of a substance on heating is called 'thermal expansion' of substance. Thermal expansion is the phenomenon observed in solids, liquids and gases.

In this process, an object or body expands on application of heat (temperature). Thermal expansion defines the tendency of an object to change its dimension either in length, area or volume due to heat. Thermal expansion is of three types: 1. Linear expansion, 2. Area expansion, 3. Volume expansion.

1. **Linear Expansion:** Linear expansion is the change in the length due to heat. By experiments it is observed that on heating a rod, there is increase in its temperature and hence there is increase in its length is directly proportional to its original length and increase in its temperature. Let at any temperature length of a rod be L and rise in temperature Δt its length becomes $L + \Delta L$. Then increase in length

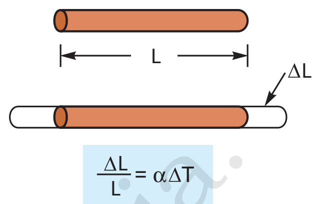

Fig. 4.11. Linear expansion

$$\Delta L \propto L \times \Delta t$$

or $$\Delta L = \alpha \times L \times \Delta t, \quad ...(1)$$

where α is the constant of proportionality and is called coefficient of linear expansion, which depends upon the material of the rod.

From eq. (1)

$$\alpha = \frac{\Delta L}{L \times \Delta t} = \frac{\text{Increase in length}}{\text{Original length} \times \text{Rise in temperature}}$$

If $\Delta t = 1$ °C, $L = 1$, then $\alpha = \Delta L$.

Thus, coefficient of linear expansion of the material of a rod is equal to the increase in unit length of the rod when its temperature rises to 1°C. Its unit is per °C.

2. **Area Expansion:** Area expansion also called superficial expansion is the change in area due to temperature changes. Like linear expansion, superficial expansion of a solid also depends upon the original area of the solid, rise in temperature and upon the material of the solid.

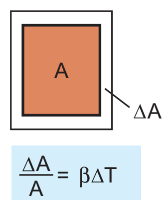

Fig. 4.12. Area expansion

Let at any temperature original area of a lamina be A, and rise in temperature Δt°C, its area becomes A + ΔA, then coefficient of superficial expansion of the material of the lamina is given by

$$\beta = \frac{\text{Increase in area}}{\text{Original area} \times \text{Rise in temperature}} = \frac{\Delta A}{A \times \Delta t} \text{ per °C.}$$

Relation between coefficient of area expansion and coefficient of linear expansion: Let at a given temperature each side of a square lamina of a material is 1 cm and its coefficient of linear expansion is α, then area of the lamina will be 1 cm^2.

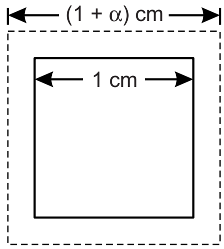

Fig. 4.13. Square lamina

Let temperature of the lamina is increased to 1°C. (Fig. 4.13).

Then at new temperature each side of the lamina = (1 + α) cm

$$\text{Area of lamina} = (1+\alpha)^2 \text{ cm}^2$$

$$\text{Increase in area} = (1+\alpha)^2 - 1$$

$$= 1 + 2\alpha + \alpha^2 - 1 = 2\alpha + \alpha^2.$$

Since, α in much less than 1, hence α^2 may be neglected.

Then,

Increase in area = 2 α

$$\therefore \quad \beta = \frac{\text{Increase in area}}{\text{Original area} \times \text{Rise in temperature}} = \frac{2\alpha}{1 \times 1} = 2\alpha.$$

Thus, coefficient of area expansion in twice its coefficient of linear expansion.

3. **Volume Expansion:** Volume expansion is the change in volume due to temperature. Volume expansion of a solid also depends upon its original volume, rise in temperature and material of the solid.

The coefficient of volume expansion of the material of a solid is equal to the increase in unit volume of the solid, when its temperature rises to 1°C.

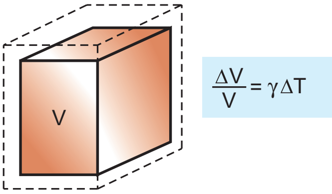

Fig. 4.14. Volume expansion

Let at any temperature original volume of a solid be *V*, and rise in temperature Δ*t* °C, its volume becomes *V* + Δ*V*, then coefficient of volume (or cubical) expansion of the material of the solid is given by

$$\gamma = \frac{\text{Increase in volume}}{\text{Original volume} \times \text{Rise in temp.}} = \frac{\Delta V}{V \times \Delta t} \text{ per °C.}$$

Relation between coefficient of volume expansion and coefficient of linear expansion.

Let at a given temperature each side of a cube of a material is 1 cm and its coefficient of linear expansion is α. Then volume of the cube will be 1 cm^3.

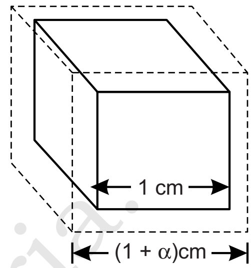

Fig. 4.15. Cube

Let temperature of the cube is raised to 1°C. (Fig. 4.15).

Then at new temperature each side of the cube = $(1 + \alpha)$ cm

$$\text{Volume of the cube} = (1 + \alpha)^3 \text{ cm}^3$$

$$\text{Increase in volume} = (1 + \alpha)^3 - 1$$

$$= 1 + 3\alpha + 3\alpha^2 + \alpha^3 - 1$$

$$= 3\alpha + 3\alpha^2 + \alpha^3.$$

Since, α is much less than 1, hence higher power terms of α may be neglected. Then,

$$\text{Increase in volume} = 3\alpha$$

$$\gamma = \frac{\text{Increase in volume}}{\text{Original volume} \times \text{Rise in temp.}}$$

$$= \frac{3\alpha}{1 \times 1}$$

$$= 3\alpha.$$

Thus, coefficient of volume expansion is three times its coefficient of linear expansion.

Relation between α, β and γ

$$\beta = 2\alpha \text{ and } \gamma = 3\alpha$$

$$\therefore \quad \alpha : \beta : \gamma = \alpha : 2\alpha : 3\alpha = 1 : 2 : 3.$$

Example 4.4: *An iron ring is to be fixed on the rim of a wooden wheel. The diameter of the ring is 5.231 m and that of the wheel is 5.243 m at 27°C. To what temperature should the ring be heated so as to fit on the rim of the wheel? The coefficient of linear expansion of iron is 1.20×10^{-5} °C^{-1}.*

Fig. 4.16. Wooden wheel

Solution: The ring would be fixed on the rim of the wheel if the diameter of the ring increases from 5.231 m to 5.243 m, that is

$$\Delta l = 5.243 \text{ m} - 5.231 \text{ m} = 0.012 \text{ m}.$$

Let ΔT be the required rise in temperature of the ring. Then

$$\Delta l = \alpha l \Delta T,$$

where l is the original diameter of the ring.

$$\therefore \quad \Delta T = \frac{\Delta l}{\alpha l}$$

$$= \frac{0.012 \text{ m}}{(1.20 \times 10^{-5}\,°\text{C}^{-1}) \times 5.231}$$

$$= 191°\text{C}$$

The ring should be heated to a temperature of

$$T + \Delta T = 27\,°\text{C} + 191\,°\text{C} = 218\,°\text{C}$$

Example 4.5: *Railway lines are laid with gaps to allow for expansion. If the gap between steel rails 66 m long be 3.63 cm at 10°C, then at what temperature will the lines just touch? Coefficient of linear expansion for steel = 11 × 10^{-6} per °C.*

Solution: Since the rail expands in both directions therefore the gap between two rails is filled by the expansions of half lengths of each rail.

An equivalent problem will be to study the expansion of one rail only in one direction to fill the gap.

$$L_0 = 66 \text{ m},$$

$$L_t - L_0 = \Delta L = 3.63 \times 10^{-2} \text{ m}$$

Change in temperature ΔT = ?,

$\alpha = 11 \times 10^{-6}$ per °C

$$\Delta L = L_0\, \alpha\, \Delta T \quad \text{or} \quad \Delta T = \frac{\Delta L}{L_0 \alpha}$$

or $$\Delta T = \frac{3.63 \times 10^{-2}}{66 \times 11 \times 10^{-6}} = 50°\text{C}$$

Final temperature – Initial temperature = ΔT

or Final temperature = ΔT + Initial temperature = (50 + 10)°C = 60°C

Example 4.6: *A metal ball 0.1 m in radius is heated from 273 K to 348 K. Calculate the increase in surface area of the ball. Given : Coefficient of superficial expansion is 0.000034/K.*

Solution: Radius of ball at 273 K,

$r_{273} = 0.1$ m

Surface area at 273 K, $S_{273} = 4\pi r_{273}^2$

or $S_{273} = 4\pi(0.1)^2 m^2$

$= \frac{4\pi}{100} m^2$

$\beta = 0.000034/K,$

$\Delta T = (348 - 273)K$

$= 75$ K

Increase in surface area,

$\Delta S = S_{273}\beta\Delta T$

or $\Delta S = \frac{4\pi}{100} \times 0.000034 \times 75 \ m^2$

$= 3.206 \times 10^{-4} \ m^2$

Example 4.7: *An iron sphere has a radius of 10 cm at a temperature of 0°C. Calculate the change in volume of the sphere if it is heated to 100°C. Coefficient of linear expansion of iron = 11 × 10^{-6} °C^{-1}.*

Solution: $\alpha = 11 \times 10^{-6}$ °C^{-1},

$\gamma = 3\alpha = 33 \times 10^{-6}$ °C^{-1}

Volume at 0°C,

$V_0 = \frac{4}{3}\pi r^3 = \frac{4}{3} \times \frac{22}{7} \times (10)^3 cm^3$

$= 4190.48 \ cm^3$

$\Delta V = \gamma V_0 \Delta T$

$= 33 \times 10^{-6} \times 4190.48 \times 100 \ cm^3$

$= 13.83 \ cm^3$

4.9. BOYLE'S LAW

ACTIVITY 4.6

Take a medical syringe. Keep the needle in the fluid (water or medicine) pull out the plunger of a syringe, whereas temperature of surrounding is constant.

1. What will be the effect on volume of the air inside the barrel of the syringe?
2. Do you observe that fluid flow into the syringe?

   Now push the plunger back in the syringe.
3. What will be the effect on volume of the air inside the barrel of the syringe?
4. Do you observe that fluid inside the barrel will flow out?

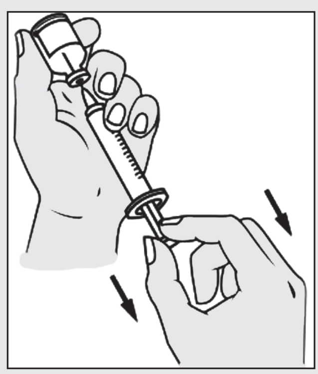

Fig. 4.17. Medical syringe

The working of a syringe can be explained using Boyle's law. When the plunger of a syringe is pulled out the volume inside the barrel increases. Fluids (such as water or medicine) flow from a high pressure area to a low pressure area. This means that once the pressure inside a syringe is lower than the pressure outside the syringe, a fluid near the needle will flow into the syringe. When the plunger is pushed back in, the volume decreases and the pressure increases. Once the pressure is greater than that outside the syringe, the fluid inside the barrel will flow out.

From the above activity we can conclude that at constant temperature the volume of a fixed amount of a gas is inversely proportional to the pressure applied to the gas.

This is called Boyle's Law.

Graph for Boyle's law represents an inverse proportion (Fig. 4.18). When two quantities are in inverse proportion, their product is a constant. *So, the product of pressure and its corresponding volume is always a constant.*

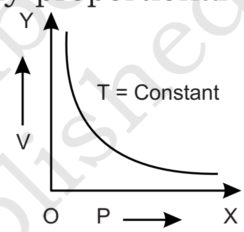

Fig. 4.18. Variation of P with V at constant T

In equation form, $PV = \text{a constant} \quad \text{or} \quad V \propto \frac{1}{P}$

In all cases, except under very high pressures, or very low temperatures or both,

$$PV = P'V' \quad \text{and} \quad V' = \frac{PV}{P'}$$

Here P is the original pressure, V is the original volume, P′ represents the new pressure and V′ the new volume.

Figure 4.19 shows the graph between P and $\frac{1}{V}$ for a given mass of gas at a constant temperature T.

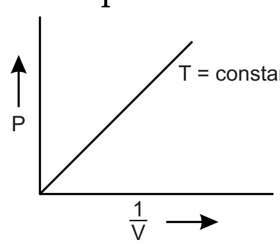

Fig. 4.19. P versus $\frac{1}{V}$ graph

Boyle's law describes the behaviour of an ideal gas. It applies to real gases with a fairly high degree of accuracy. But it does not apply to gases under such high pressure that the molecules are close enough together to attract each other. Under this condition, the gas is almost at the point at which it will condense into a liquid.

4.10. CHARLES' LAW (LAW OF VOLUME)

ACTIVITY 4.7

Take a syringe and seal its tip using a rubber stopper so that air inside the cylinder gets isolated. Thus it acts like a piston.

Dip the syringe into cold water and keep the pressure constant equal to atmospheric pressure.

1. What will be the effect on the temperature of the air inside the syringe?
2. Do you observe that the plunger of the syringe moves inwards? Why?

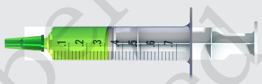

Fig. 4.20. Sealed syringe with rubber stopper

When the syringe is dipped into cold water, the temperature of the air inside the syringe decreases. Consequently, the volume of the air also decreases as the pressure remains constant which is equal to atmospheric pressure. Therefore the plunger of the syringe moves inwards.

From the above activity we can conclude that at constant pressure, the volume of a gas is directly proportional to its temperature for a fixed amount of a gas.

This is called Charles' law.

Therefore, $V \propto T$, provided P is constant

In equation form, $$\frac{V}{T} = \frac{V'}{T'}$$

where V is the original volume, T is original kelvin temperature, V′ is the new volume and T′ is the new kelvin temperature.

If we plot a graph between kelvin temperature and gas volume, it comes out to be a straight line (Fig. 4.21).

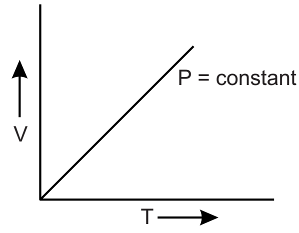

Fig. 4.21

Charles' law, like Boyle's law, applies strictly to an ideal gas. However, since the behaviour of a real gas is similar to that of an ideal gas except near its condensation conditions, Charles' law can be used with reasonable exactness for real gases.

4.11. PRESSURE LAW

Pressure Law states that: At constant volume, the pressure of the given mass of a gas is directly proportional to its kelvin temperature.

If P be the pressure and T be the kelvin temperature, then

$$P \propto T \quad \text{or} \quad \frac{P}{T} = \text{constant.}$$

Let P_1 be the pressure of a certain mass of a gas at temperature T_1 and having a volume V. Now, if temperature is changed to T_2 at the same volume so that the corresponding pressure becomes P_2. Then according to the law:

$$\frac{P_1}{T_1} = \frac{P_2}{T_2} \qquad \text{(At constant V)}$$

The law can be illustrated by pressure-temperature graph. The plot of P vs T for a fixed mass of a gas at constant volume is a straight line as shown in Fig. 4.22. This plot of P vs T at constant V is called **isometric**. The slopes of various isometrics at different volumes are different but all these lines meet the temperature axis on extrapolation at 0 (K) as shown in Fig. 4.22.

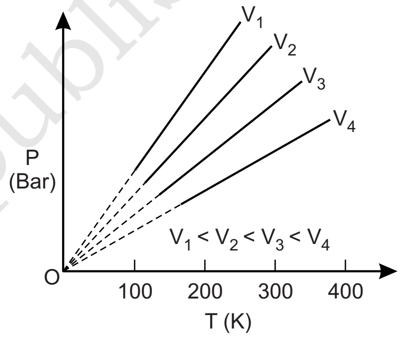

Fig. 4.22. Isometrics of ideal gas

4.12. COMBINING BOYLE'S LAW AND CHARLES' LAW

Let us derive a formula which combines Boyle's law and Charles' law. At constant temperature T_1, a certain mass of gas occupying volume V_1 is subject to a change in pressure from P_1 to P_2. The new volume V_2, from Boyle's law, is

$$V_2 = \frac{P_1 V_1}{P_2} \qquad \text{...(1)}$$

Now if V_2 is subjected to an increase in temperature from T_1 to T_2 at constant pressure P_2, the new volume V_3, from Charles' law, is

$$V_3 = \frac{V_2 T_2}{T_1} \qquad \text{...(2)}$$

Substituting the value of V_2 in equation (2), we get

$$V_3 = \frac{P_1V_1T_2}{T_1P_2}$$

Rearranging terms, $$\frac{P_1V_1}{T_1} = \frac{P_2V_3}{T_2}$$

But V_3 is the volume at pressure P_2 and temperature T_2.

∴ In general, $$\frac{PV}{T} = \frac{P'V'}{T'}$$

where, P, V and T are original pressure, volume and kelvin temperature, and P′, V′ and T′ are new pressure, volume and kelvin temperature respectively.

Example 4.8: *A balloon is filled with hydrogen at room temperature. It will burst if pressure exceeds 0.2 bar. If at 1 bar pressure the gas occupies 0.27 L volume, upto what volume can the balloon be expanded by filling H_2?*

Solution:

Here, P_1 = 1 bar,
P_2 = 0.2 bar
V_1 = 0.27 L,
V_2 = ?

From Boyle's law equation:

$$P_1V_1 = P_2V_2$$

$$\therefore \quad V_2 = \frac{P_1V_1}{P_2} = \frac{1 \times 0.27}{0.2}$$

$$= 1.35 \text{ L}$$

Since the balloon bursts at 0.2 bar pressure. Hence the volume of balloon should remain less than 1.35 L.

Example 4.9: *It is desired to increase the volume of 80 cm^3 of a gas by 20% without changing the pressure. To what temperature the gas be heated if its initial temperature is 25 °C?*

Solution: The desired increase in the volume of gas

$$= 20\% \text{ of } 80 \text{ cm}^3$$

$$= \frac{80}{100} \times 20 = 16 \text{ cm}^3$$

Thus, the final volume of the gas

$$= 80 + 16 = 96 \text{ cm}^3$$

Now, V_1 = 80 cm^3
V_2 = 96 cm^3
T_1 = 25 °C = 298 K
T_2 = ?

Applying Charle's law, $\frac{V_1}{T_1} = \frac{V_2}{T_2}$

$$\therefore \quad T_2 = \frac{V_2 T_1}{V_1}$$

$$= \frac{96\,cm^3 \times 298\,K}{80\,cm^3}$$

$$= 357.6\ K$$

$$= 357.6 - 273$$

$$= 84.6°C.$$

Example 4.10: *An iron tank contains helium at a pressure of 2.5 atmosphere at 25°C. The tank can withstand a maximum pressure of 10 atmosphere. The building in which tank has been placed catches fire. Predict whether, the tank will blow up first or melt. (The melting point of iron = 1535°C).*

Solution: Let us proceed to calculate at pressure build up in the tank at the melting point of iron.

Thus, $P_1 = 2.5$ atm. $P_2 = ?$

$T_1 = 25\ °C = 298\ K$

$T_2 = 1535°C = 1808\ K$

According to pressure law equation,

$$\therefore \quad \frac{P_1}{T_1} = \frac{P_2}{T_2}$$

Thus, $$P_2 = \frac{P_1 T_2}{T_1} = \frac{2.5 \times 1808}{298}$$

$$= 15.1\ atm.$$

Since, pressure of the gas in the tank is much more than 10 atm at the melting point. Thus, the tank will blow up before reaching the melting point.

Example 4.11: *When a ship is sailing in Pacific ocean where temperature is 23.4°C, a balloon is filled with 2.0 L of air. What will be the volume of the balloon when the ship reaches other ocean, where temperature is 26.1°C.*

Solution:

$T_1 = 23.4°C$

$= 23.4 + 273.15$

$= 296.55\ K$

$T_2 = 26.1°C$

$= 26.1 + 273.15$

$= 296.25\ K$

$V_1 = 2.0\ L;\ V_2 = ?$

Apply Charle's law

$$\frac{V_1}{T_1} = \frac{V_2}{T_2} \text{ or}$$

$$V_2 = \frac{V_1 T_2}{T_1} = \frac{2.0(L) \times 299.25\,(K)}{296.55\,(K)}$$

$$= 2.018\ L.$$

Example 4.12: *A fixed mass of gas occupying 5 litres at 27°C is compressed at constant temperature until the pressure is doubled. It then cooled at that pressure until the volume is 3 litres. What is the new temperature?*

Solution:

P_1 = ?, V_1 = 5 litres,

T_1 = 27 °C
= (27 + 273) K = 300 K

V_2 = 3 litres, $P_2 = 2\,P_1$, T_2 = ?

$$\text{Using, } \frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_2}$$

$$\frac{P_1 \times 5}{300} = \frac{2P_1 \times 3}{T_2}$$

$$\text{or} \quad T_2 = \frac{2 \times 300 \times 3}{5} = 360 \text{ K}$$

Example 4.13: *A sample of helium gas has a volume of 0.180 litre, a pressure of 0.800 atm and a temperature of 29°C. What is the new temperature of the gas at a volume of 90 ml and a pressure of 3.20 atm?*

Solution:

P_1 = 0.800 atm,

V_1 = 0.180 litre = 180 ml,

T_1 = 29°C = (29 + 273)K = 302 K

P_2 = 3.20 atm, V_2 = 90 ml, T_2 = ?

Using combined gas law equation

$$\frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_2}$$

$$\frac{0.800 \text{ atm} \times 180 \text{ ml}}{302 \text{ K}} = \frac{3.20 \text{ atm} \times 90 \text{ ml}}{T_2}$$

$$T_2 = \frac{302 \text{ K} \times 3.20 \text{ atm} \times 90 \text{ ml}}{0.800 \text{ atm} \times 180 \text{ ml}}$$

$$\text{or} \quad T_2 = 604 \text{ K}$$

$$\text{or} \quad T_2 = 604 - 273 = 331 \text{ °C}$$

GLOSSARY

Boiling point: The temperature at which a liquid changes into its vapour state.

Calibration: Dividing or marking with gradations, graduations, as other indexes of degree, quantity, etc.

Clinical thermometer: The thermometer that measures our body temperature.

Heat: It is a form of energy stored in the molecules of a substance. It flows from one body to another due to temperature difference between the two.

Kink: It is the bent portion of the thermometer. It is used in a clinical thermometer to prevent the backward flow of mercury. It keeps the reading of the thermometer constant.

Laboratory thermometer: A thermometer that measures temperature of objects other than human body.

Lower fixed point (L.F.P): Melting point of pure ice at normal atmospheric pressure.

Maximum and Minimum thermometer: A thermometer used to measure lowest and highest temperature of a day.

Melting point: The temperature at which a solid changes into its liquid state.

Solute: The minor component in a solution, dissolved in the solvent.

Temperature: It is the measure of the degree of hotness or coldness of a substance.

Thermal Equilibrium: The condition under which two substance in physical contact with each other exchange no heat energy.

Thermal expansion: It is the tendency of matter to change in shape, volume and area in response to a change in temperature.

Thermometer: A device used to measure temperature.

Thermometric liquids: The liquids used in the liquid-in-glass thermometers.

Upper fixed point (U.F.P): Boiling point of pure water at normal atmospheric pressure.

REVIEW EXERCISES

Do the review exercises in your notebook.

A. Choose the correct option.

1. Which instrument is used for measuring heat?
(a) Thermometer (b) Seismograph
(c) Anemometer (d) Calorimeter

2. What is the range of clinical thermometer; in degree Celsius?
(a) 42 to 65 (b) 35 to 42
(c) 0 to 100 (d) 15 to 65

3. What is the range of laboratory thermometer; in degree Celsius?
(a) 15 to 65 (b) 52 to 65
(c) –10 to 110 (d) 35 to 42

4. Which material is normally filled inside conventional thermometer?

(a) Silver (b) Halogen

(c) Sodium (d) Mercury

5. Temperature is

(a) a form of heat transfer where energy is radiated in the form of rays.

(b) a form of heat transfer.

(c) a form of energy contained in a object associated with the motion of molecules.

(d) a measure of the hotness or coldness of an object.

6. The unit of measurement of temperature is

(a) meter (b) kilogram

(c) degree Celsius (d) second

7. The normal temperature of Human body is

(a) 40°C (b) 37°C

(c) 42°C (d) 35°C

8. The maximum and minimum temperatures of a day are measured with a

(a) celsius thermometer

(b) fahrenheit thermometer

(c) maximum-minimum thermometer

(d) kelvin thermometer

9. There is a concentric spherical cavity in a solid metallic sphere. When the sphere is heated, the volume of the cavity:

(a) increases (b) decreases

(c) does not change (d) first decreases then decreases

10. Two iron spheres of same size, one solid and the other hollow, are heated through the same temperature range. Then,

(a) both the spheres will expand equally

(b) hollow sphere will expand more than solid sphere

(c) solid sphere will expand more than the hollow sphere

(d) there will no effect on their size.

11. A metal disc has a hole in it. When the disc is heated the size of hole will

(a) not change (b) increase

(c) decrease (d) first increase then decrease

12. Consider P – V diagram for in ideal gas shown in Fig. 4.23.

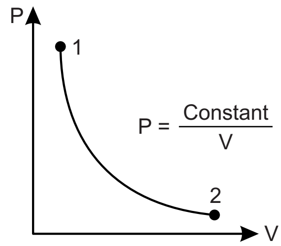

Fig. 4.23.

Out of the following diagrams, which represents the T – P diagram?

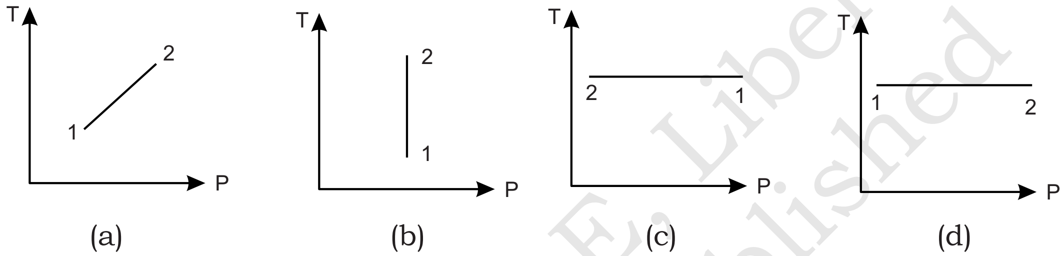

Fig. 4.24

B. Fill in the blanks.

1. The hotness of an object is determined by its _______.

2. Temperature of boiling water cannot be measured by a _______ thermometer.

3. Human body temperature is measured in degree _______.

4. _______ prevents mercury level from falling on its own in a clinical thermometer.

5. The heat flows from a body at a _______ temperature to a body at a _______ temperature.

6. The expansion of a substance on heating is called _______ .

7. The coefficient of area expansion is _______ its coefficient of linear expansion.

8. Linear expansion depends upon rise in _______ and _______ of the solid.

9. Boyle's law states that the product of pressure and its corresponding _______ is always constant at constant temperature.

10. Charle's law states that the volume of a gas is directly proportional to the _______ provided pressure is constant.

C. State whether the following statements are true or false.

1. The flow of heat from the hotter body to the colder body will stop when the temperatures of the two bodies become equal.
2. Mercury is a toxic substance.
3. Mercury-in-glass thermometer is more sensitive than alcohol-in-glass thermometer.
4. When a solute is added to a liquid its boiling point decreases.
5. Mercury expands up to eight times more than alcohol.
6. The ratio between the coefficient of linear, area and volume expansions i.e. $\alpha : \beta : \gamma = 1 : 2 : 3$.
7. Thermal expansion is the phenomena observed in solids, liquids and gases.
8. The constant quantity of Boyle's law is only mass of a gas.
9. The constant quantities in Charle's law are pressure and mass of gas.
10. Plot of a graph between Kelvin temperature and gas volume comes out to be a straight line.

D. Answer the following questions.

1. Explain the difference between heat and temperature.
2. Describe different thermometer scales.
3. Describe different thermometric liquids used.
4. Explain steps of calibrating thermometers.
5. Explain different types of thermometers.
6. Explain the advantages of mercury over alcohol as a thermometric liquid.
7. What do you mean by thermal expansion?
8. State Boyle's law.
9. State Charle's law.
10. State Pressure law.

E. Numericals.

1. Here TC = temperature in degrees Celsius, TF = temperature in degrees Fahrenheit, TK = temperature in Kelvin
   (a) If TF = 77, find TC and TK (b) If TF = 5, find TC and TK
   (c) If TK = 73, find TC and TF (d) If TF = – 40, find TC
2. At what temperature will the reading of a Fahrenheit thermometer be double that of a Celsius reading?

3. A newly designed thermometer has its lower fixed point and upper fixed point marked 5 and 95 respectively. Compute the temperature on this scale corresponding to 50 °C.
4. Consider a steel bridge 200 m long in a locality where the temperature varies from 273 K to 313 K. Find the change in the length of the bridge. Take α of steel is $11 \times 10^{-6}\ K^{-1}$.
5. The volume of a lead ball at 0 °C is 100 cm^3 and at 100 °C, it is 100.85 cm^3. Calculate the coefficient volume of expansion and linear coefficient of expansion of lead.
6. A metal ball of radius 10 cm is heated from 20 °C to 69 °C. The coefficient of volume expansion is 0.000080 K^{-1}. Find (i) the change in volume (ii) the change in surface area and (iii) the coefficient of linear expansion of the material of the ball.
7. At 0 °C, the mass of 1.000 m^3 volume of mercury is 13,600 kg. Find the density of mercury at 100 °C. The coefficient of cubical expansion of mercury is $1.8 \times 10^{-4}\ °C^{-1}$.
8. A weather balloon having 150 L volume when filled with H_2 gas had a pressure of 1.1 atmosphere. What volume the balloon would have when the balloon rises to 1000 m where the atmospheric pressure is 0.9 atm. Assume that the temperature is constant.
9. A patient is usually given an anesthetic gas at 20 °C. But his body temperature is 37 °C. What would this temperature change do, to 1500 cm^3 of gas if mass and pressure remain unchanged?
10. A constant volume hydrogen thermometer records a pressure of $40 \times 10^3\ Nm^2$ at triple point of water and pressure of $28.6 \times 10^3\ Nm^{-2}$ at temperature of dry ice. What is temperature of dry ice?
11. When the bulb of a constant volume gas thermometer is surrounding by melting ice, the level of mercury in the open tube is 5 cm below the level in the closed tube. When the bulb is placed inside oil, the level in the open tube is 65 cm higher. Find the temperature of oil bath, if atmospheric pressure = 75 cm of Hg column.
12. A chemistry student is interested to fill a cylinder of one litre capacity with hydrogen at 25 °C and 80 atm pressure. What will be the volume of H_2 gas under standard conditions of temperature and pressure (STP).

F. Questions based on Higher Order Thinking Skills (HOTS).

1. Can we use a laboratory thermometer instead of a clinical thermometer to measure our body temperature? Why?
2. What is the effect of adding solutes on boiling points of liquids?