Space charge dynamics in low density polyethylene under dc electric fields

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Abstract. In this paper space charge dynamics in low-density polyethylene (LDPE) under different dc electric fields, ranging from 25 kV/mm to 125 kV/mm, have been investigated using the pulsed electroacoustic (PEA) technique. Bipolar space charges have been found to present in the sample and the amount of charge increases with both the applied electric field and the duration of electric field applied. Double injection is believed to be responsible for the charge measured. Negative charge dominates due to electrode configuration used in the research. The formation of charge leads to an increase in the maximum electric field. Results show that the maximum electric field depends on both the magnitude and the duration of the applied field. The charge decay after the removal of the applied field shows a fast decaying rate for the charge formed at high applied electric field.

1. Introduction

There is increasing evidence that degradation of polymer insulation under high electric stress is associated with space charge formation. In fact, space charge accumulation in dc regime is the main reason that still limits the use of polymers as insulation for high voltage dc power cables. Techniques used to measure space charge non-destructively in solid dielectrics have been developed and improved over the last twenty years [1]. Consequently, space charge research in solid dielectrics has been intensified and significant amount of work has been published [2-4]. However, due to complexity in charge dynamics a good understanding of space charge characteristic in polymeric materials has not been reached so far.

In this paper space charge dynamics in low-density polyethylene (LDPE) under different dc electric fields ranging from 25 kV/mm to 125 kV/mm have been investigated using the pulsed electroacoustic (PEA) technique. The influence of space charge on electric field distribution has been investigated. More importantly, characteristics of charge decay after the removal of different applied electric fields have been examined.

2. Experimental details

Polyethylene has been widely used as an insulating material for high voltage application. Additive-free low density polyethylene (LDPE) film with a thickness around 100 μm was purchased from the Goodfellow Co. and then cut into a disc shape with a diameter of 50 mm. Space charge was measured using the PEA technique [5]. In this technique, acoustic waves are produced at charge layers at both electrodes and internal charge when an electrical pulse is applied to a sample. The acoustic signals are detected by a piezo-electric transducer. The electric signal obtained in time domain represents the charge distribution. To obtained quantitative charge distribution, a proper calibration is required [6]. This should be done at low voltage with a short period of voltage application time to minimise the influence of space charge. In the present study, 1 kV dc was applied to the sample for a short period of time (less than 10 seconds) for calibration purpose. It has been noticed that electrodes have significant effect on space charge formation and dynamics [3]. In the present study, a conventional electrode arrangement was adopted, i.e. semiconducting polymer (Sc) as the top electrode and aluminium (Al) as the bottom electrode. The spatial resolution of a PEA system is determined by electric pulse width, sound velocity of the insulating material and characteristics of the acoustic sensor. The PEA system used in the present study has a spatial resolution of ~10μm. Consequently, the charge profiles on the electrodes have also been broadened.

To observe space charge dynamics, the electric fields ranging from 25 kV/mm to 125 kV/mm were applied to samples and space charge dynamics over a period of 60 minutes were monitored. In addition, space charge evolution after the removal of the applied electric field was also measured over at least 30 minutes.

3. Results and discussion

3.1 Charge distribution in the presence of the applied field

Bipolar charges have been observed in the sample and double injections are believed to take place. It has been found that that charge dynamics are very different and depend on electric fields applied as shown in Figure 1. To improve signal to noise ratio, averaging operation is often used in the PEA technique. This means that the first measurement was normally obtained a few seconds (3 to 5 s) after a voltage application and it is donated as t=0 min in the present study as shown in Figure 1. The positions of electrodes are indicated. At low fields, charge movement is slow and the charge profile changes little in a few seconds. However, at high fields there are significant changes in charge profile especially at the beginning of the voltage application due to accelerated charge movement.

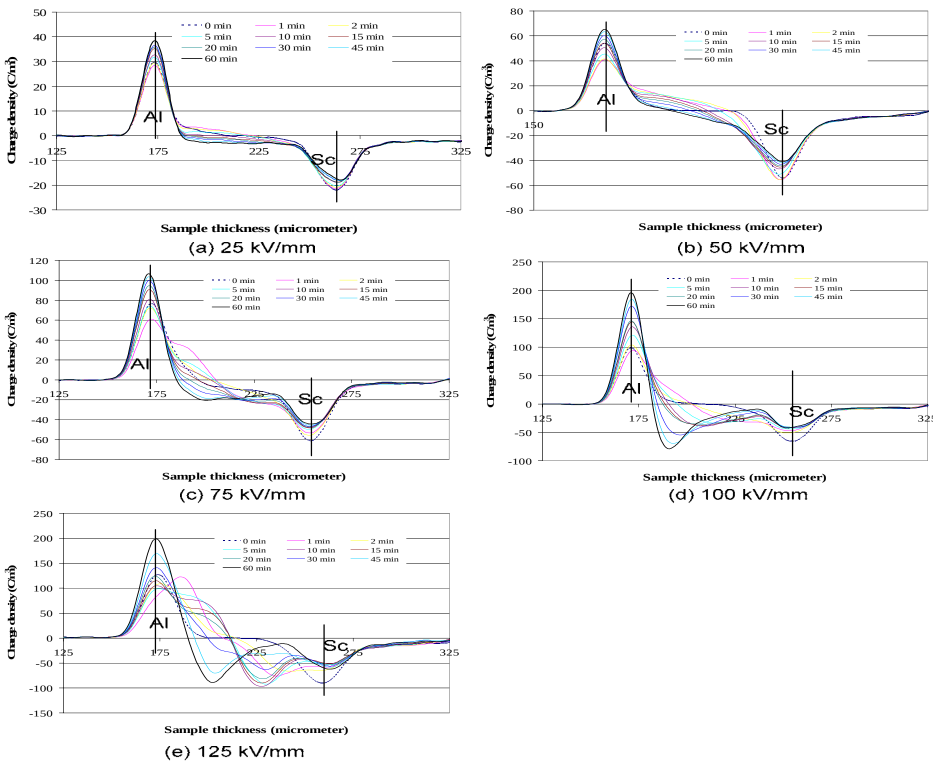


Figure 1. Space charge dynamics at different dc electric fields.

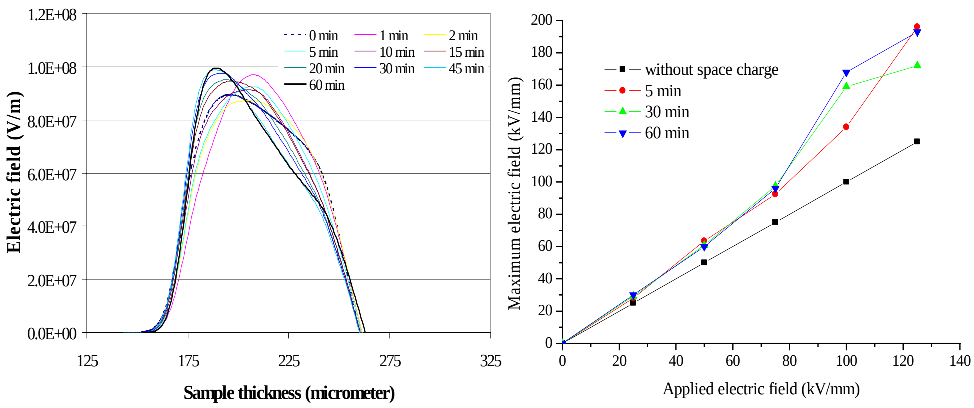
At low electric field, initial charge distribution is dominated by injected positive charge. This is gradually taken over by negative charge injected from the cathode. However, at high field both injected positive charge and negative charge show their presence initially and this is quickly taken over by the injected negative charge. In our previous paper [3] it has been established that Sc electrode injects charge more easily than Al electrode. Therefore, negative charge domination in the present study furthers our earlier founding. It is important to remember that the PEA technique only shows a net charge. The processes such as recombination and cancellation between positive and negative charge carriers may well take place in the sample. Therefore, it is not possible to estimate charge mobility for each type of charge carrier.

3.2 Electric field in the sample

The electric field distribution due to the presence of space charge can be estimated based on Poisson's equation

$$\frac{dE}{dx} = -\frac{\rho(x)}{\varepsilon_0 \varepsilon_r} \qquad (1)$$

Figure 2 (a) shows electric field distribution in the sample stressed at 75 kV/mm. It can be seen that the electric field distribution changes with time. Due to quick charge formation at high fields, the electric field a few seconds after the voltage application is no longer a constant value across the sample thickness. The maximum electric filed increases initially and then decreases before resuming increase with time. The changes in electric field distribution with time are the reflection of charge dynamics in the material. The position where the maximum electric field occurs changes with time and the final maximum electric field tends to occur at the anode interface, presumably, due to the dominant negative charge in the sample.



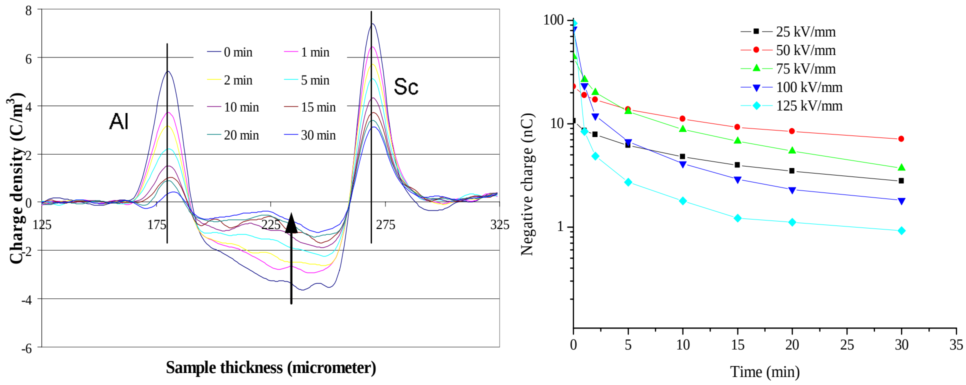
(a) Electric field distribution at 75 kV/mm (b) Maximum electric field

Figure 2. Electric field enhancement due to the presence of space charge.

Figure 2 (b) illustrates the relationship between the applied field and the maximum field in the samples at different times. A modest increase in electric field has been found below the applied field of 75 kV/mm while significant field enhancement has occurred at high applied fields. It is clear that the maximum electric field shows time dependent with marked variation at high fields. The electric field enhancement due to the presence of space charge reaches approximately 60% of the applied electric field at high fields.

3.3 Charge decay

Charge decay after the removal of the applied field was also monitored. A typical example of charge evolution after the removal of an applied electric field of 25 kV/mm is shown in Figure 3 (a). The negative charge decay with time for samples with different applied fields is illustrated in Figure 3 (b). Generally, when the applied voltage is higher, the charge decay is faster with an exception of 50 kV/mm. In this case, significant amount of positive charge has been found adjacent to the anode (Al) which is also evident from Figure 1 (b). The presence of positive charge will undoubtedly affect the rate at which the negative charge decays. The exact mechanism why the charge formed at high field decreases quickly is not yet known. This may be related to the trapping characteristics of charge carriers in the material. It is believed that the feature has a close link with the crossover phenomenon in corona charged surface potential decay across polyethylene [7].



(a) Charge decay (25 kV/mm) (b) Negative charge decay

Figure 3. Negative charge decay after the removal of the applied electric fields.

4. Conclusion

Space charge dynamics in LDPE film at the applied fields between 25 to 125 kV/mm have been observed over a period of 60 minutes using the PEA technique. Following conclusion may be drawn.

Charge dynamics is extremely complicated in LDPE, determined by electrode material, applied electric field and its duration. Negative charge dominates in the present electrode arrangement. The amount of charge formed in the sample increases with the applied field and its duration. The maximum electric field shows time dependent and its position varies as well. The electric field enhancement can reach upto 60% at high applied fields. It is also evident that charge decays fast when it is formed at high applied fields. Further research is required to understand charge decay mechanisms.

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