Dielectric Properties Of Materials

INTRODUCTION : Dielectric or electrical insulating materials are understood as the materials in which electrostatic fields can persist for a long time. These materials offer a very high resistance to the passage of electric current under the action of the applied direct-current voltage and therefore sharply differ in their basic electrical properties from conductive materials. Dielectric materials or insulators have the unique property of being able to store electrostatic charge. As well as appearing in a material in the presence of a field, dipoles may be present as a permanent feature of the molecular structure. Such dipoles are called permanent dipoles. Materials in which polarization effects are important are called dielectrics.

Coulomb's Law : The basic law of electrostatics is Coulomb's Law, which states that the electrostatic force (Attraction or Repulsion) acting between two point charges of magnitude q_1 and q_2 (in Coulomb) positioned at a distance of 'r' (meter) from each other in a homogeneous dielectric medium (Fig: 1) is equal to :

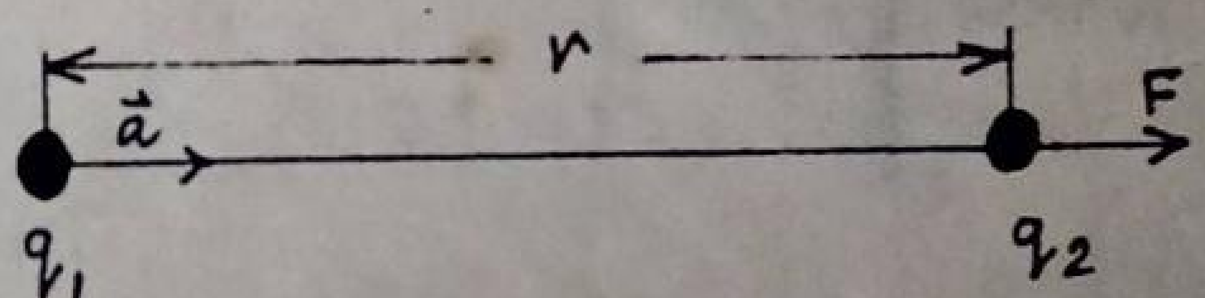

Fig: 1

$$\boxed{\vec{F} = \frac{q_1 q_2}{4\pi\epsilon r^2}\,\vec{a} \text{ Newton}} \quad --- (1)$$

ϵ = Permittivity of the medium in which they are embeded.

Parallel Plate Capacitor : When a parallel plate capacitor is subjected to a voltage 'V' as shown in fig-2., the total magnitude of a free charge across each plate of a capacitor is denoted by 'Q'. The charge 'Q' is proportional to the applied voltage between the plates of the capacitor, i.e

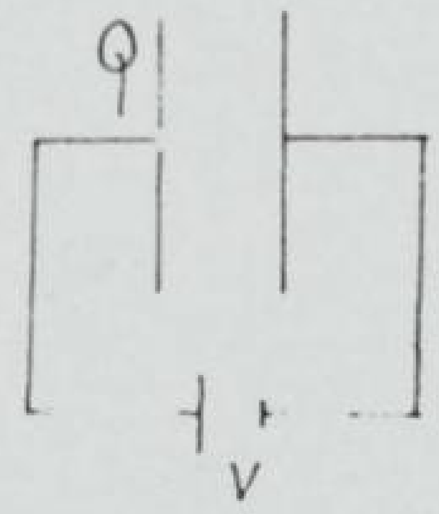

Fig-2.

$$Q \propto V$$

$$\boxed{\Rightarrow Q = CV} \quad \text{--- (2)}$$

C = Capacitance of the capacitor (Generally of a given insulation portion).

$$\Rightarrow C = \frac{Q}{V} = \frac{\text{Coulombs}}{\text{Volts}}$$

= Farad (Unit of measurement of capacitance)

The capacitance of a parallel plate capacitor (As shown in Fig-2) is proportional to the plate area, A, and is inversely proportional to the distance between the 2 plates d.

$$C \propto A \quad \text{and} \quad C \propto 1/d$$

In vacuum, the capacitance C_0 is

$$\boxed{C_0 = \epsilon_0 \frac{A}{d}} \quad \text{---- (3)}$$

where ϵ_0 is the permittivity of vacuume and a constant

$$\boxed{\begin{aligned} \epsilon_0 &= \frac{1}{36\pi} \times 10^{-9}\ \text{F/m.} \\ &= 8{\cdot}85 \times 10^{-12}\ \text{F/m.} \end{aligned}}$$

As, $\epsilon_0 = C_0 \frac{d}{A}$ = Farad. $\frac{\text{meter}}{\text{meter}^2}$

= Farad/meter

(Unit of dielectric constant or permittivity)

If a dielectric material is inserted into the plate (As shown in Fig-3), the capacitance of the capacitor increases from C_0 to C and it may be expressed as

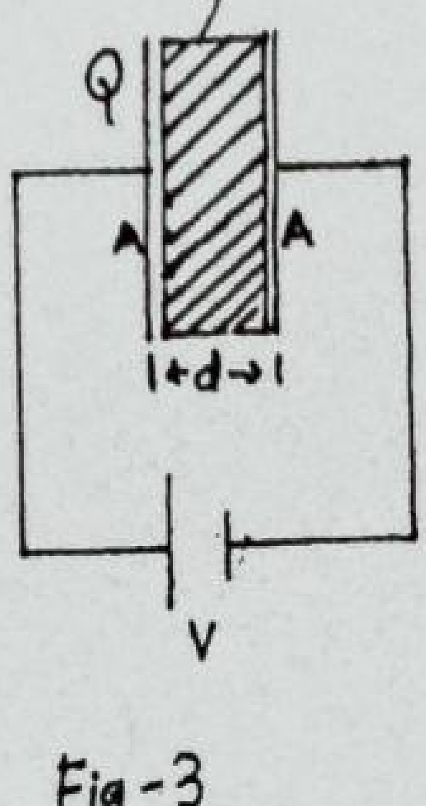

Fig-3

$$\boxed{C = \epsilon \frac{A}{d}} \quad \text{---- (4)}$$

where ϵ = Permittivity of that material.

Relative Permittivity : The relative permittivity 'ϵ_r' is the ratio of the permittivity of the dielectric material to the permittivity of vacuum. Using Eq.(3) and (4),

$$\epsilon_r = \frac{\epsilon}{\epsilon_0} = \frac{C}{C_0}$$

If ~~we recall the equation~~ (4)

$$C = \epsilon \frac{A}{d} = \epsilon_0 . \frac{\epsilon}{\epsilon_0} . \frac{A}{d} = \epsilon_0 \epsilon_r \frac{A}{d} \quad --- (5)$$

Then ϵ_r is known as the Relative permittivity or ~~Relative~~ Dielectric constant, of ~~that material which is used as the medium between 2 parallel plate capacitor~~. is a measure of the increase in the charge storage capacity of condenser in the presence of a dielectric medium between the condenser plates.)

From equation (5) & (3)

$$C = \epsilon_r \epsilon_0 \frac{A}{d}$$
$$= \epsilon_r C_0 \quad --- (6)$$

This means that the inserted dielectric material has increased the capacity by a factor of ϵ_r.

For a capacitor containing 'n' parallel conductor plates

$$C_n = \epsilon_r \epsilon_0 (n-1) \frac{A}{d} \quad --- (7)$$

This equation (7) represents that, in order to built a capacitor with high capacity, many plates are needed which have a large surface area. A small separation between the plates and a dielectric material with high permittivity and high dielectric strength are required also.

Electric Field Intensity : Intensity of an electric field due to a charge 'q' may be defined as the force experienced by a test unit positive charge ~~of magnitude q~~ at a distance 'r' and ~~set up by a point charge of magnitude 'q' at a distance 'r'~~ is given by

$$\boxed{\vec{E} = \frac{q}{4\pi\epsilon r^2}\vec{a}} \quad \frac{\text{Volt}}{\text{meter}} \quad ----- (8)$$

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Electric Displacement Field

When a dielectric material is placed in an electric field already existing in a homogeneous medium such as air, it has the effect of changing the distribution of the field to a degree depending upon its relative permittivity, as shown in equation (8). That is, the electric field intensity is a function of the medium in which it exists. The situation can be represented mathematically by defining an <u>electric flux density</u> or <u>electric displacement field</u> $\vec{D}$, in the dielectric by the equation

$$\boxed{\vec{D} = \epsilon \vec{E}} \quad ----(9)$$

Combining equation (8) and (9)

$$\boxed{\vec{D} = \frac{q}{4\pi r^2}\,\vec{a}} \quad ----(10)$$

Since 'ϵ' does not appear in equation (10), the flux density arising from a point charge 'q', is independent of the medium and is a function of the charge and its position only.

If we take q to be at the centre of a sphere (as shown in Fig.-4) of radius 'r', the flux density will be the same at all points on the surface.

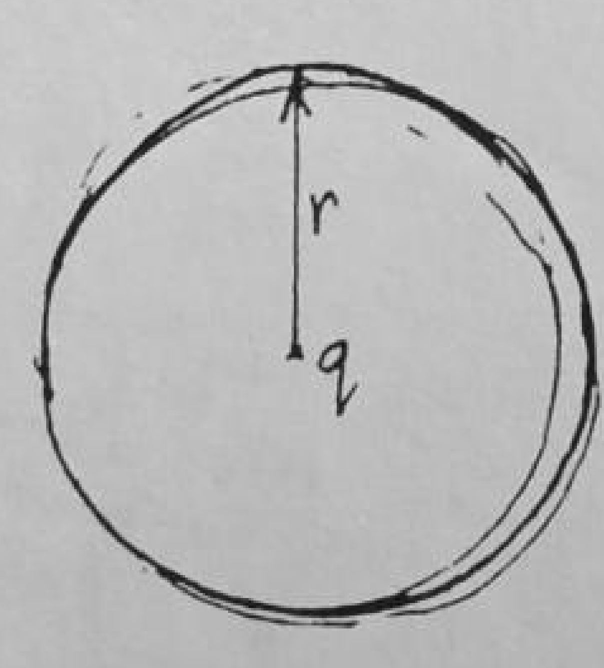

Fig-4

The total flux $\Psi = \frac{q}{4\pi r^2} \cdot \vec{a} \cdot 4\pi r^2$

$= q \cdot \vec{a}$

So, from equation (10) it is seen that the electrical displacement field or electrical flux Density $\vec{D}$ <u>can be define as the total flux crossing per unit area of the sphere surface with a charge at it's centre.</u>

Consider 2 metal plates of area A separated in vacuum by a distance d and having a battery (applied Voltage) 'V' connected across them (Fig-5). The electric field E between the plates is directed as shown and has a magnitude V/d Volt/meter arising from the charge density ±Q on the ~~field~~ plates.

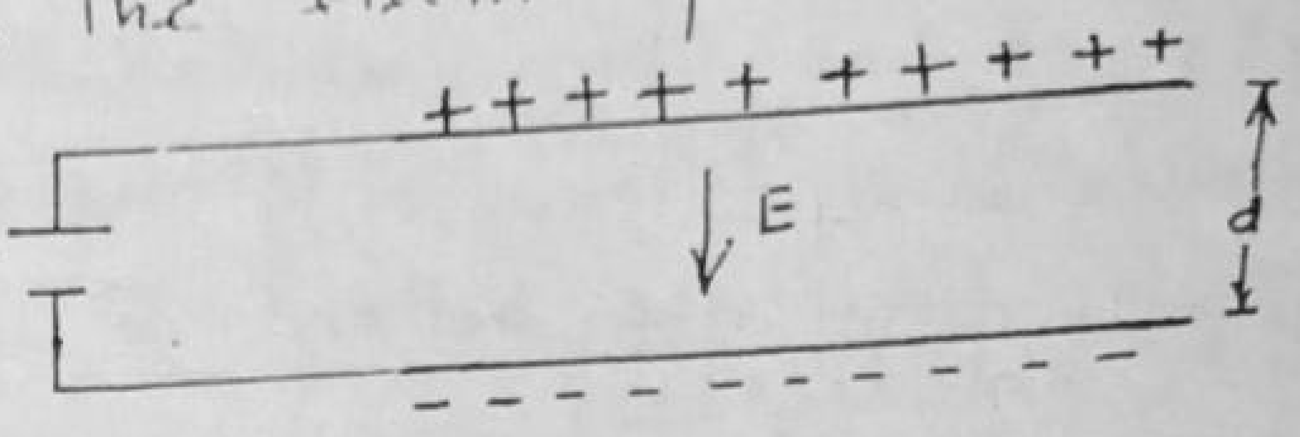

Fig-5

The relationship between Q and the field E is obtained by introducing a dimensional factor ϵ_0, the permittivity of vacuum.

$$\boxed{\cancel{D}\,Q = \epsilon_0 E} \quad ---- (11)$$

If we consider Q as a source of electric flux lines in the space between the plates, the density of these flux lines is called the electric displacement field $\vec{D}$.

So, $$\boxed{\vec{D} = \cancel{Q} = \epsilon_0 \vec{E}} \quad ---- (12)$$

Let us consider that with the battery still connected, a dielectric medium is introduced so as to just fit the space between the plates (As shown in Fig-6). The medium becomes polarized by the field E and dipoles appear throughout the material, lined up in the direction of the field. All dipole ends of opposite charge inside the material will cancel but there will be an uncompensated surface charge, negative at the top and positive at the bottom.

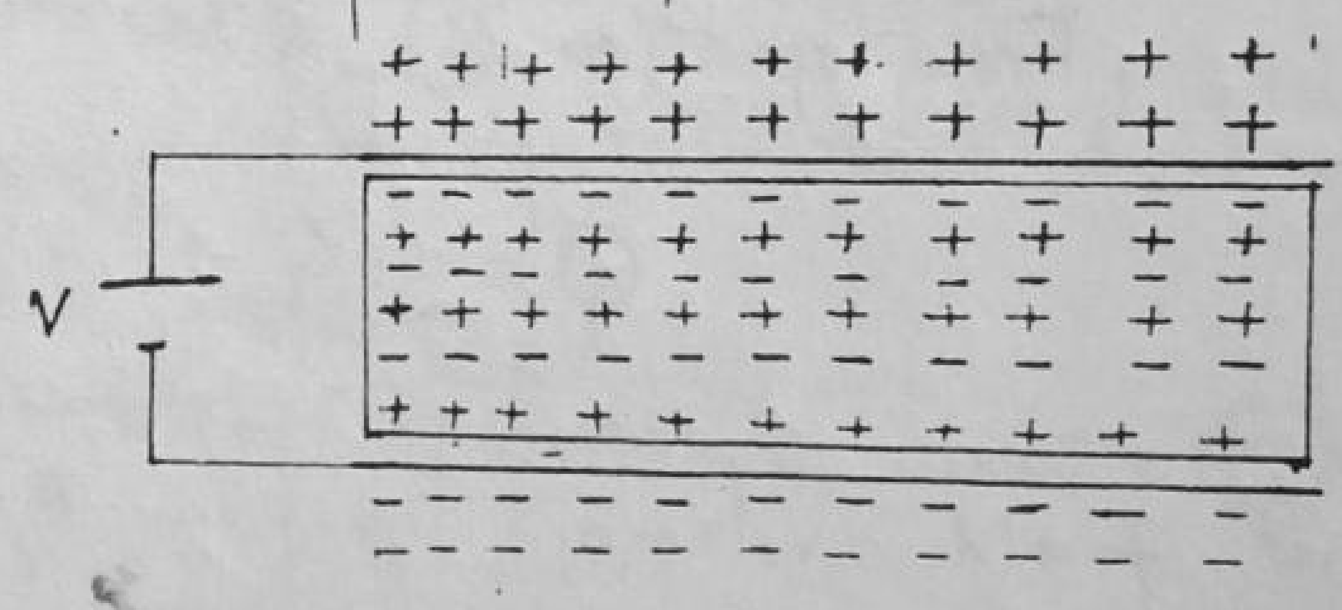

Fig-6

These surface charges will attract and hold corresponding charges of opposite sign on the plates, because the latter, unlike dipoles, are able to move freely. The field between the plates must be that appropriate to the voltage applied, irrespective of whether a dielectric is present or not. Thus the field in the dielectric must still be 'E'. If the effect of some of the original surface charges has been neutralized by being bound to surface dipoles ends, 'E' can only be maintained if more charges flow from the battery to make up for those which have become bound. There is now more charge density 'Q'' on the plates some of which is tied up and is not contributing to the field 'E' in the dielectric.

So, the capacitance of the plate increases.

Therefore, $\boxed{C > C_0}$ or $\boxed{\frac{C}{C_0} > 1}$

For same plate area 'A' and inter plate distance 'd'.

$$\boxed{\epsilon > \epsilon_0} \quad \text{i.e} \quad \boxed{\frac{\epsilon}{\epsilon_0} > 1}$$

$$\boxed{\epsilon_r > 1}$$

Now, the amount of charge that is contributing to the field is the same as before, and the total charge

$$\boxed{Q' = Q + Q_B} \quad \text{----} \ (13)$$

Q_B = Bound charge density
Q = Free charge density.

From equation (6) Q has been multiplied by a factor ϵ_r such that –

$$Q' = \epsilon_r Q \quad \text{----} \ (14)$$

From equation (12) and (14) $\vec{D}$, the electric displacement field, is now given by

$$\boxed{D' = \epsilon_r \epsilon_0 E} \quad \text{---} \ (15)$$

From, equation (13) and (15) finally we get,

$$\boxed{D' = \epsilon_0 E + Q_B} \quad \text{----} \ (16)$$

Where $\underline{D' = Q' = \epsilon_r Q}$.

The bound charge density is called the polarization 'P'

$$\boxed{D' = \epsilon_0 E + P} \quad ---- (17)$$

From equation (12) and (17), the electric displacement field of the Capacitor with dielectric material will becomes,

$$\boxed{D' = D + P} \quad ---- (18)$$

The Polarization P is identical with the dipole moment per unit volume..

Let, a block of dielectric having a bound charge Q_B per unit area on opposite faces of area 'A', a distance 'd' apart as shown in fig-7. The total dipole moment

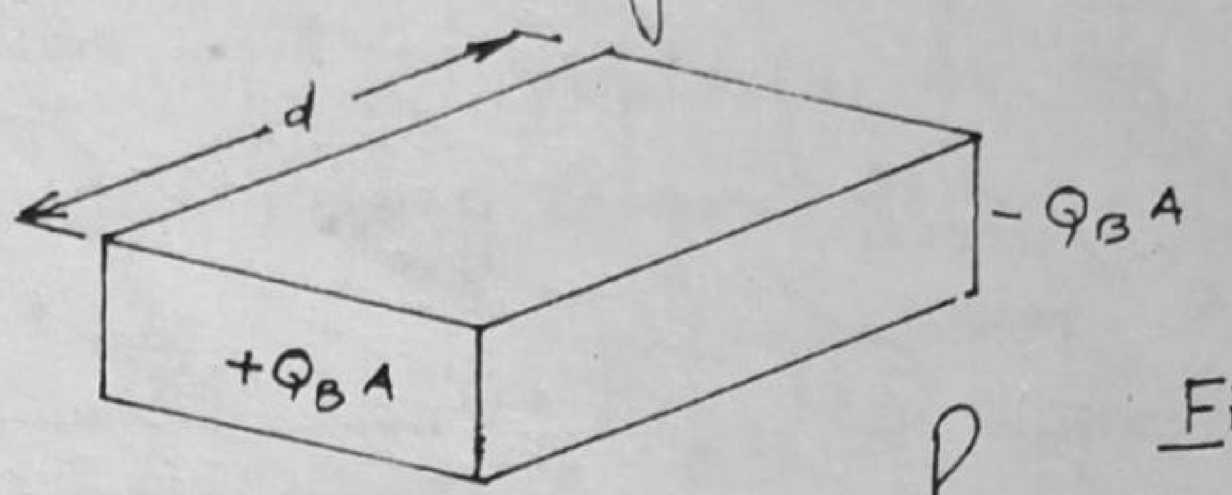

Fig-7

$$\left.\begin{aligned} \text{The total dipole moment} &= \overset{P}{\cancel{Q_B}} \cdot A \cdot d \\ &= \overset{P}{\cancel{Q_B}} \cdot \text{Volume} \end{aligned}\right] ---- (18a)$$

i.e. the surface bound charge density Q_B equals the dipole moment per unit volume P.