DIELECTRIC PROPERTIES

Introduction

- Dielectrics are insulating materials. In dielectrics, all electrons are bound to their parent molecules and there are no free charges.
- Even with normal voltage or thermal energy electrons are not released.
- Dielectrics are non metallic materials of high specific resistance and have negative temperature coefficient of resistance.
- Dielectrics are electrical insulators. They possess high resistivity values within the range 10^6 Ωm to $10^{16}\Omega$m. Under high voltage bias, they allow very little current. They with stand for very high voltages. The conduction is mostly associated with ionic motion through defects or hopping of charges. They have no free charges. The electrical properties of a dielectric are associated with inherent property of possessing electric dipoles.
- Dielectrics are the materials having electric dipole moment permanently or temporarily by applying electric field. These are mainly used to store electrical energy and as electrical insulators. All dielectrics are electrical insulators. But all electrical insulators need not be dielectrics. For example the vacuum is a perfect insulator. But it is not a dielectric. The study of dielectrics is essentially study of insulators.

Basic Definitions

Electric dipole

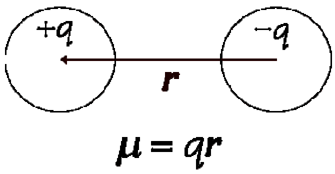


Fig.Electric dipole

Two equal and opposite charges separated by a distance ‘r’ constitute a dipole.

Electric dipole moment (μ)

The product of charge and distance between two charges is called electric dipole

moment.

$$\mu = q \times r\text{; Units: coulomb - meter or Debye; Debye} = 3.33 \times 10^{-30}\text{ coulomb - meter}$$

Non-polar dielectrics

Mono atomic materials are made up of atoms. The centre of gravity of negative charge and the centre of gravity of positive charge of an atom coincide. That means even though there are two equal and opposite charges are not separated.

Their dipole moment is zero.

$\because\ \mu = q \times r = q \times 0 = 0$

Such dielectrics are called Non- polar dielectrics.

Non-Polar Molecule

- Consider an atom. The positive charge of nucleus may be concentrated at a single point called as centre of gravity of the positive charge.
- The negative charge of electrons may be supposed to be concentrated at a single point called as Center of gravity of the positive charge.
- When the two centre of gravity coincide, the molecule is known as Non-polar molecule. The Non-polar molecules have symmetrical structure and zero electric dipole moment.
- Examples: H_2, N_2, O_2, CO_2, Benzene.

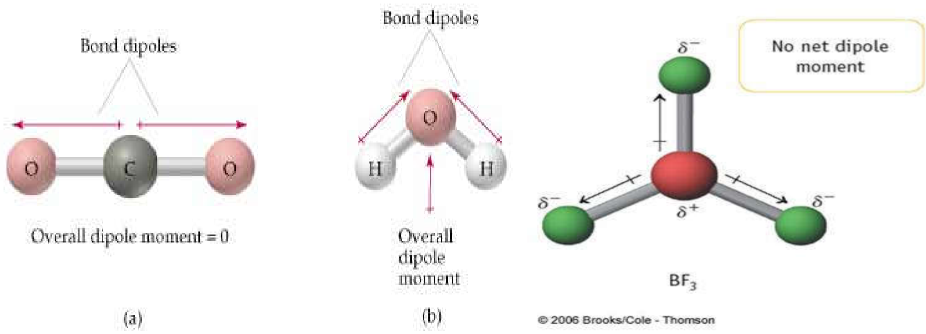


Fig. 5.2 Non polar molecules with zero dipole moment ***(μ=0)***

- The electric dipole moment has a direction from positive charge to negative charge.

Polar dielectrics

- In polyatomic molecules, the center of gravity of negative charge distribution may not coincide with the center of positive charge distributions.
- There is an effective separation between centers of negative and positive charge distributions.
- The molecule has a net dipole moment. Such dielectrics are called Polar dielectrics.

Polar Molecules

They have unsymmetrical structure and have a permanent electric dipole moment.

The Center of gravity of positive and negative charges do not coincide, the molecule is called as polar molecule.

e.g.:- H_2O, HCl, CO, NH_3 etc.

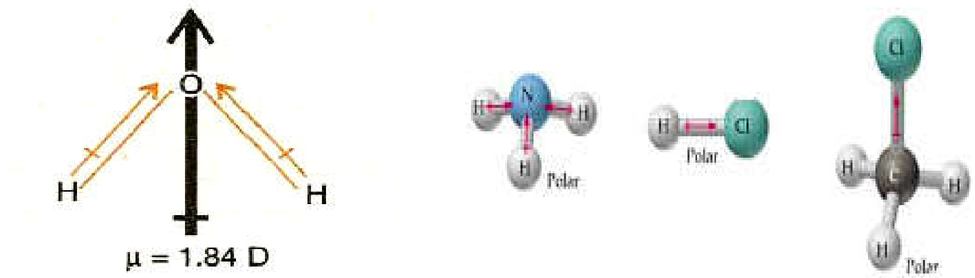


*Fig.5.3 Polar molecules with net dipole moment (**$\mu \neq 0$**)*

Dielectric constant $\in_r$ (or) Relative permittivity of the medium

- It is the ratio between the permittivity of the medium and the permittivity of free space.

$\epsilon_r = \frac{\epsilon}{\epsilon_0}$. It has no units.

- Єr is also called as relative permittivity of the medium. It is a measure of polarization in the dielectric material.

$\epsilon_r = \epsilon_0 \epsilon_r$ where Є = absolute permittivity of the medium

Where Єo = permittivity of free space=8.854 x 10^{-12} F/m

Electric Polarization

When a dielectric substance is placed in an electric field, then positive and negative charges are displaced in opposite direction.

- The displacement of charges produces local dipoles.
- This process of producing dipoles by the influence of electric field is called electric polarization.

$$\text{Dielectric Polarization} = P = \frac{\text{electric dipolemoment}}{\text{volume}}$$

$$P = \frac{\mu}{V}$$

$$P = \frac{q \times l}{A \times l} = \frac{q}{A}$$

$$P = \frac{\text{charge}}{\text{area}} = \text{surface charge density } \text{‘}\sigma\text{’}$$

Polarizability (α)

The average dipole moment μ is directly proportional to the electric field (E) applied.

$\mu \; \alpha \; E$

$\mu = \propto E$

$\propto = \text{Polarizability} = \frac{\mu}{E}$ Farad/m^2

Polarization Vector (P)

It is defined as the average dipole moment per unit volume of a dielectric. If 'N' molecules are present per unit volume,

Then polarization vector $\vec{P} = \frac{N\mu}{volume}$

$$\vec{P} = N\mu \text{ coulomb/m}^2$$

Electric flux density (or) Electric displacement (D)

The number of electric lines of forces received by unit area is called Electric flux density.

$$D \; \alpha \; E$$

$$D = \epsilon E$$

$$\text{But } \epsilon = \epsilon_0 \epsilon_r$$

$$D = \epsilon_0 \epsilon_r E$$

Electric Susceptibility (χ)

The electric susceptibility 'χ' is defined as the ratio of polarization vector to the applied electric field 'E'.

$$\chi = P/\epsilon_0 E$$

χ has no units.

$$\Rightarrow P = \chi \epsilon_0 E$$

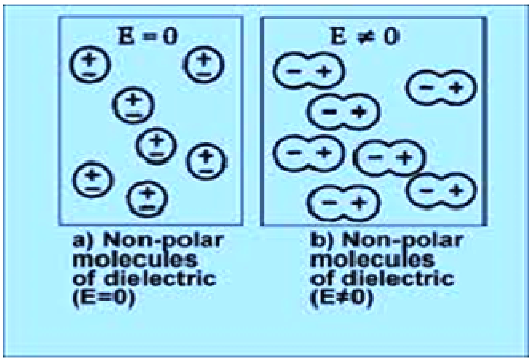
Where $\chi = \epsilon_r - 1$

Dielectric strength

It is defined as the minimum voltage required producing dielectric break down. Dielectric strength decreases with rising of temperature, humidity and age of the material.

Non-Polar Dielectric in an electric field

When a dielectric is placed in an electric field, say between the plates of a charged Condenser; the positive and negative charges are re oriented i.e. the center of gravity of positive charges is pulled towards the negative plate of the condenser and vice versa. Thus the net effect of the applied field is to separate the positive charges from the negative charges. This is known as Polarization of dielectric. The dielectrics which are polarized only when they are placed in an Electric field are called Non-polar dielectrics.



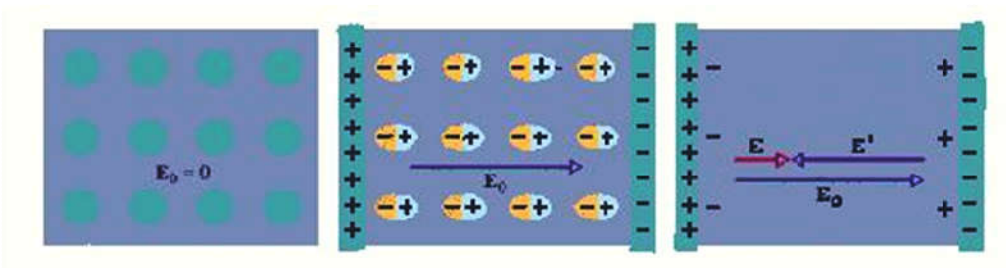


Fig. (a) non polar dielectric in E=0 (b) Non polar dielectric when 'E' is applied

(c) Totally polarized non polar dielectric with net field

Thus if the dielectric is placed in an electric field, induced surface charges appear which tend to weaken the original field with in the dielectric. That means E^1 opposes the original field E_o.

Polar dielectric in electric field

We know that polar dielectric have permanent dipole moments with their random orientations. In the presence of an electric field, the partial alignment of dipoles takes place.

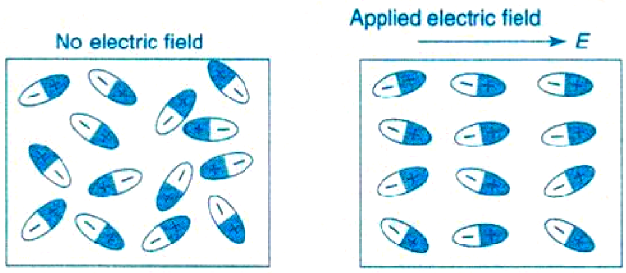


Fig.Polar dielectric orientation without field and with field.

Polar dielectrics already possess some dipole moment inside due to the presence of permanent atomic dipoles. But these are randomly oriented when no field is applied. Their dipole moment and polarization increases since dipoles align along the field direction gives some extra polarization. Hence

$$P = \left\{ \begin{array}{l} \text{Polarization already} \\ \text{Existing due to permanent} \\ \text{dipoles} \end{array} \right\} + \left\{ \begin{array}{l} \text{Polarization induced} \\ \text{due to electric} \\ \text{field} \end{array} \right\}$$

$$P = P_p + P_i$$

The Local field (or) Internal field E_i (or) E_{local}

Definition: In dielectric solids, the atoms or molecules experienced not only the external applied electric field but also the electric field produced by the dipoles. Thus the resultant electric field acting on the atoms or molecules of dielectric substance is called the "Local field or an internal field."

Derivation:

Consider a dielectric material placed in an External field 'E_1', placed between the parallel plates of a capacitor. As a result opposite type of charges are induced on the surface of dielectric.

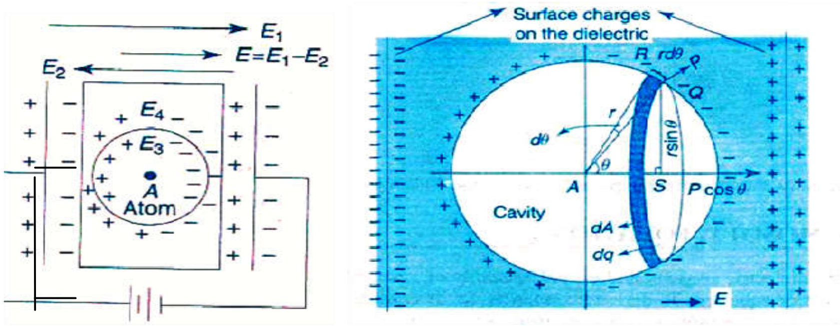


Fig. (a) Polar dielectric in electric field (b) Enlarged view of spherical cavity

Imagine a small spherical cavity of radius 'r'. In this sphere inside dipoles are present. Consider a dipole at the center of spherical cavity. This dipole experiences the following fields, in addition to the externally applied field 'E_1'.

The total internal field experienced by the dipole

$E_{local} = E_i = E_1 + E_2 + E_3 + E_4$ → (1)

Where E_1 = External applied field. Here,

(a) The field 'E_2' produced by induced charges on the dielectric sample near the surface.
(b) The field E_3 arising from dipoles inside the sphere. E_3depends on crystal symmetry. [For isotropic materials E_3=0]
(c) The field E_4 is due to polarization of charges on the surface of spherical cavity. It is called the Lorentz cavity field.

The surface charge density on the surface of the spherical cavity is $P\cos\theta$.

If 'ds' is the area of the surface element shaded in figure shown.

Then charge on the surface element (q_1) is

= (normal component of polarization) x (area of the surface element)

q_1= (Pcos θ) (ds) →(2)

Let a test charge q_2 = q placed at the center of cavity.

From coulombs' law, the force experienced between the surface charges.

$$dF = \frac{1}{4\pi}\frac{q_1 q_2}{r^2} dF = \frac{1}{4\pi\epsilon_0}\frac{(P\cos\theta ds).q}{r^2}$$

$$\frac{dF}{q} = \left[\frac{1}{4\pi\epsilon o}\right]\left[\frac{P\cos\theta ds}{r^2}\right] \rightarrow (3)$$

The resulting electric field $dE_4 = \frac{dF}{q} = \left[\frac{1}{4\pi\epsilon o}\right]\left[\frac{P\cos\theta ds}{r^2}\right] \rightarrow (4)$

The electric field is resolved into two components:

One component is along the direction of 'P' & other perpendicular to it.

The Perpendicular components cancel themselves out leaving only the horizontal components. Hence the sum of all such horizontal components of electric field for the whole Surface is:

$$E_4 = \int dE_4 \cos\theta = \int \frac{1}{4\pi\epsilon o}\frac{(P\cos\theta)(\cos\theta ds)}{r^2} \rightarrow (5)$$

The surface area of the ring ds = $2\pi r^2 \sin\theta d\theta \rightarrow (6)$

Substitute (6) in (5)

$$E_4 = \frac{1}{4\pi\epsilon o}\int \frac{P\cos^2\theta 2\pi r^2 \sin\theta d\theta}{r^2}$$

Limits are θ = 0 to π

$$E_4 = \frac{P}{2\epsilon o}\int_0^{\pi} \cos^2\theta d\theta \rightarrow (7)$$

Let cosθ = z

-sindθ = dz & Limits are z = 1 to z = -1

Equation (7) becomes $E_4 = \frac{P}{2\epsilon o}\int_1^{-1} z^2 (-dz)$

$$E_4 = \frac{-P}{2\epsilon 0}\int_{+1}^{-1} z^2 dz$$

$$= \frac{-P}{2\epsilon o}\left[\frac{z^3}{3}\right]_1^{-1} = \frac{+P}{3\epsilon o}$$

$$E_4 = \frac{P}{3\epsilon o} \rightarrow (8)$$

Substitute the value of E_4 in equation (1)

Total internal field (or) local field

$$E_i = E_{loc} = E_1 + E_2 + E_3 + E_4$$

$$\text{Here } E_3 = 0$$

$$\therefore E_i = E_1 + E_2 + E_4$$

$$\text{Let } E_1 + E_2 = E$$

$$\Longrightarrow \quad E_i = E + E_4$$

$$E_i = E + \frac{P}{3\epsilon_o}$$

Clausius – Mosotti relation

This makes the relation between microscopic & macroscopic quantities of Polarization. From Polarization Vector

$\vec{P} = N\mu \rightarrow (1)$

Where N = No. of molecules per unit volume, μ = average dipole moment

$$\mu = \alpha E = \alpha E_i \qquad \rightarrow (2)$$

Where E_i = local (or) internal field ~~$= \frac{P}{3\epsilon_o}$~~ $= E + \frac{P}{3\epsilon_o}$ →(3)

Substituting (2) & (3) in (1)

$$P = N\alpha E_i$$

$$P = N\alpha\left[E + \frac{P}{360}\right]$$

$$P = N\alpha E + \frac{N\alpha P}{3\epsilon o}$$

$$\left[P - \frac{N\alpha P}{3\epsilon o}\right] = N\alpha E$$

$$P\left[1 - \frac{N\alpha}{3\epsilon o}\right] = N\alpha E$$

$$P = \frac{N\alpha E}{\left[1 - \frac{N\alpha}{3\epsilon o}\right]} \qquad \text{———}(4)$$

We know that P= $\epsilon_0 \mathrm{E}[\epsilon_r - 1]$ → (5)

Equating (4) & (5)

$$\frac{N\alpha E}{\left(1-\frac{N\alpha}{360}\right)} = \epsilon_0 \mathrm{E}[\epsilon_r - 1]$$

$$\frac{N\alpha}{\epsilon_0[\epsilon_r-1]} = \left(1 - \frac{N\alpha}{3\epsilon_0}\right)$$

$$\frac{N\alpha}{\epsilon_0[\epsilon_r-1]} = 1 - \frac{N\alpha}{3\epsilon_0}$$

$$\frac{N\alpha}{\epsilon_0[\epsilon_r-1]} + \frac{N\alpha}{3\epsilon_0} = 1$$

$$1 = \frac{N\alpha}{3\epsilon_0}\left[\frac{3}{\epsilon_{r-1}} + 1\right]$$

$$1 = \frac{N\alpha}{3\epsilon_0}\left[\frac{3+\epsilon_r-1}{\epsilon_r-1}\right]$$

$$1 = \frac{N\alpha}{3\epsilon_0}\left[\frac{\epsilon_r+2}{\epsilon_r-1}\right]$$

$$\frac{\epsilon_r-1}{\epsilon_r+2} = \frac{N\alpha}{3\epsilon_0}$$

Types of Polarization

Polarization is the process of inducing dipole moment in a molecule. There are four types of polarization. They are:

(1) Electronic Polarization
(2) Ionic Polarization
(3)Orientation (or) Dipolar Polarization
(4) Space charge polarization
[illegible])

Electronic Polarization:

Definition:

When an electric field is applied on a dielectric material then all the positive nuclei of atoms move in the field direction and all the negative electron cloud of atoms move in opposite directions, hence dipoles are formed to produce dipole moment.

- The electron cloud readily shifts towards the positive end of the field. The extent of shift by electrons is proportional to field strength.
- Hence dipole moment is the product of charge and shift distance.

Expression for Electronic Polarizability α_e

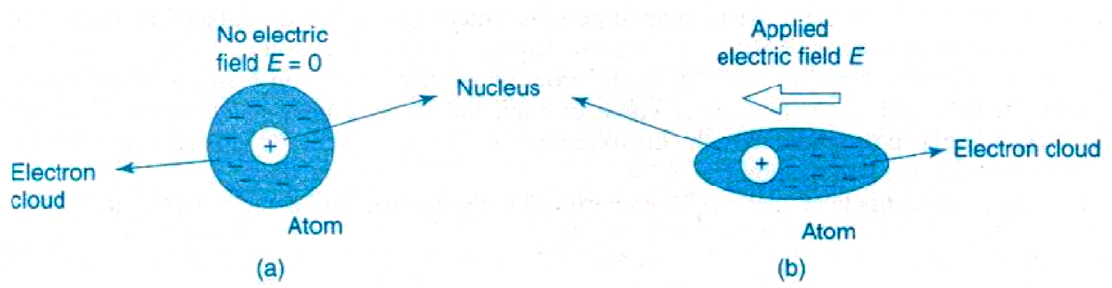


Fig. (a) Un polarized atom in the absence of field

(b)Electronic polarization due to distortion of electron cloud by the field E

- Consider an atom of dielectric material such that its atomic radius is 'R' & atomic number 'Z'. When no field is applied the charge centers of electron cloud and positive nucleus are at the same point & hence there is no dipole moment.
- Suppose an atom is placed in an electric field of strength E, due to Lorentz force the positive nucleus move towards the field direction and electron cloud will move in opposite direction of the field.
- When nucleus and electron cloud are displaced from their equilibrium positions, an attractive Coulomb force act between them to maintain original position. But Lorentz force will tend to separate them from them equilibrium position.
- When these forces are equal and opposite produces a net dipole moment.

Let the displacement between centers of nucleus and electron could be 'X'. Let 'ze' is charge of nucleus.

'-ze' is charge of electron cloud in a sphere of radius 'R'.

⟹ The charge density due to negative electron cloud of radius R (E=0) is

$$\rho = \frac{(-ze)}{(\frac{4}{3}\pi r^{3})}$$

$$\rho = \frac{-3}{4}\frac{ze}{\pi R^{3}} \qquad \rightarrow (1)$$

Lorentz force which tends to separate positive nucleus from negative electron cloud is

$$= (-ze)\, E \qquad \rightarrow (2)$$

Coulomb force which tends force of attraction between them is

$\Longrightarrow$ (ze) $\frac{[\,charged\ enclosed\ in\ sphere\ of\ radius\ x]}{4\pi \epsilon o x^2}$ $\longrightarrow$ (3)

But the charge enclosed in the sphere of radius 'x' due to electrons of radius 'x'

$$= \frac{4}{3}\pi x^3 \rho$$

$$= \frac{4}{3}\pi x^3 \left[\frac{-3}{4}\frac{ze}{\pi R^3}\right] \{from\ equation\ (1)\}$$

$$= \frac{-zex^3}{R^3} \qquad \longrightarrow (4)$$

Substitute equation (4) in (3) we get

$$\text{Coulomb force} = \frac{(ze)\left[\frac{-zex^3}{R^3}\right]}{4\pi \epsilon o x^2}$$

$$\text{Coulomb force} = \frac{-z^2e^2x}{4\pi \epsilon 0 R^3} \qquad \longrightarrow (5)$$

In equilibrium position coulomb & Lorentz forces are equal.

∴ Comparing equations (5) & (2) we get

$$\frac{-z^2e^2\,x}{4\pi \epsilon o R^3} = (\text{-ze})\ \text{E}$$

Hence electron cloud displacement 'x' = $\left[\frac{4\pi \epsilon o R^3}{ze}\right]$E $\longrightarrow$ (6)

The two charges (+ze) of nucleus & (-ze) of electron cloud are displaced through 'X'. Hence electric dipole moment is μ_e= | charge | ×(displacement)

= | ze | (X)

$$= (\text{ze})\left(\frac{4\pi \epsilon o R^3}{ze}\right)\text{E} \quad [i.e\ from\ equation\ (6)]$$

$$\mu_e = (4\pi \epsilon_0 R^3)\ \text{E} \ \longrightarrow (7)$$

We know that electronic polarizability

$$\alpha_e = \frac{dipole\ electric\ moment}{electric\ field}$$

$$\alpha_e = \frac{(4\pi R^3\ )E}{E} [i.e\ from\ equation\ (7)]$$

$\Longrightarrow$ Electronic Polarisability $\quad \alpha_e = 4\pi \epsilon_0 R^3$

Where R= radius of an atom.

Ionic Polarization

Ionic polarization takes place in ionic dielectrics due to displacement of positive and negative ions by the influence of external electric field.

Expression for Ionic Polarisability

When an electron field is applied on an ionic dielectric then positive ions move in the field direction & negative ions move in opposite direction, hence dipoles will be formed. This phenomenon is known as ionic polarization.

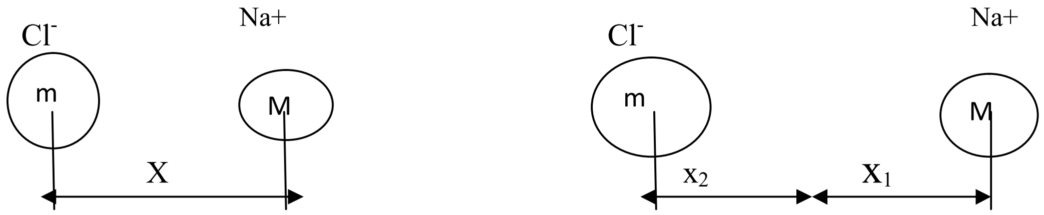


Fig. 5.9 (a) In the absence of field *Fig. 5.9(b) when field is applied*

Let 'e' the charge of ions and M and m be the masses of positive and negative ions respectively. When an electricfield 'E' is applied on an ionic dielectric then positive ions displaces in the field direction through x_1 distance and negative ion displaces in opposite direction through $x_2$distance.

The induced dipole moment

$$\mu = |\text{charge}| \times \text{displacement}$$

$$\mu = |e|\ (x_1 + x_2) \quad \rightarrow (1)$$

But against to the displacement of positive and negative ions, restoring force acts and opposes the displacements of cation and anion.

Under equilibrium conditions, the restoring force

$$F = k_1\, x_1 \quad \text{[for negative ion]}$$

$$F = k_2\, x_2 \quad \text{[for positive ion]}$$

$$\left.\begin{aligned} \Rightarrow x_1 &= \frac{F}{k_1} \\ x_2 &= \frac{F}{k_2} \end{aligned}\right\} \rightarrow (2)$$

where$k_1 k_2$ are force constants

But

$$\left.\begin{aligned} k_1 &= M\omega_0^2 \\ k_2 &= m\omega_0^2 \end{aligned}\right\} \rightarrow (3)$$

Where ω_0= angular velocity of the ions

Substituting (3) in (2) we get

Hence $x_1 = \frac{F}{M\omega_0^2}$ & $x_2 = \frac{F}{m\omega_0^2}$

But F = e E

$$\left.\begin{aligned} \Rightarrow x_1 &= \frac{eE}{M\omega_0^2} \\ x_2 &= \frac{eE}{m\omega_0^2} \end{aligned}\right\} \rightarrow (4)$$

Substituting equation (4) in equation (1)

$\Rightarrow$ Electric dipole moment

$$\mu = e[x_1 + x_2]$$

$$\mu = e\left[\frac{eE}{M\omega_0^2} + \frac{eE}{m\omega_0^2}\right]$$

$$\mu = \frac{e^2 E}{\omega_0^2}\left[\frac{1}{M} + \frac{1}{m}\right] \rightarrow (5)$$

We know that the Ionic Polarizability

$$\alpha_i = \frac{dipole\ moment}{electric\ field} = \frac{\mu}{E}$$

$$\alpha_i = \frac{\frac{e^2 E}{\omega_0^2}\left[\frac{1}{M} + \frac{1}{m}\right]}{E}$$

$$\alpha_i = \frac{e^2}{\omega_0^2}\left[\frac{1}{M} + \frac{1}{m}\right]$$

Here ω_0 = natural frequency of the ionic molecule.

Orientational Polarization

When Electric field is applied on a polar dielectric then all the dipoles tend to rotate in the field direction, hence dipole moment increases gradually. This phenomenon is known as dipolar (or) orientational polarization.

Expression for Orientational (or) Dipolar Polarizability

Orientation Polarisation takes place only in polar dielectrics in which dipoles orient in random manner such that the net dipole moment is zero. When Electric field is applied, all the dipoles try to rotate in the field direction as shown in the figure.

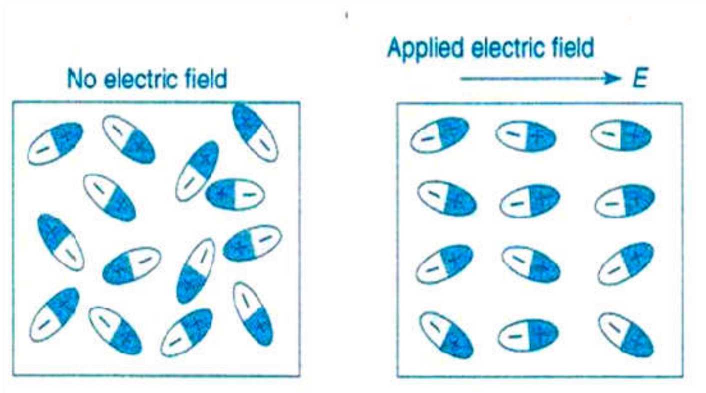


Fig. Orientational polarization

$$\alpha_d = \alpha_0 = \frac{\mu^2}{3K_BT}$$

α_0= Orientational (or) dipolar polarisability

μ= dipole moment

K_B= Boltzmann constant; T= absolute temperature.

The total polarizability, $\alpha = \alpha_e + \alpha_i + \alpha_0$

$$\alpha = \{4\pi\epsilon_0 R^3\} + \left\{\frac{e^2}{\omega_0^2}\left[\frac{1}{M} + \frac{1}{M}\right]\right\} + \left\{\frac{\mu^2}{3K_BT}\right\}$$