

Semester- 2
PHYCC203: Electricity and Magnetism
Unit- 1

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Dielectric Properties of Matter

Dielectric:

Dielectric is an insulating material or a very poor conductor of electric current. When dielectrics are placed in an electric field, practically no current flows in them because, unlike metals, they have no loosely bound, or free, electrons that may drift through the material. Instead, electric polarization occurs. The positive charges within the dielectric are displaced minutely in the direction of the electric field, and the negative charges are displaced minutely in the direction opposite to the electric field. This slight separation of charge, or polarization, reduces the electric field within the dielectric.

The presence of dielectric material affects other electrical phenomena. The force between two electric charges in a dielectric medium is less than it would be in a vacuum, while the quantity of energy stored in an electric field per unit volume of a dielectric medium is greater. The capacitance of a capacitor filled with a dielectric is greater than it would be in a vacuum. The effects of the dielectric on electrical phenomena are described on a large, or macroscopic scale by employing such concepts as dielectric constant, permittivity, and polarization.

Dielectric constant

Dielectric constant is the property of an electrical insulating material (a dielectric) equal to the ratio of the capacitance of a capacitor filled with the given material to the capacitance of an identical capacitor in a vacuum without the dielectric material. The insertion of a dielectric between the plates of, say, a parallel-plate capacitor always increases its capacitance, or ability to store opposite charges on each plate, compared with this ability when the plates are separated by a vacuum. If C is the value of the capacitance of a capacitor filled with a given dielectric and C_0 is the capacitance of an identical

capacitor in a vacuum, the dielectric constant, symbolized by the Greek letter kappa, κ , is simply expressed as

$$\kappa = C/C_0$$

The dielectric constant is a number without dimensions. It denotes a large-scale property of dielectrics without specifying the electrical behaviour on the atomic scale. The value of the static dielectric constant of any material is always greater than one, its value for a vacuum. The value of the dielectric constant at room temperature (25° C, or 77° F) is 1.00059 for air, 2.25 for paraffin, 78.2 for water, and about 2,000 for barium titanate (BaTiO₃) when the electric field is applied perpendicularly to the principal axis of the crystal. Because the value of the dielectric constant for air is nearly the same as that for a vacuum, for all practical purposes air does not increase the capacitance of a capacitor. Dielectric constants of liquids and solids may be determined by comparing the value of the capacitance when the dielectric is in place to its value when the capacitor is filled with air.

The dielectric constant is sometimes called relative permittivity or specific inductive capacity. In the centimetre–gram–second system the dielectric constant is identical to the permittivity.

Permittivity

Permittivity is the constant of proportionality that relates the electric field in a material to the electric displacement in that material. It characterizes the tendency of the atomic charge in an insulating material to distort in the presence of an electric field. The larger the tendency for charge distortion (also called electric polarization), the larger the value of the permittivity. The permittivity of an insulating, or dielectric, material is commonly symbolized by the Greek letter epsilon, ϵ ; the permittivity of a vacuum, or free space, is symbolized ϵ_0 ; and their ratio ϵ/ϵ_0 , called the dielectric constant, is symbolized by the Greek letter kappa, κ .

In the rationalized metre-kilogram-second (mks) and SI systems, the magnitude of the permittivity of a vacuum ϵ_0 is 8.854×10^{-12} . Its units and those of permittivity ϵ are square coulombs per newton square metre. In the mks system, permittivity ϵ and the dimensionless dielectric constant κ are formally distinct and related by the permittivity of free space ϵ_0 ; $\epsilon = \kappa\epsilon_0$. In the centimetre-gram-second (cgs) system, the value of the permittivity of free space ϵ_0 is chosen arbitrarily to be 1. Thus, the permittivity ϵ and the dielectric constant κ in the cgs system are identical; both of them are dimensionless numbers.

Electric Polarization

Electric polarization is the slight relative shift of positive and negative electric charge in opposite directions within an insulator, or dielectric, induced by an

external electric field. Polarization occurs when an electric field distorts the negative cloud of electrons around positive atomic nuclei in a direction opposite the field. This slight separation of charge makes one side of the atom somewhat positive and the opposite side somewhat negative. In some materials whose molecules are permanently polarized by chemical forces, such as water molecules, some of the polarization is caused by molecules rotating into the same alignment under the influence of the electric field. One of the measures of polarization is electric dipole moment, which equals the distance between the slightly shifted centres of positive and negative charge multiplied by the amount of one of the charges. Polarization P in its quantitative meaning is the amount of dipole moment p per unit volume V of a polarized material, $P = p/V$.

Polarization or dielectric polarization

Consider a dielectric placed in an external electric field E_0 (say between the plates of a charged capacitor). Due to external field, there will be shifting of the centres of gravity of positive and negative charges. The positive charges are displaced in the direction of the applied field whereas the negative charges will get displaced in a direction opposite to the applied field E_0 . Therefore, the positive charge is induced on one surface while negative charge on other.

This phenomenon of appearance of the charge on the surfaces of dielectric induced by the external electric field is called polarization or dielectric polarization.

The charge on the plates of the capacitor is called free charge and charge induced on the surfaces of the dielectric is called bound charge.

We can also say that when the atoms are placed in an electric field, they acquire an induced electric dipole moment in the direction of the field. This process is called the dielectric polarization and atoms are said to be **polarized**. The induced dipole moment p is proportional to applied electric field E , that is, p proportional to E

$$p = \alpha E$$

where α is proportionality constant known as molecular or atomic polarizability of dielectric.

Also, the induced surface charges appear in such a way that the electric field E_p set up by them opposes the external field E_0 . The resultant field will be

$$E = E_0 - E_p$$

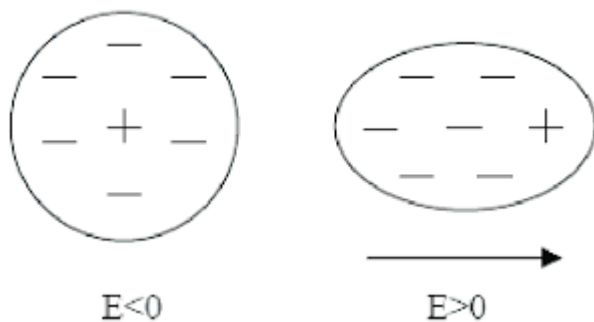
Types of Polarization:

The four types of polarization which occur in dielectrics are:

- Electronic polarization,
- Ionic polarization,
- Orientation or dipole polarization,
- Space charge or interfacial polarization

Electronic polarization:

Electronic polarization occurs due to displacement of the centre of the negatively charged electron cloud relative to the positive nucleus of an atom by the electric field. Example: Monoatomic gases exhibit only electronic polarization.



The shifting of electron cloud results in dipole moment and dipole moment p is defined as the product of the charge and shift distance,

$$\mathbf{p} = qd$$

Dipole moment p is also directly proportional to electric field strength; E thus p is proportional to E

$$\mathbf{p} = \alpha_e \mathbf{E}$$

where α_e is constant of proportionality known as electronic polarizability constant.

Electronic polarization \mathbf{P}_e is given as

$$\mathbf{P}_e = n\mathbf{p}$$

where n is number of molecules per unit volume.

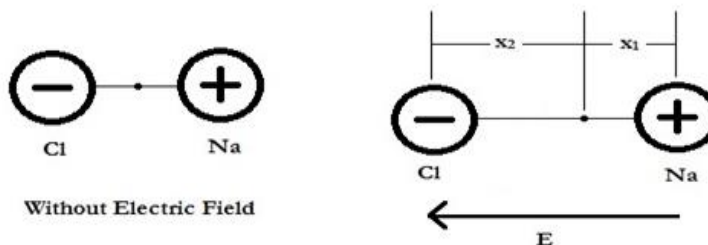
By putting value of p in above equation, we get

$$\mathbf{P}_e = n \alpha_e \mathbf{E}$$

This polarization is independent of temperature.

Ionic polarization :

Ionic polarization occurs in ionic materials. It occurs when an electric field is applied to an ionic material then cations and anions get displaced in opposite directions giving rise to a net dipole moment. This type of polarization typically occurs in ionic crystal elements such as NaCl, KCl, and LiBr. There is no net polarization inside these materials in the absence of an external electric field because the dipole moments of the negative ions are canceled out with the positive ions. However, when an external field is applied, the ions become displaced, which leads to an induced polarization. Example: Polyatomic gases. In absence of electric field E , the distance between the ions is d but in presence of electric field, distance between the ions increases.



The dipole moment \mathbf{p} for each ion pair is equal to the product of charge on each ion and relative displacement.

$$\mathbf{p} = qd$$

Thus ionic polarization is given as

$$\mathbf{P}_i = n \alpha_i \mathbf{E}$$

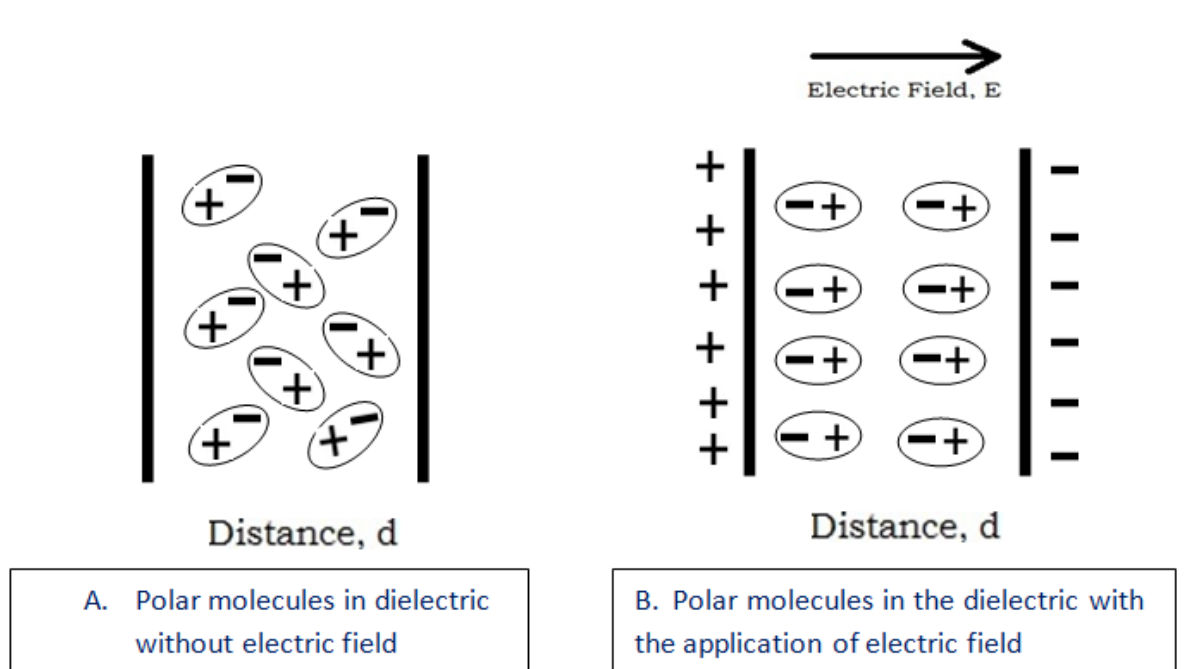
where α_i is constant of proportionality known as ionic polarizability constant. This polarization is independent of temperature.

Orientation polarization:

It occurs with molecules that have permanent dipole moments. These molecules are partially aligned by the field and contribute heavily to the polarization.

Materials such as HCl and H₂O will have a net permanent dipole moment because the charge distributions of these molecules are skewed. For example, in a HCl molecule, the chlorine atom will be negatively charged and the hydrogen atoms will be positively charged causing the molecule to be dipolar. The dipolar nature of the molecule should cause a dipole moment in the material, however, in the absence of an electric field, the dipole moment is canceled out by thermal agitation resulting in a net zero dipole moment per molecule. When an electric field is applied however, the molecule will begin to rotate to align the molecule with the field, causing a net average dipole moment per molecule.

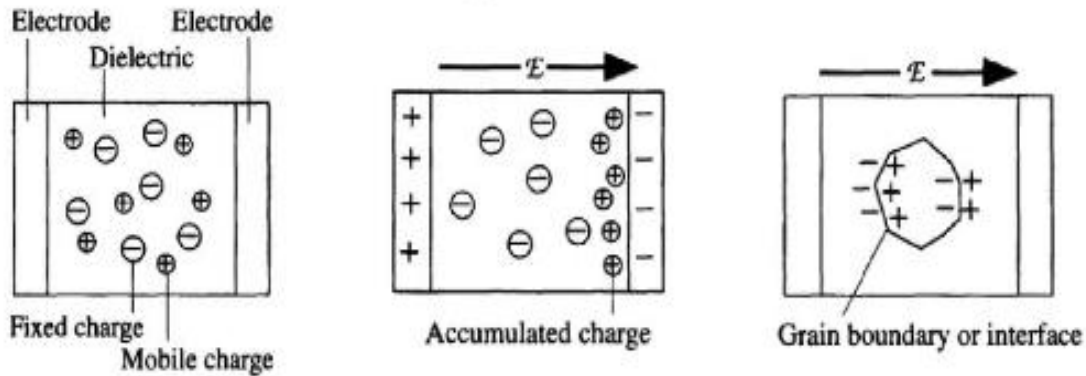
Thus, the dielectric constant of a nonpolar liquid, such as a hydrocarbon, is about 2, that of a weakly polar liquid, such as chloroform or ethyl ether, about 5, while those of highly polar liquids, such as ethanol and water, range from 25 to 80.



Interfacial Polarization:

Interfacial or space charge polarization occurs when there is an accumulation of charge at an interface between two materials or between two regions within a material because of an external field. This can occur when there is a compound dielectric, or when there are two electrodes connected to a dielectric material. This type of electric polarization is different from orientational and ionic polarization because instead of affecting bound positive and negative charges i.e. ionic and covalent bonded structures, interfacial polarization also affects free charges as well. As a result interfacial polarization is usually observed in

amorphous or polycrystalline solids. The electric field will cause a charge imbalance because of the dielectric material's insulating properties. However, the mobile charges in the dielectric will migrate over maintain charge neutrality. This then causes interfacial polarization.



Electric susceptibility:

It is the quantitative measure of the extent to which an electric field applied to a dielectric material causes polarization, the slight displacement of positive and negative charge within the material. For most linear dielectric materials, the polarization P is directly proportional to the average electric field strength E so that the ratio of the two, P/E , is a constant that expresses an intrinsic property of the material. The electric susceptibility, χ_e , in the centimetre-gram-second (cgs) system, is defined by this ratio; that is,

$$\chi_e = P/E$$

In the metre-kilogram-second (mks) system, electric susceptibility is defined slightly differently by including the constant permittivity of a vacuum, ϵ_0 , in the expression; that is,

$$\chi_e = P/(\epsilon_0 E)$$

In both systems the electric susceptibility is always a dimensionless positive number. Because of the slight difference in definition, the value of the electric susceptibility of a given material in the mks system is 4π times its value in the cgs system.

The amount of charge stored in a capacitor is the product of the voltage and the capacity. The voltage can be increased, but electric breakdown will occur if the electric field inside the capacitor becomes too large. The capacity can be increased by expanding the electrode areas and by reducing the gap between the

electrodes. In general, capacitors that can withstand high voltages have a relatively small capacity. If only low voltages are needed, however, compact capacitors with rather large capacities can be manufactured. One method for increasing capacity is to insert between the conductors an insulating material that reduces the voltage because of its effect on the electric field. Such materials are called dielectrics (substances with no free charges). When the molecules of a dielectric are placed in the electric field, their negatively charged electrons separate slightly from their positively charged cores. With this separation, referred to as polarization, the molecules acquire an electric dipole moment. A cluster of charges with an electric dipole moment is often called an electric dipole.

There is an electric force between a charged object and uncharged matter, such as a piece of wood. The force is attractive. The reason is that under the influence of the electric field of a charged object, the negatively charged electrons and positively charged nuclei within the atoms and molecules are subjected to forces in opposite directions. As a result, the negative and positive charges separate slightly. Such atoms and molecules are said to be polarized and to have an electric dipole moment. The molecules in the wood acquire an electric dipole moment in the direction of the external electric field. The polarized molecules are attracted toward the charged object because the field increases in the direction of the charged object.

The electric dipole moment \mathbf{p} of two charges $+q$ and $-q$ separated by a distance l is a vector of magnitude $p = ql$ with a direction from the negative to the positive charge. An electric dipole in an external electric field is subjected to a torque

$$\tau = pE \sin \theta$$

where θ is the angle between \mathbf{p} and \mathbf{E} .

The torque tends to align the dipole moment \mathbf{p} in the direction of \mathbf{E} . The potential energy of the dipole is given by

$$U_e = -pE \cos \theta$$

or in vector notation

$$U_e = -\mathbf{p} \cdot \mathbf{E}.$$

In a nonuniform electric field, the potential energy of an electric dipole also varies with position, and the dipole can be subjected to a force. The force on the dipole is in the direction of increasing field when \mathbf{p} is aligned with \mathbf{E} , since the potential energy U_e decreases in that direction.

The polarization of a medium \mathbf{P} gives the electric dipole moment per unit volume of the material; it is expressed in units of coulombs per metre square. When a dielectric is placed in an electric field, it acquires a polarization that depends on the field. The electric susceptibility χ_e relates the polarization to the electric field as $\mathbf{P} = \chi_e \mathbf{E}$. In general, χ_e varies slightly depending on the strength

of the electric field, but for some materials, called linear dielectrics, it is a constant. The dielectric constant κ of a substance is related to its susceptibility as

$$\kappa = 1 + \chi_e / \epsilon_0$$

It is a dimensionless quantity.

The presence of a dielectric affects many electric quantities. A dielectric reduces by a factor K the value of the electric field and consequently also the value of the electric potential from a charge within the medium. The insertion of a dielectric between the electrodes of a capacitor with a given charge reduces the potential difference between the electrodes and thus increases the capacitance of the capacitor by the factor K . For a parallel-plate capacitor filled with a dielectric, the capacity becomes $C = K\epsilon_0 A/d$. A third and important effect of a dielectric is to reduce the speed of electromagnetic waves in a medium by the factor \sqrt{K} .

Electric displacement

Electric displacement is the auxiliary electric field or electric vector that represents that aspect of an electric field associated solely with the presence of separated free electric charges, purposely excluding the contribution of any electric charges bound together in neutral atoms or molecules. If electric charge is transferred between two originally uncharged parallel metal plates, one becomes positively charged and the other negatively charged by the same amount, and an electric field exists between the plates. If a slab of insulating material is inserted between the charged plates, the bound electric charges comprising the internal structure of the insulation are displaced slightly, or polarized; bound negative charges (atomic electrons) shift a fraction of an atomic diameter toward the positive plate, and bound positive charges shift very slightly towards the negative. This shift of charge, or polarization, reduces the value of the electric field that was present before the insertion of the insulation. The actual average value of the electric field E , therefore, has a component P that depends on the bound polarization charges and a component D , electric displacement, which depends on the free separated charges on the plates. The relationship among the three vectors D , E , P in the metre-kilogram-second (mks) or SI system is:

$$D = \epsilon_0 E + P$$

ϵ_0 is a constant, the permittivity of a vacuum.

In the centimetre-gram-second (cgs) system the relationship is:

$$D = E + 4\pi P.$$

The value of the electric displacement D may be thought of as equal to the amount of free charge on one plate divided by the area of the plate. From this point of view D is frequently called the electric flux density, or free charge surface density, because of the close relationship between electric flux and electric charge. The dimensions of electric displacement, or electric flux density, in the metre-kilogram-second system are charge per unit area, and the units are coulombs per square metre. In the centimetre-gram-second system the dimensions of D are the same as those of the primary electric field E , the units of which are dynes per electrostatic unit, or statvolts per centimetre.

Relation between \mathbf{E} , \mathbf{P} and \mathbf{D} :

There will be electric field due to polarized charges, this field is called electric field due to polarization (\mathbf{E}_p).

Rewrite equation:

$$\mathbf{E} = \mathbf{E}_0 - \mathbf{E}_p \quad (1)$$

Polarization vector, \mathbf{P} is equal to the bound charge per unit area or equal to the surface density of bound charges (because surface charge density is charge per unit area),

$$\text{Thus, } \mathbf{P} = q_b/A = \sigma_p \quad (2)$$

Where q_b is bound charge and σ_p is surface density of bound charges.

\mathbf{P} is also defined as the electric dipole moment of material per unit volume.

$$\mathbf{P} = n\mathbf{p}$$

where n is number of molecules per unit volume.

Displacement vector, \mathbf{D} is equal to the free charge per unit area or equal to the surface density of free charges,

$$\text{Thus } \mathbf{D} = q/A = \sigma \quad (3)$$

where q is free charge and σ is surface density of free charges.

As for parallel plate capacitor:

$$\mathbf{E} = \sigma / \epsilon_0 \quad (4)$$

$$\mathbf{E}_p = \sigma_p / \epsilon_0 \quad (5)$$

By substituting equations 4 and 5 in equation 1, we get

$$\mathbf{E} = \sigma / \epsilon_0 - \sigma_p / \epsilon_0$$

$$\text{Or } \epsilon_0 \mathbf{E} = \sigma - \sigma_0$$

By putting equations 2 and 3 in above equation, we get

$$\epsilon_0 \mathbf{E} = \mathbf{D} - \mathbf{P}$$

$$\text{or } \mathbf{D} = \epsilon_0 \mathbf{E} + \mathbf{P}$$

This is the relation between \mathbf{D} , \mathbf{E} and \mathbf{P} .