States of Matter : Gases and Liquids

1. **Existence of Matter** In general, matter exist in three states:

   (i) **Solids** They have definite volume, a definite shape and are rigid.

   (ii) **Liquids** They have definite volume, but not definite shape and are non-rigid.

   (iii) **Gases** They have neither definite shape nor definite volume and are non-rigid.

   Note Fourth state is called plasma state and fifth state refers to super cooled solid (Bose-Einstein).

2. **Intermolecular Forces** The attractive or repulsive forces that exist between interacting particles (i.e. atoms or molecules) are called the intermolecular forces.

   (i) **Dispersion or London forces** These forces exist in between neutral atoms and/or non-polar molecules as in them electronic charge cloud is distributed symmetrically.

   (ii) **Dipole-dipole forces** Such forces exist in the molecules having permanent dipoles, like HCl, NH_3 etc.

   (iii) **Dipole-induced dipole forces** These forces exist between the polar molecules having permanent dipole and non-polar molecules lacking dipole. As the charged terminal of the polar molecule induces dipole in the

non-polar molecule by deforming its electron cloud and hence, both the molecules get attracted by dipole-induced dipole forces.

Note *Dipole-induced dipole and dispersion forces are collectively called **van der Waals' forces**.*

3. **Thermal Energy** The energy of a body which arises because of the motion of its atoms or molecules is called the thermal energy.

Intermolecular forces vs thermal interactions Predominance of thermal energy and the intermolecular forces in the three states of matter is as follows:

Gas ⟶ Liquid ⟶ Solid
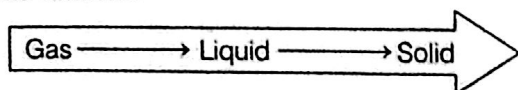
Predominance of intermolecular interactions

Gas ⟵ Liquid ⟵ Solid
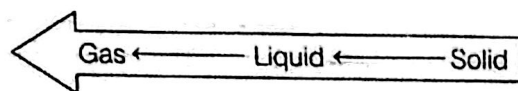
Predominance of thermal energy

4. **Gaseous State** It is the simplest state of matter. Only 11 elements, out of the total 118 elements known so far, exist in gaseous state.

Gas laws

(i) **Boyle's law** (Pressure-volume relationship) It states that at constant temperature, the pressure of a fixed amount of a gas varies inversely with its volume.

Mathematically, $p \propto 1/V$ (at constant T and n)

or $\qquad p = k_1 \dfrac{1}{V}$

Here, k_1 = proportionality constant.

$p_1 V_1 = p_2 V_2$ = constant (at constant temperature)

or $\qquad \dfrac{p_1}{p_2} = \dfrac{V_2}{V_1}$

(ii) **Charles' law** (Temperature-volume relationship) "It states that, at constant pressure, the volume of a given mass of a gas is directly proportional to its absolute temperature".

Mathematically,

$V \times T$ (at constant p and n)

Thus, the general form of the reaction can be written as

$\dfrac{V_2}{V_1} = \dfrac{T_2}{T_1}$ or $\dfrac{V_1}{T_1} = \dfrac{V_2}{T_2}$

or $\qquad \dfrac{V}{T}$ = constant = k_2

Thus, $V = k_2 T$

Here, k_2 is a constant.

(iii) **Gay-Lussac's law** (Pressure-temperature relationship) According to this law, "at constant volume, pressure of a fixed amount of a gas varies directly with the temperature".

Mathematically, $p \propto T$ (at constant V and n)

or $\qquad p/T$ = constant = k_3

(iv) **Avogadro's law** (Volume-amount relationship) "Under the same conditions of temperature and pressure, equal volumes of all gases contain equal number of molecules, irrespective of the nature of the gas".

Mathematically,

$V \propto n$ (n = number of moles of the gas)

or $\qquad V = k_4 n$

Since, 1 mol = 6.022×10^{23} molecules

$= N_A$ molecules

(where, N_A = Avogadro's number)

5. **Density and Molar Mass of a Gaseous Substance**

The molar mass of a gas is given as:

$$M = \dfrac{d\,RT}{P}$$

where, d = density of gaseous substance.

6. **Ideal Gas Equation**

$$\boxed{pV = nRT}$$

This equation is called ideal gas equation and is applicable for all gases that behave ideally. It describes the state of any gas, so it is also called equation of state. This represents the simultaneous effect of temperature and pressure on the volume of a gas.

7. **Dalton's Law of Partial Pressures** According to this law, the total pressure exerted by the mixture of non-reactive gases is equal to the sum of the partial pressures of individual gases if they were enclosed separately in the same volume and under the same conditions of temperature.

$$p_{total} = p_1 + p_2 + p_3 + \ldots$$

Partial pressure of a gas

= mole fraction of the gas × total pressure

8. **Kinetic Gas Equation** On the basis of postulates of kinetic theory of gases, the following gas equation was derived.

$$pV = \dfrac{1}{3}mn\bar{u}^2$$

This equation is called kinetic gas equation.

where, p = pressure exerted by the gas

V = volume of the gas

n = number of molecules

$\bar{u}^2$ = root mean square velocity of the gas

9. **Behaviour of Real Gases : Deviation from Ideal Gas Behaviour** A gas which obeys gas law or the gas equation, $(pV = nRT)$ strictly for all the values of temperature and pressure is known as an **ideal gas** or a **perfect gas** but in actual behaviour, no real gas is ideal or perfect in this sense. Real gases are the commonly known gases like O_2, CO_2, H_2 and N_2 etc.

Real gases tend to show ideal behaviour, when temperature is raised above the boiling points of their liquefied forms and pressure is lowered. Real gases show deviation from gas laws at high pressure and low temperature

However, there is no gas that obeys the ideal gas equation under all conditions of temperature and pressure.
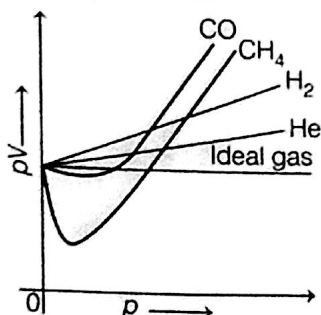
Plot of pV vs p for real gas and ideal gas

If a gas obeys Boyle's law perfectly, it would give a horizontal line showing that it obeys the law strictly. It can be seen in figure that at a constant temperature, the pV versus p plot for real gases is not a straight line, thus there is significant deviation from ideal behaviour.

van der Waals' equation,

$$\left(p + \frac{an^2}{V^2}\right)(V - nb) = nRT$$

where, a and b are van der Waals' constant, value of which depend upon the nature of the gas. This equation is known as van der Waals' equation.

Significance of van der Waals' constant
a is a measure of the magnitude of attractive forces whereas b is a measure of the effective size of the gaseous molecules.

10. **Liquefaction of Gases** A gas can be liquefied by increasing the intermolecular forces of attraction to such a large extent that they hold the gaseous molecules together to form the liquid state.

11. **Critical Constants** The phenomenon of converting a gas into liquid is known as liquefaction at particular temperature, pressure and volume. When a gas changes into liquid, these conditions are called critical conditions. e.g. Critical temperature,

$$T_c = \frac{8a}{27Rb}$$

Critical pressure, $p_c = \dfrac{a}{27b^2}$

Critical volume, $V_c = 3b$

12. **Liquid State** The state of matter in which the intermolecular forces of attraction are stronger enough to keep the molecules together, is called the liquid state.

13. **Physical Properties of Liquids**
    (i) **Vapour pressure** The pressure exerted by the vapour, present in equilibrium with a liquid in a closed vessel at a particular temperautre is known as vapour pressure.
    (ii) **Heat of vaporisation** (ΔH_v) The amount of heat required to change 1 mole of liquid into its vapours at the boiling point is called the heat of vaporisation of the liquid.
    (iii) **Surface tension** The force acting per unit length perpendicular to the line drawn on the surface of liquid is called the surface tension (γ).

    Surface tension,
    $$\gamma = \frac{\text{work } (W)}{\text{change in area } (\Delta A)} = \frac{\text{force } (F)}{\text{length } (l)}$$

    Its unit is kg s^{-2} and in SI unit, it is expressed as Nm^{-1}. The energy required to increase the surface area of the liquid by one unit is called the **surface energy** and has unit Jm^{-2}.

    Factors affecting surface tension
    (a) **Pressure** Surface tension increases with increase in external pressure because the force of attraction will increase.
    (b) **Temperature** Surface tension decreases with increase of temperature because kinetic energy increases and hence, intermolecular force of attraction decreases.

14. **Viscosity** It is a measure of resistance of flow which arises due to the internal friction between layers of fluid as they slip over one another. while liquid flows.

    or $$\eta = \frac{F\,dx}{A\,dv}$$

    where, η is the proportionality constant, known as **coefficient of viscosity**. Its unit is poise, or g cm^{-1} s^{-1}. In SI system, it is Pa.s or Nm^{-2}s or kg m^{-1}s^{-1}.

    Factors affecting viscosity
    (a) **Pressure** Viscosity increases with increase in pressure.
    (b) **Temperature** Viscosity of a liquid decreases with increase of temperature because kinetic energy increases and hence, intermolecular forces of attraction decreases.