7 STUDY OF GAS LAWS

SYLLABUS

(i) The behaviour of gases under changes of temperature and pressure; explanation in terms of molecular motion (particles, atoms, molecules); Boyle's Law and Charles' Law; absolute zero; gas equation; simple relevant calculations.

- The behaviour of gases under changes of temperature and pressure, explanation in term if molecular motion (particles, atoms, molecules) • *Boyle's Law: statement, mathematical form, simple calculations.* • *Charles' Law: statement, mathematical form, simple calculations.* • *Absolute zero Kelvin scale of temperature.* • *Gas equation $P_1 V_1 / T_1 = P_2 V_2 / T_2$; simple relevant calculations based on gas equation.*

(ii) Relationship between Kelvin scale and Celsius Scale of temperature; Standard temperature and pressure. Conversion of temperature from Celsius Scale to Kelvin scale and vice versa.
Standard temperature and pressure. (Simple calculations)

7.1 INTRODUCTION

The state of matter in which inter-particle attraction is weak and inter-particle space is so large that the particles become completely free to move randomly in the entire available space is known as ***Gas***. Gas occupies the entire space of the vessel in which it is kept and so takes the shape of the vessel. *All gases show uniform behaviour under similar conditions of temperature and pressure irrespective of their chemical nature or colour or odour.*

7.2 BEHAVIOUR AND CHARACTERISTIC PROPERTIES OF GASES

Gases are composed of molecules (particles) that are in constant random motion. Kinetic theory helps in explaining the simple relationship that exists between the pressure, the volume, and the temperature of a gas.

The kinetic molecular theory, explains the behaviour and characteristic properties of gases:

(1) Composition of gases : Gases are made up of tiny particles (molecules) moving in all possible directions at all possible speeds. The molecules are negligibly small in size as compared to the volume occupied by the gas.

(2) Gases have neither a fixed volume nor a fixed shape : There is negligible force of attraction between the particles (gas molecules). Therefore, the particles (gas molecules) are free to move in the entire space available to them, their movement is restricted only by the walls of the container. Thus, they attain the shape of the containing vessel.

(3) Gases exert pressure in all directions: The moving particles (molecules) of a gas collide with each other and also with the walls of the container. Due to these *collisions*, gas molecules exert pressure. It has been found, that at a given temperature, time and area, the same number of molecules of a gas strike against the walls of the container. Thus, gases exert the same pressure in all directions.

(4) Gases are highly compressible : There are large inter-particle (inter-molecular) spaces between gas molecules, and this accounts for the high compressibility of gases. On applying pressure, the molecules come closer, thus decreasing the volume of the gas.

(5) Gases are highly expansible : Gases increase in volume on decrease in pressure and increase in temperature.

When pressure on an enclosed gas is reduced, its particles (molecules) move apart, thus increasing their inter-molecular spaces. As a result, the volume of the gas increases.

When an enclosed gas is heated, kinetic energy of its molecules increases. Thus, the molecules start moving faster and farther apart from each other, resulting in an increase in the volume of the gas.

(6) Gases have low density : The number of molecules per unit volume in a gas is very small as compared to solids and liquids. Gases have large inter-molecular space between their molecules. Therefore, gases have very low density.

(7) Gases have a natural tendency to mix with one another (diffusion) : Inter-particle (inter-molecular) spaces in a gas are very large. When two gases are brought in contact with each other, their molecules mix with each other in such a manner that a homogeneous gaseous mixture is formed.

Diffusion is the process of gradual mixing of two substances, kept in contact, by molecular motion.

If you open a jar of chlorine or ammonia in a large room, the odorous presence of the gas can be detected in every part of the room within a few seconds. Although chlorine is heavier than air, it does not remain at the floor but spreads throughout the room.

The particles (molecules) of chlorine coming out of the jar collide with air particles (molecules) and due to the collisions of the particles, they start moving in a haphazard manner in all possible directions. This process continues till there is an equal concentration of chlorine particles (molecules) throughout the room.

(8) Gases can be liquefied : On cooling, the kinetic energy of the molecules of a gas is reduced and on applying pressure on a cooled gas, the molecules come closer. Hence, the inter-molecular space gets reduced and there is an increase in the number of molecules per unit volume. Thus, the gas liquefies.

7.3 MOLECULAR MOTION: RELATIONSHIP OF TEMPERATURE, PRESSURE AND VOLUME

According to the kinetic model, particles (molecules) of a substance are in constant random motion, so they possess kinetic energy.

The average kinetic energy of a particle (molecule) is directly proportional to its absolute temperature.

As temperature increases, molecular motion increases, and when temperature decreases, molecular motion also decreases. This suggests that when the temperature is zero, molecular motion ceases (theoretical concept). This fact is applied in defining a scale of temperature called *Kelvin scale**.

The temperature at which the molecular motion completely ceases (theoretical concept), on the Kelvin scale, is called *absolute zero*.

Absolute zero or zero kelvin is equal to –273°C. Obviously, temperatures lower than absolute zero, *i.e.*, –273°C are not possible.

When a gas is enclosed in a vessel, it exerts uniform pressure on the walls of the containing vessel. The reason is that the particles (molecules) of the gas collide with each other and with the walls of the containing vessel. Since a large number of particles (molecules) suffer collisions with the wall, an appreciable force acts on the wall. ***The force exerted on a unit area of the wall of the vessel is equal to the pressure of the gas.***

But, when the temperature of the gas is increased, keeping its volume constant, the average kinetic energy of the gas molecules increases and therefore average speed of the molecules also increases. The molecules now strike the walls of the container with greater momentum (momentum is the product of mass and velocity) and the rate of collision of the particles (molecules) also increases. Thus, the force exerted on the walls of the container increases, which results in an increase in the pressure exerted by the gas.

If one of the walls of the container is movable, then, due to the increased pressure, that wall is pushed back and the gas expands. Thus, volume also increases with the increase in molecular motion.

7.4 THE GAS LAWS

*The behaviour of a gas under known conditions of pressure, volume and temperature is described by laws known as **Gas Laws**.*

Standard variables for gas laws :

The physical behaviour of gases can be described by three **standard variables** :

(i) volume (V) (ii) pressure (P)

(iii) temperature (T).

All gases are similar in their physical behaviour; they expand and contract equally under similar conditions of temperature and pressure. *For a given mass of a gas, a change in one or more than one variable, i.e., pressure, volume and temperature, results in a change in the remaining variables.*

* Kelvin scale is also called the absolute scale of temperature.

(a) The volume *(V) of a gas is the space occupied by that gas. The space occupied by a gas is equal to the volume of its container.*

Units of volume :

In S.I. system, volume of a gas is measured in cubic metre (m^3). Other units are:

(i) cubic centimetre (cm^3)
(ii) millilitre (mL)
(iii) cubic decimetre (dm^3)
(iv) litre (L)

Relationship between units :

$1\ m^3 = 1000\ dm^3 = 1000$ litres

1 Litre $= 1000$ mL $= 1000\ cm^3$.

(b) The pressure *(P) of a gas is the force that the gas exerts per unit area on the walls of its container.*

Our planet is surrounded by a thick blanket of air known as atmosphere. The pressure exerted by air (present in the atmosphere) on the surface of the earth is called **atmospheric pressure**.

> Standard pressure of one atmosphere (1 atm) is defined as the pressure exerted by 76 cm of mercury at 0°C and at standard gravity of 9·8 m s^{-2} (density of mercury = 13·5951 g cm^{-3}).

The S.I. unit of pressure is Pascal (Pa)

Pascal (Pa) is defined as the pressure exerted when a force of 1 Newton acts on an area of 1 m^2.

Units of pressure :

(i) Pascal (Pa)
(ii) Atmosphere (atm)
(iii) *(a)* in centimetre (cm Hg),
(b) in millimetre (mm Hg),
(c) in torr (named after Torricelli),

Relationship between these units :

1 atm = 76·0 cm Hg = 760 mm Hg
= 760 torr

(c) The temperature *(T) of a gas is defined as the degree of hotness of that gas.*

The more commonly used scale of temperature is **Celsius scale**, formerly known as the **Centigrade scale**. The zero on Celsius scale is purely arbitrary. In other words, temperature of a substance may go below zero *i.e.* a substance can have negative temperatures too. The behaviour of gases show that it is not possible to have temperature below –273°C. This fact has led to the formulation of another scale known as **Kelvin scale**. The zero on this scale corresponds to –273°C.

Relationship between Kelvin (K) and degree Celsius (°C)

Celsius scale values can be converted to Kelvin scale values by adding 273 to degree Celsius values.

Kelvin (K) = °C + 273.

7.5 PRESSURE AND VOLUME RELATIONSHIP IN GASES

Experiment —Take a 10 mL syringe fitted with a piston. Raise the latter to the 10 mL mark and wrap an adhesive tape over its nozzle. Fit the wrapped nozzle tightly into a hole, bored half way through a rubber stopper (Fig. 7.1).

Observation : On placing some weight on the piston (to put pressure), it moves downward and reduces the volume of air. Gradually, put some more weight. The piston moves further downward and the volume of the air is further reduced.

Now remove the weights one by one. You will notice that, on decreasing the pressure, piston moves upward, as such, the volume of the air increases.

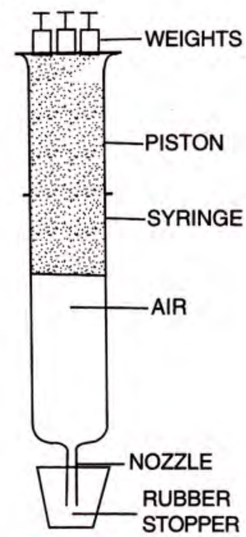

Fig. 7.1 Pressure-volume relationship

Conclusion :

1. *An **increase** in pressure at constant temperature causes a **decrease** in the volume of a gas; conversely, if the volume of a fixed mass of a gas at constant temperature is **decreased**, the pressure of the gas **increases**.*
2. *A **decrease** in pressure at constant temperature causes an **increase** in the volume of a gas; conversely, if the volume of a fixed mass of a gas at constant temperature is **increased**, the pressure of the gas **decreases**.*

7.5.1 Boyle's law

Robert Boyle systematically studied the relationship between pressure and volume of gases.

In 1662, he found that, at constant temperature, the volume of a fixed mass of a dry gas decreased by half when the pressure on it was doubled, and it became four times its original volume when its pressure was decreased to one-fourth. He described this behaviour in the form of a law, known as Boyle's law.

> ***Boyle's law :*** *Volume of a given mass of a dry gas is inversely proportional to its pressure at constant temperature.*

Mathematical expression of Boyle's law :

Suppose a gas occupies volume V_1 when its pressure is P_1; then

$$V_1 \propto \frac{1}{P_1} \quad \text{or} \quad V_1 = \frac{k}{P_1}$$

or $\quad P_1V_1 = k = \text{constant}$

If V_2 is the volume occupied when the pressure is P_2 at the same temperature, then

$$V_2 \propto \frac{1}{P_2} \quad \text{or} \quad V_2 = \frac{k}{P_2}$$

or $\quad P_2V_2 = k = \text{constant}$

$\therefore$ **$P_1V_1 = P_2V_2 = k$; at constant temperature.**

This is called **Boyle's law equation.**

> **Boyle's law** may also be stated as : *the product of volume and pressure of a given mass of a dry gas at a constant temperature is constant.*

7.5.2 Graphical verification of Boyle's law

The law can be verified by plotting a graph

(i) V *vs* $\frac{1}{P}$ (ii) V *vs* P (iii) PV *vs* P

(i) V *vs* $\frac{1}{P}$: a straight line passing through the origin is obtained (Fig 2.2).

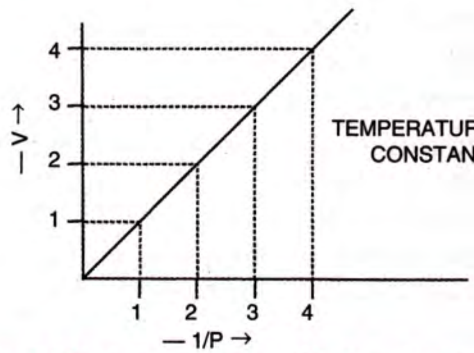

Fig. 7.2 Variation in volume (V) plotted against 1/P at constant temperature

(ii) V *vs* P : a hyperbolic curve in the first quadrant is obtained (Fig. 7.3).

Note : The term **isotherm** (meaning at constant temperature) is used to describe such graphs.

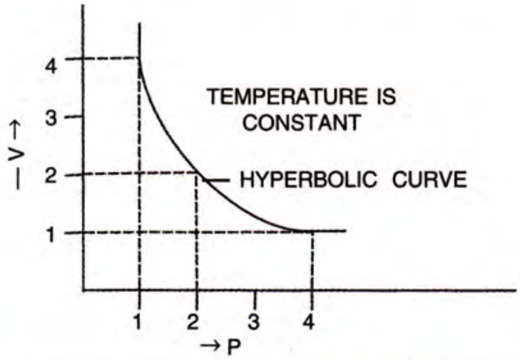

Fig. 7.3 Variation in volume (V) plotted against pressure (P) at constant temperature.

(iii) PV *vs* P : a straight line is obtained parallel to the pressure axis (Fig. 7.4).

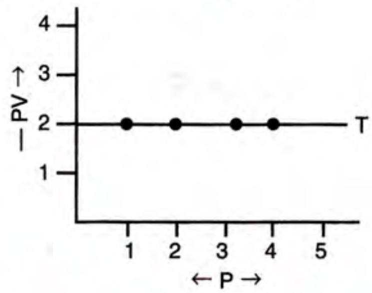

Fig. 7.4 Variation in PV plotted against P at a constant temperature

7.5.3 Explanation of Boyle's law in terms of molecular motion (kinetic theory).

According to the kinetic theory of gases, number of particles (molecules) present in a given mass and the average kinetic energy possessed by the particles is constant.

If volume of a given mass of a dry gas is reduced to half its original volume, the same number of particles (molecules) will have half the space to move. As a result, the number of molecules striking at unit area of the walls of the container at a given time will get doubled and so the pressure also gets doubled. *Conversely*, if the volume of a given mass of a gas is doubled at constant temperature, the same number of molecules will have double the space to move about. Consequently, the number of molecules striking at unit area of the walls of the container at a given time will become one half of the original value. Thus, pressure of the gas will be reduced to half of its original pressure. Hence it is seen that if pressure increases, the volume of a given mass of gas decreases at constant temperature (BOYLE'S LAW).

7.5.4 Significance of Boyle's Law

On increasing pressure, volume decreases. The gas becomes denser. Thus at constant temperature, the density of a gas is directly proportional to its pressure.

Atmospheric pressure is low at high altitudes, so air is less dense. Hence, a lesser quantity of oxygen is available for breathing. This is the reason why *mountaineers have to carry oxygen cylinders with them.*

Note : When air is blown into a balloon, volume and pressure inside the balloon increase. Here, Boyle's law is not violated as the law is valid for a definite mass, whereas mass increases when more air is blown into the balloon.

Solved examples

Example 1 : A gas occupies 800 cm^3 under 760 mm Hg pressure. Find under what pressure the gas will occupy 380 cm^3, the temperature remaining constant.

Solution :

P_1 = 760 mm Hg; V_1 = 800 cm^3

P_2 = ? mm Hg; V_2 = 380 cm^3

By Boyle's law, $P_1V_1 = P_2V_2$

Substituting the values,

$$760 \times 800 = P_2 \times 380$$

$$\therefore P_2 = \frac{760 \times 800}{380} = 1600$$

$$= 1600 \text{ mm Hg} = 160 \text{ cm Hg}$$

Ans. : The required pressure is 160 cm Hg.

Example 2 : A gas occupies 600 cm^3 under a pressure of 700 mm Hg. Find under what pressure the volume of the gas will be reduced by 20 per cent of its original volume, the temperature remaining constant throughout?

Solution :

$$20\% \text{ of } 600 \text{ cm}^3 = \frac{600 \times 20}{100} = 120 \text{ cm}^3$$

∴ The new volume of the gas

= 600 – 120 = 480 cm^3

P_1 = 700 Hg; V_1 = 600 cm^3

P_2 = ? mm Hg; V_2 = 480 cm^3

By Boyle's law, $P_1V_1 = P_2V_2$

Substituting the values,

$$700 \times 600 = P_2 \times 480$$

$$\therefore P_2 = \frac{700 \times 600}{480} = 875 \text{ mm Hg}$$

Ans. : The required pressure is 875 mm Hg.

Example 3 : Two cylinders, both containing carbon dioxide, are connected together by a tube fitted with a tap. The capacity of one cylinder is 4 dm^3 and that of the other is 1 dm^3; the pressure in the first cylinder is 560 mm Hg and that in the second is 1000 mm Hg. What will be the final pressure in either cylinders on opening the tap if the temperature remains constant ?

Solution :

Total volume of carbon dioxide (after opening the tap) = 4 + 1 = 5 dm^3.

For the first cylinder

$$P_1V_1 = P_2V_2$$

$$560 \times 4 = P_2 \times 5$$

$$\therefore P_2 = \frac{560 \times 4}{5} = 448 \text{ mm Hg}$$

For the second cylinder

$$P_1V_1 = P_2V_2$$

$$1000 \times 1 = P_2 \times 5$$

$$\therefore P_2 = \frac{1000 \times 1}{5} = 200 \text{ mm Hg}$$

Ans. : Final pressure = 448 + 200 = 648 mm Hg

Example 4 : The volume of a given mass of a gas with some pieces of marble in a container at 760 mm Hg pressure is 100 mL. If the pressure is changed to 1000 mm Hg, the new volume is 80 mL. Find the volume occupied by the marble pieces, if the temperature remains constant.

Solution : Let the volume occupied by the marble pieces = V mL

At 760 mm Hg, the volume occupied by the gas = (100 – V) mL

At 1000 mm Hg, the volume occupied by the gas = (80 – V) mL

By Boyle's law, $P_1V_1 = P_2V_2$

$$\therefore 760 \times (100 - V) = 1000 \times (80 - V)$$

$$\text{or} \quad 24\,V = 400 \text{ mL}$$

$$\text{or} \quad V = 16{\cdot}6 \text{ mL}$$

Ans. : The required volume = 16·6 mL.

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Numericals based on Boyle's law

1. Volume of certain amount of a gas at 25°C and 100 cm Hg pressure is 80 mL. The gas is expanded to 160 mL keeping the temperature constant. Calculate the pressure of the expanded gas. **(Ans. 50 cm of Hg)**
2. At a particular temperature, a certain quantity of gas occupies a volume of 74 cm^3 at a pressure of 760 mm. If the pressure is decreased to 740 mm, what will be the volume of the gas at the same temperature ? **(Ans. 76 cm^3)**
3. A student performed an experiment to measure pressure and volume of a gas at constant temperature and noted the following :

Pressure (mm of Hg)	Volume (cm^3)
100	80
125	x
200	40
y	32

Calculate the value of x and y. Which law was used in the calculations ? Draw a suitable graph. **(Ans. x = 64 cm^3, y = 250 mm)**

4. At a constant temperature, volume of a gas was found to be 400 cm^3 at a pressure of 760 mm Hg. If the pressure of the gas is increased by 25%, find the new volume. **(Ans. 320 cm^3)**
5. A vessel of capacity 600 cm^3 contains hydrogen gas at a pressure of 304 cm Hg. What will be the pressure of hydrogen gas, when the vessel is connected to another vessel of 300 cm^3 capacity ? **(Ans. 202·67 cm of Hg)**
6. At constant temperature, a gas is at a pressure of 1080 mm Hg. If the volume is decreased by 40%, find the new pressure of the gas. **(Ans. 1800 mm of Hg)**

7.6 TEMPERATURE-VOLUME RELATIONSHIP IN GASES

This relationship is seen easily when an inflated balloon, is left in bright sun and it bursts. This is because the air inside the balloon expands with the rise in temperature.

In general, *an **increase** in temperature at constant pressure causes an **increase** in volume; and a **decrease** in temperature at constant pressure causes a **decrease** in volume.*

In 1787, Jacques Charles studied the temperature-volume relationship of gases. His work was further extended by Joseph Gay-Lussac in 1802.

Experimentally, it was found that a fixed mass of any gas expands or contracts respectively by 1/273 of its volume at 0 °C for each degree Celsius rise or fall in temperature, provided the pressure remains constant.

Charles's law :
Pressure remaining constant, the volume of a given mass of a dry gas increases or decreases by 1/273 of its volume at 0°C for each 1°C increase or decrease in temperature respectively.

Mathematical expression of Charles's law

Let V_0 be the volume of a fixed mass of a gas at 0 °C, and let V be its volume at temperature t °C at constant pressure. Then, according to Charles's law,

$$V = V_0 + \frac{V_0}{273}t \quad \text{(when } P \text{ is constant)}$$

$$V = V_0\left(1+\frac{t}{273}\right) = V_0\left(\frac{273+t}{273}\right) \qquad ...(1)$$

$$V = \frac{V_0}{273}\,\mathrm{T} \quad \text{where T} = 273 + t$$

For a given mass of a gas,

$$\frac{V_0}{273} = \text{constant}$$

$$\therefore \quad V = k \times T \text{ (where k is constant)}$$

$$\text{or} \quad V \propto \mathrm{T} \text{ and } \frac{V}{T} = k$$

Charles's law may be restated as : *Volume of a given mass of a dry gas is directly proportional to its absolute (Kelvin) temperature, if the pressure remains constant.*

Suppose, a gas occupies V_1 cm^3 at T_1 temperature and V_2 cm^3 at T_2 temperature, then by Charles's law,

$$V_1 \propto T_1$$

$$\text{or} \quad V_1 = kT_1 \quad (k \text{ is constant})$$

$$\text{or} \quad \frac{V_1}{T_1} = k \text{ and } V_2 \propto T_2 \text{ or } \frac{V_2}{T_2} = k$$

$$\therefore \frac{V_1}{T_1} = \frac{V_2}{T_2} = k \text{ (at constant pressure)}$$

This is called the **Charles's law equation**.

According to this equation :

(i) *if the temperature is doubled, the volume would be doubled.*

(ii) *if it is reduced by half, the volume would also be reduced by half.*

Graphical representation of Charles's law :

The relationship between volume and temperature of a gas can be plotted on a graph, as shown in Fig. 7.5. A straight line is obtained.

The general term *isobar* (constant pressure) is assigned to such graphs.

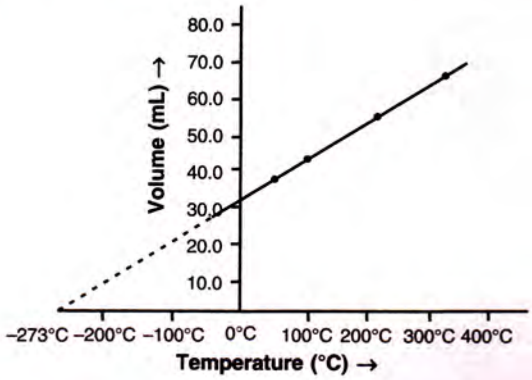


Fig. 7.5 Graph showing volume –temperature relationship in a gas (at constant pressure)

7.6.1 Explanation of Charles's law in terms of molecular motion (kinetic theory).

According to the kinetic theory of gases, the average kinetic energy of gas particles (molecules) is directly proportional to its absolute temperature. Thus, when the temperature of a gas is increased, the particles (molecules) would move faster **(kinetic energy is the energy by virtue of its motion)**, and will strike the walls of the container more frequently and vigorously. If the pressure is kept constant, volume increases proportionately. Hence, at constant pressure, volume of a given mass of a gas is directly proportional to temperature (CHARLES'S LAW).

7.6.2 Significance of Charles's law

Volume of a given mass of a gas is directly proportional to its temperature, hence density decreases with an increase in temperature. This is the reason why hot air is filled into balloons used for meteorological purposes.

7.7 ABSOLUTE ZERO

From equation (1) $V = V_0\left(\frac{273+t}{273}\right)$

Volume at $-273°C = V_0\left(\frac{273-273}{273}\right) = 0.$

Thus, it can be concluded that the volume of a gas would be reduced to zero at –273°C.

According to Lord Kelvin, if temperature of an enclosed gas at 0°C is lowered to –273°C, its volume becomes zero. ***However, this is not possible, because gas is one of the states of matter and hence, must have some definite mass and volume.***

The temperature –273°C is called absolute zero. All gases liquefy or solidify before reaching this temperature.

Theoretically, this is the lowest temperature that can ever be reached. At this temperature, all molecular motions cease. However, practically speaking, this temperature is impossible to attain.

7.8 ABSOLUTE OR KELVIN SCALE OF TEMPERATURE

The temperature scale with its zero at –273·15°C (for convenience in calculations, –273°C is used) and whose each degree is equal to one degree on the Celsius scale, is called the ***Kelvin or absolute scale of temperature***.

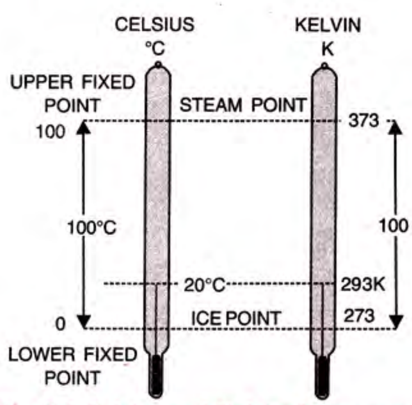


Fig. 2.6 Celsius and Kelvin thermometers

7.9 CONVERSION OF TEMPERATURE FROM CELSIUS SCALE TO KELVIN SCALE AND VICE-VERSA

The value on the Celsius scale can be converted to Kelvin scale by adding 273 to it.

0°C = 0 + 273 = 273 K

$20°C = 20 + 273 = 293$ K

$27°C = 27 + 273 = 300$ K

$-273°C = -273 + 273 = 0$ K

Kelvin scale values can be converted to degree Celsius values by subtracting 273 from it.

0 K = 0 – 273 = –273°C

273 K = 273 – 273 = 0°C (freezing point of water or ice point)

13 K = 13 – 273 = –260°C

373 K = 373 – 273 = 100°C (boiling point of water)

Note :
1. No degree sign is written for absolute temperature values.
2. The size of 1 degree on the Kelvin scale is the same as the size of 1 degree on the Celsius scale *i.e.* unit size on Kelvin scale is equal to the unit size on Celsius scale.
3. The real advantage of Kelvin scale is that it makes application and use of gas laws simple. Even more significantly, all values on Kelvin scale are positive.

Example 5 : 120 cm^3 of a gas is taken at 27.3 K. The temperature is then raised to 0 °C. What is the new volume of the gas ? The pressure is kept constant.

Solution :

$V_1 = 120\ cm^3$; $T_1 = 27.3$ K; $V_2 = ?\ cm^3$

$T_2 = 273$ K, since 0 °C = 273 K

By Charles's law,

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

Substituting the values,

$$\frac{120}{27.3} = \frac{V_2}{273}$$

$$\therefore V_2 = \frac{120 \times 273}{27.3} = 1200\ cm^3$$

Ans. : The gas at 0°C would occupy a volume of 1200 cm^3.

Examples 6 : At what temperature will 500 cm^3 of a gas measured at 20 °C occupy half its volume ? The pressure is kept constant.

Solution :

Let the required temperature be t °C.

$V_1 = 500\ cm^3$; $T_1 = (273 + 20)$ K = 293 K;

$V_2 = 250\ cm^3$; $T_2 = (273 + t)$ K

By Charles's law,

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

Substituting the values,

$$\frac{500}{293} = \frac{250}{273+t}$$

or $\quad 500\,(273 + t) = 250 \times 293$

or $\quad 2\,(273 + t) = 293$

or $\quad 273 + t = \frac{293}{2} = 146.5$

or $\quad t = 146.5 - 273 = -126.5°C$

Ans. : The gas would occupy half its volume at –126.5°C.

Example 7: The volume of a given mass of a gas at 15°C is 100 cm^3. To what temperature should it be heated under the same pressure so that it occupies a volume of 125 cm^3 ?

Solution :

Let the required temperature be t °C.

$V = 100\ cm^3$; $T = (273 + 15)$ K = 288 K

$V' = 125\ cm^3$; $T' = (273 + t)$ K

By Charles's law,

$$\frac{V}{T} = \frac{V'}{T'} \quad \text{or} \quad T' = \frac{V'}{V} \times T$$

Substituting the values,

$$T' = \frac{125 \times 288}{100} = 360\ \text{K}$$

Kelvin temperature can be converted to Celsius temperature by subtracting 273, *i.e.*

360 K = (360 – 273)°C = 87 °C

Ans. : The gas would occupy 125 cm^3 at 87°C.

Example 8 : At what centigrade temperature will the volume of a gas at 0°C triple itself if the pressure remains constant ?

Solution :

Let the volume at 0°C = V mL.

$V_1 = V$ mL; $V_2 = 3V$ mL

$T_1 = 0°$ or 273 K; $T_2 = ?$

By Charles's law,

$$\frac{V_1}{T_1} = \frac{V_2}{T_2} \quad \text{or} \quad \frac{V}{273} = \frac{3V}{T_2}$$

or $\quad T_2 = 3 \times 273 = 819\ K$

or $\quad T_2 = (819 - 273)°C = 546\ °C$

Ans. : The required temperature is 546°C.

Numericals based on Charles's law

1. Convert the following :
   (i) 37 K to °C (ii) 273 K to °C
   (iii) –27°C to K (iv) 27°C to K
2. 20 mL of hydrogen gas at 15°C is heated to 35°C at constant pressure. Find the new volume of hydrogen. **(Ans 21·39 mL)**
3. At what temperature in degree centigrade will the volume of a gas at 0°C double itself, pressure remaining constant. **(Ans. 273 °C)**
4. Calculate the volume (in cm^3) of air expelled from a vessel containing 0·4 litres of it at 250 K, when it is heated to 27°C at the same pressure. **(Ans. 480 cm^3)**
5. What will be the volume of a gas when 3 litres of it is cooled down from 15°C to –73°C at constant pressure. **(Ans. 2·0833 litres)**
6. To what temperature must a gas at 300 K be cooled down in order to reduce its volume to 1/3rd of its original volume, pressure remaining constant ? **(Ans. 100 K)**
7. Prove that the volume of a gas at 273°C is twice its volume at 273 K, at constant pressure.

7.10 THE GAS EQUATION (PRESSURE, VOLUME AND TEMPERATURE RELATIONSHIP)

If both pressure and temperature of a fixed mass of a gas are varied, a combination of Boyle's and Charles's laws gives us a fixed relation amongst its volume, pressure and temperature.

According to Boyle's law, $V \propto \frac{1}{P}$

and according to Charles's law, $V \propto T$

Now, on combining the two laws, *volume of a given mass of a gas varies inversely with pressure and directly with absolute temperature.*

$$V \propto \frac{1}{P} \times T$$

or $$V = \frac{T}{P} \times \text{constant}$$

or $$\frac{PV}{T} = \text{constant}$$

Accordingly, if the volume of a given mass of a gas changes from V_1 to V_2, its pressure from P_1 to P_2, and its temperature from T_1 to T_2, then

$$\boxed{\frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2}}$$

The above mathematical expression is called the **gas equation**. This equation is used for calculating changes in gas volume when both its pressure and temperature change.

7.11 STANDARD TEMPERATURE AND PRESSURE (S.T.P.)

Since volume of a gas changes remarkably with change in temperature and pressure, it becomes necessary to choose standard values of temperature and pressure to which gas volumes can be referred.

The standard values chosen are 0°C or 273K for temperature, and 1 atmospheric unit (atm) or 760 mm Hg for pressure. These standard values are known as **standard temperature and pressure** (S.T.P.).

Remember :

Standard temperature = 0 °C = 273 K
Standard pressure = 760 mm Hg
= 76 cm Hg
= 1 atm.

Any change in pressure or temperature is likely to change the volume of a gas. Thus, while expressing the specific volume of a gas, it is necessary to specify both its pressure and its temperature.

Note : *By increasing pressure on the volume of an enclosed gas, its volume decreases, whereas by increasing temperature, its volume increases. Thus, by keeping equilibrium between an increase in pressure and an increase in temperature, it is possible to keep the volume constant.*

7.12 THE EFFECT OF MOISTURE ON PRESSURE

Certain gases, like nitrogen and hydrogen are collected over water as shown in the Fig. 7.7. When the gas is collected over water, it is moist and contains water vapour. The total pressure exerted by this moist gas is equal to the sum of the partial pressures* of the dry gas and the pressure exerted by water vapour. Partial pressure of water vapour is also known as **aqueous tension**.

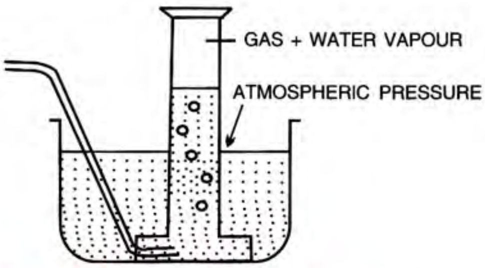


Fig. 7.7 Collection of gas over water

$$P_{total} = P_{gas} + P_{water\ vapour}$$

$$P_{gas} = P_{total} - P_{water\ vapour}$$

Actual Pressure of gas =

Total pressure – Aqueous tension

Example 9 : 87 cm^3 of moist nitrogen is measured at 9°C and 659 mm Hg pressure. Find the volume of dry nitrogen at STP. The vapour pressure of water at 9°C is 9 mm Hg.

Solution :

Pressure due to dry nitrogen alone

= 659 – 9 = 650 mm Hg

P_1 = 650 mm; $V_1 = 87$ cm^3; $T_1 = (273 + 9)$ K;

P_2 = 760 mm; $V_2 = ?$ cm^3; $T_2 = 273$ K

By the gas equation,

$$\frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2}$$

Substituting the values,

$$\frac{650 \times 87}{(273+9)} = \frac{760 \times V_2}{273} \quad \text{or} \quad \frac{650 \times 87}{282} = \frac{760 \times V_2}{273}$$

$$\text{or} \quad V_2 = \frac{650 \times 87 \times 273}{282 \times 760}$$

$$\therefore \quad V_2 = 72{\cdot}03 \text{ cm}^3$$

Ans. : The volume of dry nitrogen at S.T.P. would be 72·03 cm^3.

Example 10 : A given mass of a gas occupies 572 cm^3 at 13°C and 725 mm Hg pressure. What will be its volume at 24°C and 792 mm Hg pressure ?

Solution :

P_1 = 725 mm Hg; V_1 = 572 cm^3;

T_1 = (273 + 13) K = 286 K;

P_2 = 792 mm Hg; V_2 = ? cm^3;

T_2 = (273 + 24) K = 297 K.

Applying the gas equation,

$$\frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2}$$

Substituting the values,

$$\frac{725 \times 572}{286} = \frac{792 \times V_2}{297}$$

$$\text{or} \quad V_2 = \frac{725 \times 572 \times 297}{286 \times 792}$$

$$= 543.75 \text{ cm}^3$$

Ans. : The required volume of gas is 543.75 cm^3.

Example 11 : One litre of a gas at 10°C is heated till both its volume and pressure are tripled. Find the new temperature.

Solution :

Initial condition	*Final condition*
$P_1 = P$	$P_2 = 3P$
$V_1 = 1$ L	$V_2 = 3$ L
$T_1 = (273 + 10)$ K = 283 K;	$T_2 = ?$

From the gas equation,

$$\frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2}$$

$$\frac{P \times 1}{283} = \frac{3P \times 3}{T_2}$$

$$\text{or} \quad T_2 = \frac{3P \times 3 \times 283}{P \times 1}$$

$$= 2547 \text{ K} = (2547 - 273)°\text{C} = 2274°\text{C}$$

Ans. : The new temperature is 2274°C.

Example 12 : Gas is enclosed in a cylinder under S.T.P. conditions. At what temperature does the volume of the enclosed gas become 1/6th of its initial volume, pressure remaining constant ?

Solution :

Let the initial volume be V_1 final volume = $\frac{V_1}{6}$

Initial temp. T_1 = 273 K final temp. T_2 = ?

By Charles's law,

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

$$\therefore \quad \frac{V_1}{273} = \frac{V_1/6}{T_2} \quad \text{or} \quad T_2 = \frac{V_1 \times 273}{6 \times V_1} = 45.5 \text{ K}$$

$$= 45.5 - 273 = -227.5°\text{C}$$

Ans. : The temperature at which the volume of the enclosed gas is 1/6th of its initial volume is –227.5 °C.

* Partial pressure is the pressure, the gas would exert if it alone filled the containing vessel at the same temperature and pressure.

Example 13 : Pressure of a gas at S.T.P. is doubled and the temperature is raised to 546 K. What is the final volume of the gas ?

Solution :

$P_1 = 760$ mm Hg $\qquad P_2 = 2 \times 760$ mm Hg

$T_1 = 273$ K $\qquad T_2 = 546$ K

$V_1 = V_1 \qquad V_2 = ?$

$$\frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2}$$

$$\frac{760 \times V_1}{273} = \frac{2 \times 760 \times V_2}{546}$$

or $$V_2 = \frac{760 \times V_1 \times 546}{2 \times 760 \times 273}$$

$$\therefore V_2 = V_1$$

Ans. : The volume of the gas remains the same.

Example 14 : 16 g of oxygen gas is enclosed in a 1 dm^3 flask at 25°C. Calculate the pressure exerted by the gas, if the molecular mass (molar mass) of any gas occupies 22.4 litres at S.T.P.

Solution :

Oxygen (O_2) is a diatomic gas.

Its molar mass is $16 \times 2 = 32$ g

So, 32 g of oxygen occupies 22.4 dm^3 at S.T.P.

16 g of oxygen will occupy $\frac{22.4}{32} \times 16 = 11.2\ dm^3$

Thus,

$P_1 = 1$ atm $\qquad P_2 = ?$

$V_1 = 11.2\ dm^3 \qquad V_2 = 1\ dm^3$

$T_1 = 273$ K $\qquad T_2 = 273 + 25 = 298$

By gas equation

$$\frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2}$$

$$P_2 = \frac{P_1 V_1 T_2}{T_1 V_2} = \frac{1 \times 11.2 \times 298}{273 \times 1} = 12.2 \text{ atm}$$

Ans. The pressure exerted by the gas is 12·2 atm

CHAPTER AT A GLANCE

- Gases neither have a definite volume nor shape. The constituent particles are far away from each other and are free to move in any direction at high speed.
- The behaviour of gases is described by volume *V*, pressure *P* and temperature *T*.
- Boyle's Law : Volume of a given mass of a dry gas is inversely proportional to its pressure at constant temperature $\boxed{P_1 V_1 = P_2 V_2.}$
- Charles' Law : Pressure remaining constant, volume of a given mass of a dry gas increases or decreases by $\frac{1}{273}$ of its volume at 0°C for each 1°C increase or decrease in temperature.

  OR

  Volume of a given mass of a dry gas is directly proportional to its absolute temperature (Kelvin) if the pressure is kept constant.

  $$\boxed{\frac{V_1}{T_1} = \frac{V_2}{T_2}}$$

- The temperature –273°C is called ABSOLUTE ZERO.
- Value on the celsius scale can be converted to Kelvin scale by adding 273 to it. Kelvin scale values can be converted to degree celsius values by subtracting 273 from it.
- Standard temperature = 0°C = 273 K

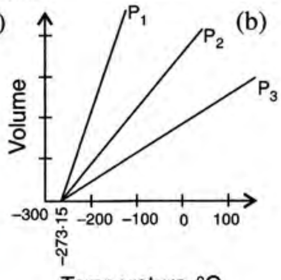
  Standard pressure = 760 cm = 76 cm Hg = 1 atm.
- Ideal Gas Equation : A mathematical expression describing the simultaneous effect of changes in temperature and pressure on volume of a given mass of a gas is called the Ideal Gas Equation.

  $$\boxed{\frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2}}$$

EXCERCISE 7

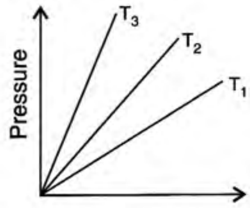
1. What do you understand by gas ?
2. Give the assumptions of the kinetic molecular theory.
3. During the practical in the lab when hydrogen sulphide gas having offensive odour is prepared for some test, we can smell the gas even 50 metres away. Explain the phenomenon.
4. Describe an experiment to show the pressure-volume relationship in gases.
5. How is molecular motion related with temperature ?
6. State (i) the three variables for gas laws (ii) S.I. units of these variables.
7. (a) State Boyle's Law.
   (b) Give its
      (i) mathematical expression,
      (ii) graphical representation and
      (iii) significance.
8. Explain Boyle's Law on the basis of the kinetic theory of matter.
9. The molecular theory states that the pressure exerted by a gas in a closed vessel results from the gas molecules striking against the walls of the vessel. How will the pressure change if :
   (a) the temperature is doubled keeping the volume constant ?
   (b) the volume is made half of its original value keeping the temperature constant ?
10. (a) State Charles's law.
    (b) Give its
       (i) graphical representation,
       (ii) mathematical expression and
       (iii) significance.
11. Explain Charles's law on the basis of the kinetic theory of matter.
12. Define absolute zero and absolute scale of temperature. Write the relationship between °C and K.
13. (a) What is the need for the Kelvin scale of temperature ?
    (b) What is the boiling point of water on the Kelvin scale ? Convert it into centigrade scale.
14. (a) Define S.T.P. or N.T.P.
    (b) Why is it necessary to compare gases at S.T.P. ?
15. Write the value of :
    (a) standard temperature in :
       (i) °C (ii) K
    (b) standard pressure in :
       (i) atm (ii) mm Hg (iii) cm Hg (iv) torr
16. (a) What is the relationship between the Celsius and the Kelvin scales of temperature ?
    (b) Convert (i) 273°C to Kelvin (ii) 293 K to °C.
17. State the laws which are represented by the following graphs.

(a)



$P_1 < P_2 < P_3$

(b)



$T_3 > T_2 > T_1$

18. Give reasons for the following :
    (a) All temperatures in the absolute (Kelvin) scale are in positive figures.
    (b) Gases have lower density compared to that of solids or liquids.
    (c) Gases exert pressure in all directions.
    (d) It is necessary to specify the pressure and temperature of a gas while stating its volume.
    (e) Inflating a balloon seems to violate Boyle's law.
    (f) Mountaineers carry oxygen cylinders with them.
    (g) Gas fills completely the vessel in which it is kept.
19. How did Charles's law lead to the concept of absolute scale of temperature ?
20. What is meant by aqueous tension ? How is the pressure exerted by a gas corrected to account for aqueous tension ?
21. State the following :
    (a) Volume of a gas at 0 Kelvin.
    (b) Absolute temperature of a gas at 7°C.
    (c) Gas equation.
    (d) Ice point in absolute temperature.
    (e) S.T.P. conditions
22. Choose the correct answer :
    (a) The graph of PV vs P for a gas is
       (i) parabolic
       (ii) hyperbolic
       (iii) a straight line parallel to X-axis
       (iv) a straight line passing through origin
    (b) The absolute temperature value that corresponds to 27°C is
       (i) 200 K (ii) 300 K
       (iii) 400 K (iv) 246 K
    (c) Volume-temperature relationship is given by
       (i) Boyle (ii) Gay Lussac
       (iii) Dalton (iv) Charles

(d) If pressure is doubled for a fixed mass of a gas, its volume will become
   (i) 4 times (ii) ½ times
   (iii) 2 times (iv) No change

23. Match the following

Column A	Column B
(a) Cm^3	(i) pressure
(b) Kelvin	(ii) temperature
(c) Torr.	(iii) Volume
(d) Boyle's law	(iv) $\frac{V}{T} = \frac{V_1}{T_1}$
(e) Charles's law	(v) $\frac{PV}{T} = \frac{P_1V_1}{T_1}$
	(vi) $PV = P_1V_1$

24. Correct the following statements.
   (a) Volume of a gas is inversely proportional to its pressure at constant temperature.
   (b) Volume of a fixed mass of a gas is directly proportional to its temperature, pressure remaining constant.
   (c) 0°C is equal to zero Kelvin.
   (d) Standard temperature is 25°C.
   (e) Boiling point of water is 273 K.

25. Fill in the blanks :
   (a) The average kinetic energy of the molecules of a gas is proportional to the ....
   (b) The temperature on the Kelvin scale at which molecular motion completely ceases is called ....
   (c) If temperature is reduced to half, ... would also reduce to half.
   (d) The melting point of ice is .... Kelvin.

Numericals

1. What will be the minimum pressure required to compress 500 dm^3 of air at 1 bar to 200 dm^3 temperature remaining constant. [**Ans.** 2·5 bar]
2. 2 litres of a gas is enclosed in a vessel at a pressure of 760 mm Hg. If temperature remains constant, calculate pressure when volume changes to 4 dm^3. **Ans.** 380 mm Hg
3. At constant temperature, the effect of change of pressure on volume of a gas was as given below :

Pressure in atmospheres	Volume in litres
0.20	112
0.25	89.2
0.40	56.25
0.60	37.40
0.80	28.10
1.00	22.4

   (a) Plot the following graphs :
   1. P vs V 2. P vs 1/V 3. PV vs P.
   Interpret each graph in terms of a law.
   (b) Assuming that the pressure values given above are correct, find the correct measurement of the volume.
4. 800 cm^3 of gas is collected at 650 mm pressure. At what pressure would the volume of the gas reduce by 40% of its original volume, temperature remaining constant ? [**Ans.** 1083.33 mm of Hg]
5. A cylinder of 20 litres capacity contains a gas at 100 atmospheric pressure. How many flasks of 200 cm^3 capacity can be filled from it at 1 atmosphere pressure, temperature remaining constant ? [**Ans.** 10,000 flasks]
6. A steel cylinder of internal volume 20 litres is filled with hydrogen at 29 atmospheric pressure. If hydrogen is used to fill a balloon at 1·25 atmospheric pressure at the same temperature, what volume will the gas occupy ? [**Ans.** 464 litres]
7. 561 dm^3 of a gas at S.T.P. is filled in a 748 dm^3 container. If temperature is constant, calculate the percentage change in pressure required. [**Ans.** 25% decrease]
8. 88 cm^3 of nitrogen is at a pressure of 770 mm mercury. If the pressure is raised to 880 mm Hg, find by how much the volume will diminish, temperature remains constant. [**Ans.** 11 cm^3]
9. A gas at 240 K is heated to 127°C. Find the percentage change in the volume of the gas (pressure remaining constant). [**Ans.** 66.6%]
10. Certain amount of a gas occupies a volume of 0·4 litre at 17°C. To what temperature should it be heated so that its volume gets (a) doubled (b) reduced to half, pressure remaining constant ? [**Ans.** (a) 307°C, (b) –128°C]
11. A gas occupies 3 litres at 0°C. What volume will it occupy at –20°C, pressure remaining constant ? [**Ans.** 2.78 litres]
12. A gas occupies 500 cm^3 at normal temperature. At what temperature will the volume of the gas be reduced by 20% of its original volume, pressure being constant ? [**Ans.** 218.4 K]
13. Calculate the final volume of a gas 'X', if the original pressure of the gas, at S.T.P. is doubled and its temperature is increased three times. [**Ans.** $1\frac{1}{2}$ times the original volume]
14. A sample of carbon dioxide occupies 30 cm^3 at 15°C and 740 mm pressure. Find its volume at S.T.P. [**Ans.** 27.7 cm^3]
15. 50 cm^3 of hydrogen is collected over water at 17°C and 750 mm Hg pressure. Calculate the volume of dry gas at S.T.P. The water vapour pressure at 17°C is 14 mm Hg. [**Ans.** 45.6 cm^3]

16. At 0°C and 760 mm Hg pressure, a gas occupies a volume of 100 cm^3. Kelvin temperature of the gas is increased by one-fifth and the pressure is increased one and a half times. Calculate the final volume of the gas. [**Ans.** 80 cm^3]

17. It is found, on heating a gas, its volume increases by 50% and pressure decreases to 60% of its original value. If the original temperature was –15°C, find the temperature to which it was heated ? [**Ans.** –40.8°C]

18. A certain mass of a gas occupies 2 litres at 27 °C and 100 pascal. Find the temperature when volume and pressure become half of their initial values. [**Ans.** –198°C]

19. 2500 cm^3 of hydrogen is taken at S.T.P. The pressure of this gas is further increased by two and a half times (temperature remaining constant). What volume will hydrogen occupy now ? [**Ans.** 5000/7 cm^3]

20. Taking the volume of hydrogen as calculated in Q.19, what change must be made in Kelvin (absolute) temperature to return the volume to 2500 cm^3 (pressure remaining constant). [**Ans.** Kelvin temperature increase to 3.5 times]

21. A given amount of gas A is confined in a chamber of constant volume. When the chamber is immersed in a bath of melting ice, the pressure of the gas is 100 cm Hg.
    (a) What is the temperature, when the pressure is 10 cm Hg ?
    (b) What will be the pressure, when the chamber is brought to 100°C.
    [**Ans.** (a) 27·3 K (b) 136·63 mm Hg]

22. A gas is to be filled from a tank of capacity 10,000 litres into cylinders each having capacity of 10 litres. The condition of the gas in the tank is as follows :
    (a) pressure inside the tank is 800 mm of Hg.
    (b) temperature inside the tank is –3°C.
    When the cylinder is filled, the pressure gauge reads 400 mm of Hg and the temperature is 0°C. Find the number of cylinders required to fill the gas.
    [**Ans.** 2022 cylinders]

23. Calculate the volume occupied by 2 g of hydrogen at 27°C and 4 atmosphere pressure, if at S.T.P. it occupies 22·4 litres. [**Ans.** 6·15 litres]

24. What temperature would be necessary to double the volume of a gas, initially at S.T.P., if the pressure is decreased to 50%. [**Ans.** 273K]

25. Which will have greater volume when the following gases are compared at S.T.P.
    (a) 1·2 l N_2 at 25°C and 748 mm Hg
    (b) 1·25 l O_2 at S.T.P. ? [**Ans.** (b)]

26. Calculate the volume of dry air at S.T.P. that occupies 28 cm^3 at 14°C and 750 mm Hg pressure when saturated with water vapour. The vapour pressure of water at 14°C is 12 mm Hg. [**Ans.** 25.9 cm^3]

27. L.P.G. cylinder can withstand a pressure of 14.9 atmosphere. The pressure gauge of the cylinder indicates 12 atmosphere at 27°C. Due to a sudden fire in the building the temperature rises. At what temperature will the cylinder explode. [**Ans.** 99.5°C]

28. 22.4 litres of a gas weighs 70 g at S.T.P. Calculate the weight of the gas if it occupies a volume of 20 litres at 27°C and 700 mm Hg of pressure. [**Ans.** 52.38 g]