Plastics Topics – Dielectric properties of plastics

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1. Introduction

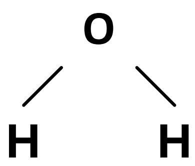
Most plastics are dielectrics or insulators (poor conductors of electricity) and resist the flow of a current[1]. This is one of the most useful properties of plastics and makes much of our modern society possible through the use of plastics as wire coatings, switches and other electrical and electronic products. Despite this, dielectric breakdown can occur at sufficiently high voltages to give current transmission and possible mechanical damage to the plastic.

The application of a potential difference (voltage) causes the movement of electrons and when the electrons are free to move there is a flow of current. Metals can be thought of as a collection of atomic nuclei existing in a 'sea of electrons' and when a voltage is applied the electrons are free to move and to conduct a current. Polymers and the atoms that make them up have their electrons tightly bound to the central long chain and side groups through 'covalent' bonding. Covalent bonding makes it much more difficult for most conventional polymers to support the movement of electrons and therefore they act as insulators.

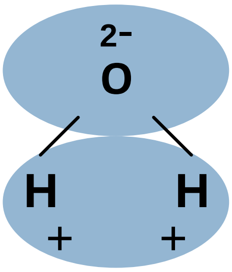
2. Polar and non-polar plastics

Not all polymers behave the same when subjected to voltage and plastics can be classified as 'polar' or 'non-polar' to describe their variations in behaviour.

The polar plastics do not have a fully covalent bond and there is a slight imbalance in the electronic charge of the molecule. A simple example of this type of behaviour would be that of the water molecule (H_2O). The conventional representation of the molecule is that shown at right. The two hydrogen atoms are attached to the oxygen atom and the overall molecule has no charge.



The conventional view of the water molecule



The actual view of the water molecule

In reality, the electrons tend to be around the oxygen atom more than around the hydrogen atoms and this gives the oxygen a slightly negative charge and the hydrogen atoms a slightly positive charge. This is shown in the diagram at right where the grey areas show where the electrons are more often found. The overall water molecule is neutral and does not carry a charge but the imbalance of the electrons creates a 'polar' molecule. This 'polar dipole' will move in the presence of an electric field and attempt to line up with the electric field in much the same way as a compass needle attempts to line up with the earth's magnetic field.

In polar plastics, dipoles are created by an imbalance in the distribution of electrons and in the presence of an electric field the dipoles will attempt to move to align with the field. This will create 'dipole polarization' of the material and because movement of the dipoles is involved there is a time element to the movement. Examples of polar plastics are PMMA, PVC, PA (Nylon), PC and these materials tend to be only moderately good as insulators.

The non-polar plastics are truly covalent and generally have symmetrical molecules. In these materials there are no polar dipoles present and the application of an electric field does not try to align any dipoles. The electric field does, however, move the electrons slightly in the direction of the electric

[1] Actually, there are some polymers that conduct electricity very well and these are perhaps even more exciting in terms of what the future may hold for plastics. These 'conductive' polymers are being developed for applications as diverse as printed electronics, new display technologies, flexible electronics and photovoltaic products.

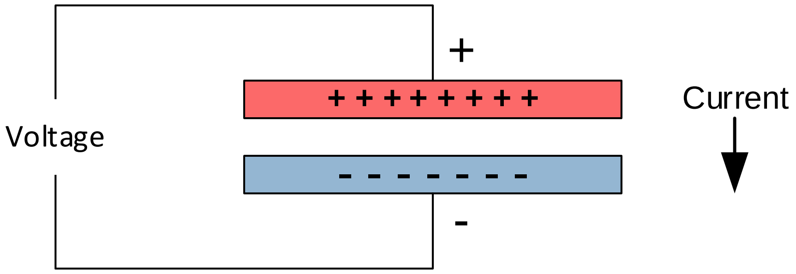
field to create 'electron polarization', in this case the only movement is that of electrons and this is effectively instantaneous. Examples of non-polar plastics are PTFE (and many other fluoropolymers), PE, PP and PS and these materials tend to have high resistivities and low dielectric constants.

The structure of the polymer determines if it is polar or non-polar and this determines many of the dielectric properties of the plastic.

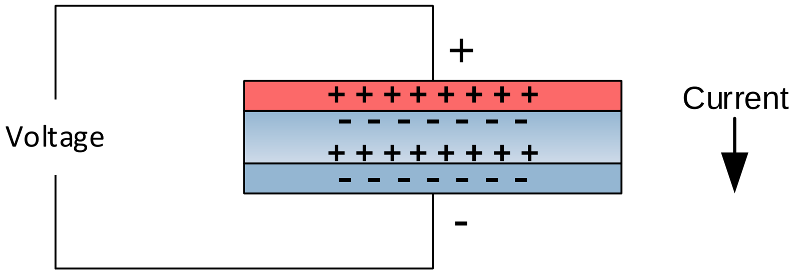
3. Measurement of electrical properties

Dielectric constant (alternating current)

The dielectric constant is a measure of the influence of a particular dielectric on the capacitance of a condenser. It measures how well a material separates the plates in a capacitor and is defined as the ratio of the capacitance of a set of electrodes with the dielectric material between them to the capacitance of the same electrodes with a vacuum between them. The dielectric constant for a vacuum is 1 and for all other materials it is greater than 1.



Condenser only



Condenser with dielectric inserted

For polar plastics the alternating current frequency is an important factor because of the time taken to align the polar dipoles. At very low frequencies the dipoles have sufficient time to align with the field before it changes direction and the dielectric constant is high. At very high frequencies the dipoles do not have time to align before the field changes direction and the dielectric constant is lower. At intermediate frequencies the dipoles move but have not completed their movement before the field changes direction and they must realign with the changed field. Polar plastics at low frequencies (60 Hz) generally have dielectric constants of between 3 and 9 and at high frequencies (10^6 Hz) generally have dielectric constants of between 3 and 5.

For non-polar plastics the dielectric constant is independent of the alternating current frequency because the electron polarization is effectively instantaneous. Non-polar plastics always have dielectric constants of less than 3.

Power factor (alternating current)

The power factor is a measure of the energy absorbed by the material as the alternating current constantly changes direction and the dipoles try to align themselves with the field. As the dipoles try to align themselves with the external field they will always be slightly out of phase and will 'lag' behind the field. The amount of lagging is measured by the phase angle (θ) and the power factor is defined as cos θ. The power factor can be thought of as a measure of the internal friction created by the alternating current and will define how much a material heats up when placed in an alternating field.

For polar plastics the power factor is dependent on the alternating current frequency. At very low and at very high frequencies both the power factor and the amount of internal heating are low - the dipoles either have time to align or do not have time to align before the field changes direction. At intermediate frequencies the power factor goes through a maximum and the internal friction is high and substantial heating of the plastic can take place.

This maximum in the power factor is also the basis for microwave ovens. The microwave generator in the oven applies an alternating field (in the microwave region) to the food. The frequency of the microwave field is matched to the frequency that is the maximum for the power factor of the water dipole. The polar dipole water molecules constantly attempt to align with the alternating field and the resulting internal friction heats up the food. Non-polar materials or polar materials with a maximum in the power factor at different frequencies either do not heat up at all or gain relatively little heat. The fact that the microwaves act directly on the water molecules means that foods heat up evenly throughout their volume and cooking takes place as much internally as it does externally.

For non-polar plastics the electronic polarization is effectively in phase with the external field (i.e., $\theta \approx 0$ and cos θ is also approximately 0) and the power factor is generally less than 0.0003. Non-polar plastics suffer from very little internal friction and minimal internal heating.

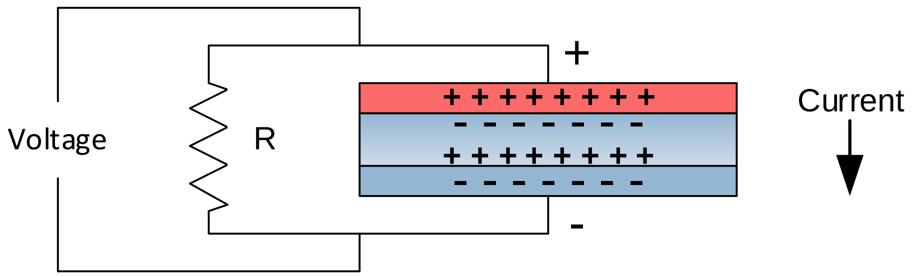
Dielectric strength (direct current)

The dielectric strength is the direct current voltage between two electrodes at which dielectric breakdown occurs and is an indicator of how good an insulator the material is. The voltage is increased until the material breaks down, there is an arc across the electrodes and substantial current flows.

Most plastics have good dielectric strengths (in the order of 100 to 300 kV/cm).

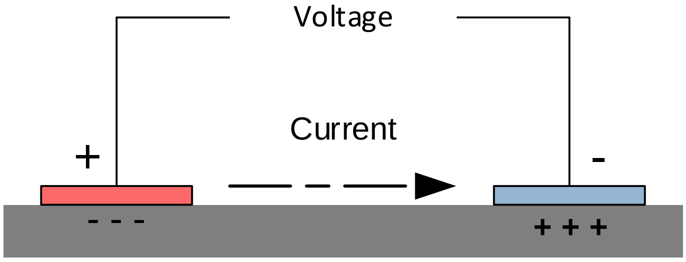
Volume resistivity (direct current)

The volume resistivity is a measure of the resistance of the material in terms of its volume. A voltage is applied across the plates and the current measured to allow calculation of the volume resistivity. Most plastics have very high volume resistivities (in the order of $10^{16} \Omega$ m) and are therefore good insulators.



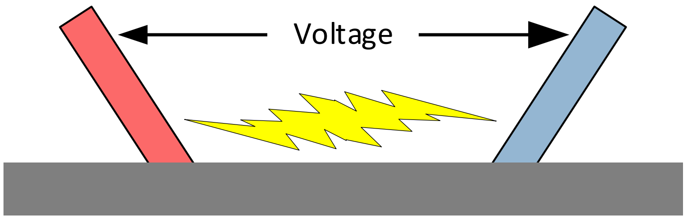
Surface resistivity (direct current)

The surface resistivity is a measure of the resistance of the material to a surface flow of current. It is the ratio of the applied direct voltage and the resulting current along the surface of the material per unit width. Surface resistivity is measured in Ω.



Tracking and arc resistance (direct current)

These are measures of how long a material can resist forming a continuous conduction path under a high voltage/low current arc.



4. The environment and electrical properties

The electrical properties of plastics may also be changed quite dramatically by the environmental conditions, such as moisture and/or temperature and this is particularly true for polar plastics.

The polar plastics have a tendency to absorb moisture from the atmosphere and can often contain a significant amount of water at normal room temperature. For these materials, the presence of the water generally raises the dielectric constant and lowers both the volume and surface resistivity.

Raising the temperature of a polar plastic allows faster movement of the polymer chains and faster alignment of the dipoles. This is particularly true if the temperature is raised above T_g because above T_g much more molecular movement is possible. Raising the temperature inevitably raises the dielectric constant of polar plastics.

Non-polar plastics, such as the fluoropolymers, are not as affected by the water because they tend not to absorb water and temperature effects are not generally as severe because increased temperature does not affect the electronic polarization.

Summary

The dielectric properties of polymers are largely predictable from the chemical structure of the polymer. The chemical structure determines the polar or non-polar nature of the final polymer and this then largely determines the behaviour of the polymer under a variety of electrical situations.