Dipole moment and polarization

An electrical dipole is an arrangement where two equal and opposite charges are held at very small distance to each other.

When any dielectric substances is kept inside any electric field then the effect of this field induces electrical dipoles in the material and try to align them into field direction. In addition to the generation of new electric dipoles, external field also try to align already existed dipoles and we have the combined effect. This total effect of an external electric field on any dielectric material is called polarization of the dielectric substance.

Any electrical dipole is characterized by its dipole moment which is the product of the magnitude of the charge and the separation between the centre of masses of +ve and –ve charges

hence dipole moment.

$$\vec{p} = q \vec{r}$$ …(1)

It is directed from negative to positive charge and hence it is a vector quantity. Its unit is debye (D).

where,

1 debye = $10^{-18}$ stat C. cm.

\[\approx 3.33 \times 10^{-30} \text{ C.m}\]

The electric dipole moment per unit volume is called polarization or polarization density \((\vec{\rho})\).

It is always directed from negative charge to positive charge.

If there are \(N\) atoms per unit volume than

$$\vec{\rho} = N\vec{p}$$ …(ii)
where \( \vec{p} \) is the electric dipole moment of individual atom.

The dielectric molecules become polarized when it is placed under some external electric field. The polarization vector (\( \vec{p} \)) is proportional to electric field experienced by the dielectric molecules so

\[ \vec{p} \propto \vec{E} \]

\[ \vec{p} = X \varepsilon_0 \vec{E} \] \( \text{...(iii)} \)

Where \( X \) is called the electrical susceptibility of the dielectric material. It is equal to the ratio of polarization per unit volume to electrical intensity in the dielectric.

Again, the net induced dipole moment (\( \vec{p} \)) of an atom of dielectric substance placed in an electric field is proportional to the applied field (\( \vec{E} \)) with its direction parallel to the field so that

\[ \vec{p} \propto \vec{E} \text{ or } \vec{p} = \alpha \vec{E} \] \( \text{...(iv)} \)

where \( \alpha \) is called atomic polarizability \( \left( \alpha = \frac{\vec{p}}{\vec{E}} \right) \).

Hence atomic polarizability is equal to the induced dipole moment for an atom when electric field of unit strength is applied on it.

\[ \alpha = \frac{p}{E} = \frac{c.m}{V.m^{-1}} = CV^{-1} m^2 = Fm^2 \]

so form (ii)

\[ \vec{p} = n \propto \vec{E} \] \( \text{...(v)} \)

As we know that polarization density

\[ p = \frac{\text{Total dipole moment}}{\text{Volume of dielectric step}} \]

\[ = \frac{qd}{sd} = \frac{q}{s} = \sigma_p \]

so

\[ p = \sigma_p \] \( \text{...(vi)} \)

When dielectric slab is placed inside a parallel plate capacitor, the effective electric field is reduced by
\[ E = \frac{\sigma - \sigma_p}{\varepsilon_0} = \frac{\sigma}{\varepsilon_0} - \frac{\sigma_p}{\varepsilon_0} \]

\[ \Rightarrow E = E_0 - \frac{\sigma_p}{\varepsilon_0} \quad \text{(or } E = E_0 - \frac{P}{\varepsilon_0} \text{)} \] ...(vii)

\[ \Rightarrow \varepsilon_0 E = \varepsilon_0 E_0 - \sigma_p \]

\[ \Rightarrow \varepsilon_0 E_0 = \varepsilon_0 E - \sigma_p \]

using (vi)

\[ \varepsilon_0 E_0 = \varepsilon_0 E - \varepsilon \]

But \( \varepsilon_0 E_0 \) is known as the electrical displacement vector \( D \), so

\[ D = \varepsilon_0 \dot{E} + \dot{P} \] ...(viii)

As

\[ \chi = \frac{\dot{p}}{\varepsilon_0 \dot{E}} \]

\[ \Rightarrow \dot{p} = \chi \varepsilon_0 \dot{E} \]

placing in above (vii)

\[ E = E_0 = \frac{\chi \varepsilon_0 E}{\varepsilon_0} = E_0 - \chi E \]

or

\[ \frac{E_0}{E} = 1 + \chi \]

\[ \Rightarrow k = 1 + \chi \] ...(ix)

where \( k = \frac{E_0}{E} \) is the dielectric constant of the dielectric material.