

# Decay of electric charge on corona charged polyethylene

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## Abstract

This paper describes a study on the surface potential decay of corona charged low density polyethylene (LDPE) films. A conventional corona charging process is used to deposit charge on the surface of film and surface potential is measured by a compact JCI 140 static monitor. The results from corona charged multilayer sample reveal that the bulk process dominates charge decay. In addition, the pulsed-electro-acoustic (PEA) technique has been employed to monitor charge profiles in corona charged LDPE films. By using the PEA technique, we are able to monitor charge migration through the bulk. Charge profiles in corona charged multilayer sample are consistent with surface potential results. Of further significance, the charge profiles clearly demonstrate that double injection has taken place in corona charged LDPE films.

(Some figures in this article are in colour only in the electronic version)

## 1. Introduction

There has been considerable interest in the surface potential decay characteristics of corona charged polymers. It is well known that the surface potential decay of negatively charged polyethylene shows an interesting phenomenon, i.e. the initial sample charged with a high potential decays more rapidly as compared with the sample that is charged with a lower potential [1]. Over the years, various theories and models have been proposed to explain this crossover phenomenon [2–5]. One proposed mechanism is the existence of deep traps on the surface and shallow traps in the bulk. Consequently, charges formed at high corona voltage are capable of overcoming the barrier of the surface and moving into the bulk. Due to shallow traps in the bulk of the polymeric material, charges are able to transport through the bulk, leading to fast decay of surface potential. On the other hand, charges formed at low corona voltage are likely to stay on the surface. Due to deep traps on the surface, charges encounter difficulty in moving either into the bulk or along the surface.

Over the years, the study of surface potential evolution with time has proved to be a powerful tool in understanding charge transport processes in polymeric materials. The

thermally stimulated discharge current technique (TSDC) has also been used which allows researchers to study trapping characteristics of corona charged polymeric materials [6]. In the last three decades, several techniques have emerged which enable space charge to be determined in solid dielectrics [7]. However, the pulsed-electro-acoustic (PEA) technique has gained wider recognition owing to its unique features [8].

In this research, we intend to elucidate the mechanism of charge decay in corona charged low density polyethylene (LDPE) by combining the surface potential decay kinetics and the PEA measurements. By using the PEA technique, we are able to monitor charge migration through the bulk. These experimental results will notably influence future theory and model development.

## 2. Experimental details

Additive-free LDPE films with different thicknesses were purchased from the Goodfellow. They were cut into discs with a cross-sectional diameter of 50 mm. A conventional corona charging process was used to deposit charges on the surface of the film as shown in figure 1.

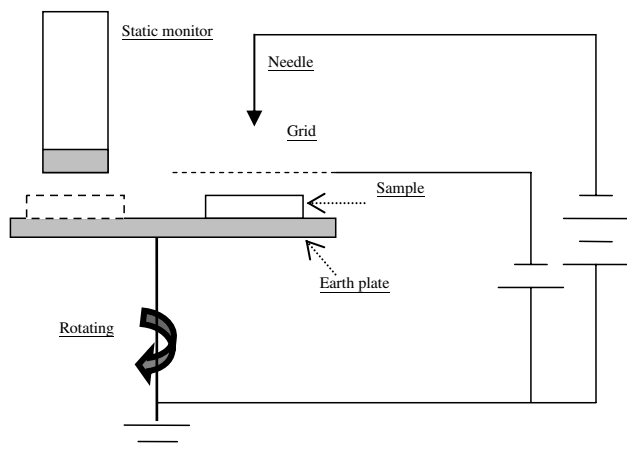


Figure 1. Potential decay measurement system.

The initial surface potential of the corona charged film was controlled by the grid inserted between the needle and the rotatable earth electrode. After corona charging, the sample was moved to the area where the surface potential was measured by a compact JCI 140 static monitor. In our study, the negative corona charging duration was varied from 30 s to 10 min but only the results from charge duration of 2 min were presented in this paper. As both temperature and relative humidity influence the electric charge decay, all experiments were carried out under a controlled environment with temperature and relative humidity at 21 °C and 45%, respectively.

Space charge distribution in corona charged LDPE films was measured by the PEA technique. PEA is currently the most widely used technique in the field of space charge measurements. This technique utilizes the interaction between high voltage pulses and charge layers accumulated in the insulating material to produce acoustic pressure waves, whose physical characteristics can represent the density and polarity of the space charge distributed in the sample. The acoustic waves traverse across the material and are converted into an electrical signal by a piezo-electric transducer, amplified by one or two amplifiers depending on the signal magnitude and finally captured with a digital oscilloscope. The principle diagram is shown in figure 2 and the detailed description of the PEA method can be found in [8,9]. If the deposited charge on the surface corona charged film can inject into the bulk then the PEA technique will capture the signal and help in the analysis of the decay mechanism.

The detailed description of the surface potential and space charge measurement can be found in our earlier work [10].

### 3. Experimental results and discussion

#### 3.1. Surface potential decay

In this section, we will discuss some surface potential decay results measured by the traditional field meter. Negative polarity was used to deposit charges on the sample surface; however, the absolute surface potential has been used throughout the paper when surface potential and time characteristics are plotted. Figures 3 and 4 show the surface

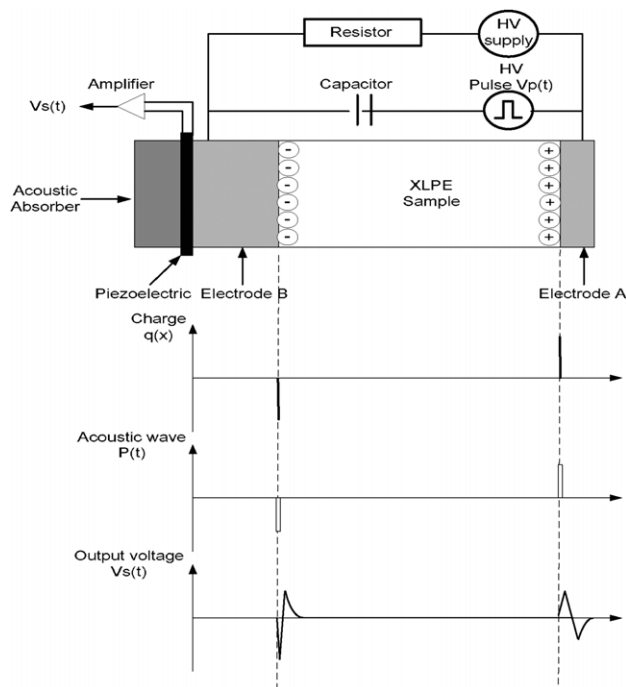


Figure 2. Basic principle of the PEA technique.

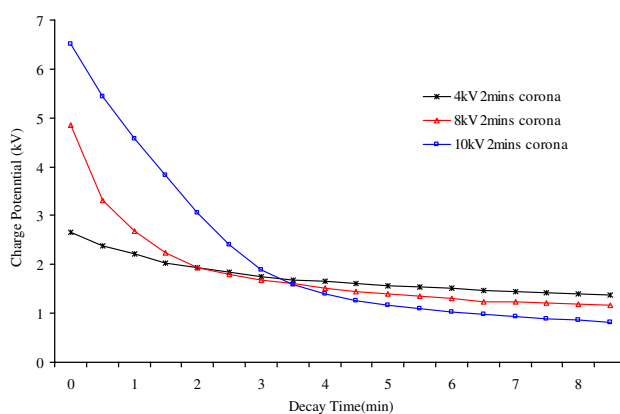
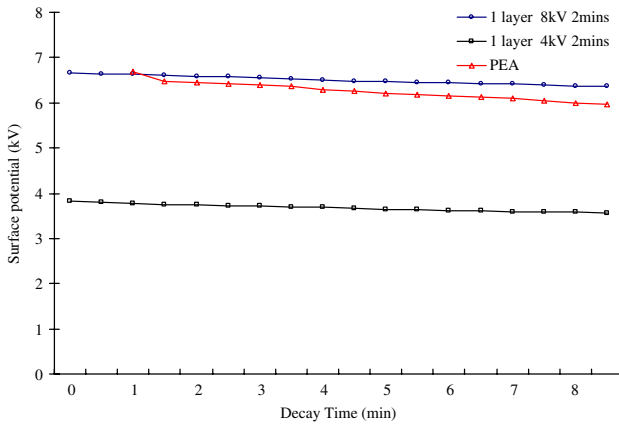


Figure 3. Potential decay for a 50  $\mu\text{m}$  single layer sample (different corona voltages).

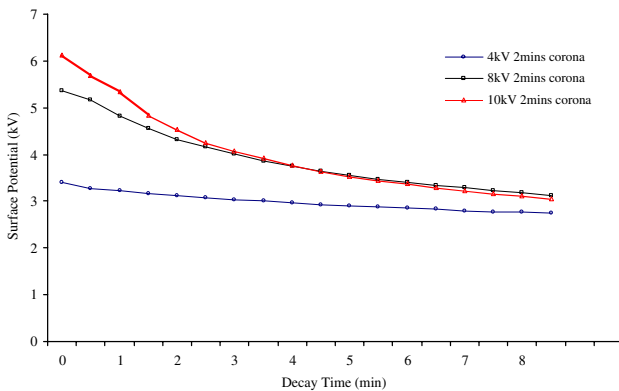
potential decay curves of 50 and 180  $\mu\text{m}$  LDPE films charged with a defined potential, controlled by the grid voltage.

For thinner samples (50  $\mu\text{m}$ , figure 3), it is clear that the crossover phenomenon occurs. However, for thicker samples (180  $\mu\text{m}$ , figure 4), there is no significant difference in the decay rate and no crossover appears. The surface potential decay of the thicker sample is much slower than that of the thinner sample. These results seem to indicate that the sample thickness plays a crucial role in the behaviour of surface potential decay.

The crossover phenomenon of surface potential decay for corona charged polyethylene has been observed in the thinner sample, indicating the influence of the high electric field. The field-dependent drift mobility and time-dependent injection have been analysed theoretically [11]. However, the kinetics of charge carrier injection is not well understood and various assumptions have to be made to simplify the mathematical description without solid experimental verification. Based on



**Figure 4.** Potential decay for 180  $\mu\text{m}$  single layer sample (different corona voltages).

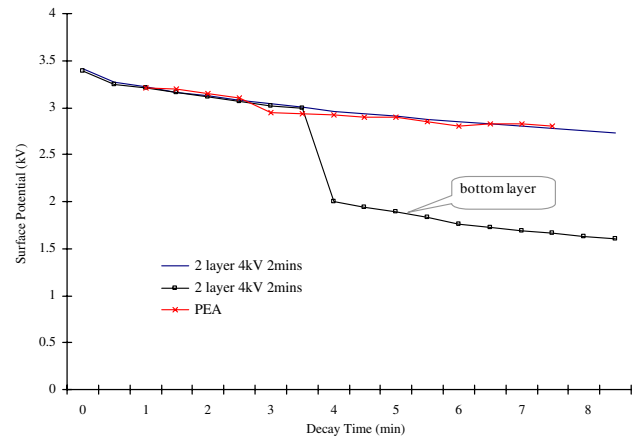


**Figure 5.** Potential decay for the two-layer 50  $\mu\text{m}$  sample (different corona voltages).

our other work, it may be assumed that the charge inject into the insulator is the main leakage route at a higher initial surface potential.

To verify our assumption the samples consisting of two-layer polyethylene films were charged and the surface potential decay was monitored. Figure 5 shows the surface potential decay of two-layer 50  $\mu\text{m}$  LDPE films at different corona charging voltages. Similarly to the results shown in figure 3, the crossover phenomenon can be observed. But it only occurs among the highly charged samples in the time range observed; the potential at which the crossover occurs is higher than that in the thinner sample. Figure 6 demonstrates the results of potential decay of one-layer and two-layer samples. The grid potential was set to  $-4\text{ kV}$  in this case. The surface potential of the one-layer sample shows a rapid decay. There are two possible reasons to explain this phenomenon. One is that the thinner sample shows a faster decay due to a higher electric field as described earlier. The other reason is that the interface between the two layers forms a barrier which makes charge transporting to the next layer more difficult, resulting in slow decay.

More importantly, when the top layer was removed carefully, the surface potential can still be observed from the bottom layer as shown in figure 6. Since the surface potential is a representation of both surface charge and bulk charge, this implies that the surface electric charge can be injected into



**Figure 6.** Potential decay for different layers 50  $\mu\text{m}$  sample (same corona voltages).

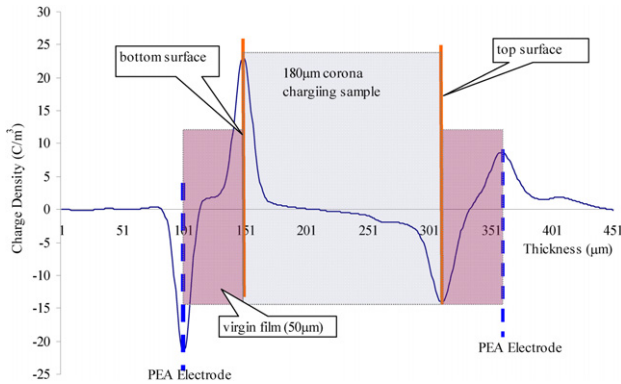
the bulk and trapped at the interface of the two-layer films. It can also be observed that the surface potential of the bottom layer decays slightly faster compared with that of the two-layer sample. Another interesting feature is that the surface potential of the bottom layer is higher than that of the one-layer sample.

Generally, there are three possible routes for charge transport in corona charged polymer, i.e. through the atmosphere, along the surface and transport through the bulk. The former two routes may not be important as the surface potential decay is highly thickness dependent. However, the surface conduction may only become important when high humidity is encountered [12]. Consequently, a majority of theories and models [2–5] for the surface potential decay are based on bulk transport process. The observed potential from the bottom layer of the corona charged two-layer films provides a direct experimental evidence to support the bulk charge transport process as there is no alternative process that can form the electric potential on the bottom layer.

### 3.2. PEA results

It is clear from the above results, in particular, the two-layer sample results, that bulk charge transport is responsible for the surface potential decay. As the surface potential changes relatively slowly in the majority of cases, it is possible to monitor charge evolution using the space charge measurement.

Figures 7 and 8 show the space charge distribution results in the negatively corona charged 180  $\mu\text{m}$  LDPE film measured by the PEA method. In the PEA measurement, it is necessary that the two electrodes are in direct contact with the measured sample. In addition, a very thin layer of silicone oil is often smeared on the electrodes to improve acoustic coupling. To minimize the disturbance to the deposited charge, the top and bottom surfaces of the corona charged samples were protected by an extra fresh 50  $\mu\text{m}$  LDPE film. There are four distinctive charge peaks present across the sample from left to right in figure 7. The first and the fourth peaks are known as induced charge peaks on the PEA electrodes. The presence of the middle two peaks is due to the existence of charge in the corona charged sample. The second peak from the left-hand side corresponds to the bottom surface of the corona charged film while the third peak correspondence to the top surface.



**Figure 7.** Space charge distribution in the corona charged  $180 \mu\text{m}$  sample (8 kV and 2 min corona charging).

The third negative peak is expected as the sample was exposed to negative corona. It can also be seen that a small amount of negative charge is present across the sample. This may serve as evidence that charge injection from the top has taken place. Polyethylene is a typical semi-crystalline material; it contains various charge traps [13]. Therefore, it is believed that the injected charge is captured by traps on its way towards the opposite electrode. Surprisingly, a significant layer of positive charge is observed at the bottom surface of the charged sample. This implies that the positive charge injection from the bottom metal plate has taken place during negative corona charging. The injection from the top surface is consistent with the existing models [2–5]. However, the injection from the bottom electrode is not well documented in the literature. This injection is possible as long as the electric field due to the deposited charge is sufficiently high. In fact, our work [14] has demonstrated that bipolar injection occurs at an applied electric field of  $25 \text{ kV mm}^{-1}$ . The estimated electric field from the surface potential measurement is about  $36 \text{ kV mm}^{-1}$ . This value is much higher than  $25 \text{ kV mm}^{-1}$ ; therefore, injection is certainly going to occur.

Charge dynamics for another sample ( $180 \mu\text{m}$ , 8 kV, 2 min corona charged LDPE) over a period of time are shown in figure 8. It can be seen that charge decreases with time and the decay rate is not so fast. This decay rate is similar to the surface potential decay result obtained using the static monitor shown in figure 4.

Once the charge density distribution  $\rho(x, t)$  in the sample is known, it is possible to calculate the electric field across the sample based on Poisson's equation:

$$\frac{dE(x, t)}{dx} = \frac{\rho(x, t)}{\epsilon_0 \epsilon_r}, \quad (1)$$

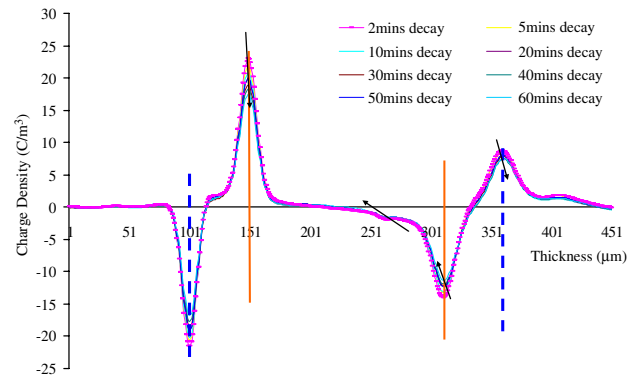
where  $\epsilon_0 = 8.85 \times 10^{-12} \text{ F m}^{-1}$  is the permittivity of vacuum and  $\epsilon_r = 2.25$  is the relative permittivity of LDPE.

The potential across the sample can then be estimated by

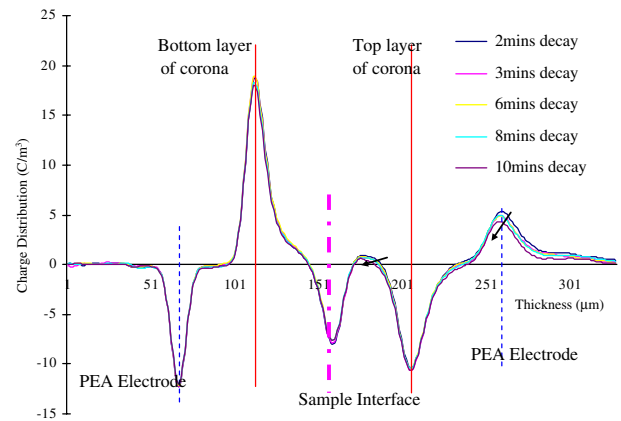
$$V(t) = - \int_0^d E(x, t) dx, \quad (2)$$

where  $d$  is the thickness of the sample.

For comparison reason,  $V(t)$  obtained based on space charge profiles in figure 8 is shown in figure 4 labelled as the PEA curve. It is very close to the potential results monitored



**Figure 8.** Space charge distribution and evolution in the charged  $180 \mu\text{m}$  sample (8 kV and 2 min corona charging).

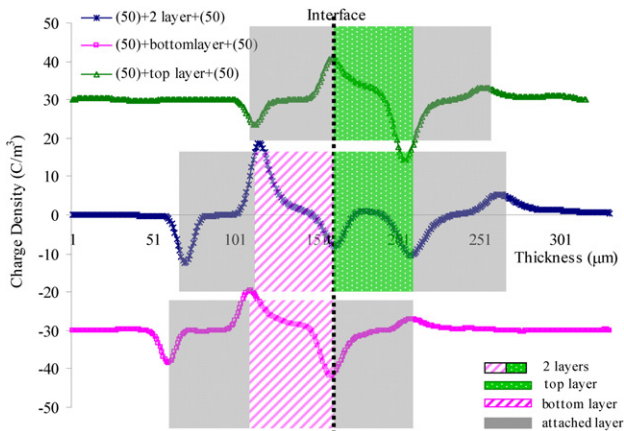


**Figure 9.** Space charge distribution in the corona charged two-layer sample (8 kV and 2 min corona charging).

by the JCI 140 static monitor. This implies that the same mechanism is in operation for both measurement results. The slight difference may be attributed to the influence of the two  $50 \mu\text{m}$  LDPE films attached to the corona charged film. And after few minutes of decaying, the electric field due to the injection charge will be changed and then the potential results will vary to some extent.

Figure 9 shows space charge distribution and dynamics in the two-layer LDPE sample. Again, to protect the deposited charge, two  $50 \mu\text{m}$  LDPE films were attached to both surfaces. Compared with space charge distribution in the single LDPE film, an extra negative charge peak is observed between the two layers. This negative charge is believed to be formed due to charge injection from the surfaces and then transported to the interface and finally trapped there. The appearance of negative charge at the interface is consistent with the early potential result obtained from the bottom layer of the two-layer LDPE sample (see figure 6). The charge injection and bulk transport processes are responsible for the surface potential decay in corona charged LDPE. Following the same procedure described in the previous section, the surface potential can be calculated based on space charge measurements. The  $V(t)$  result in the two-layer LDPE is shown as a PEA curve in figure 6. Surface potential obtained by the two methods is almost overlapping.

The interface of polyethylene is known to be able to trap both positive and negative charges [15] due to surface defects. The



**Figure 10.** Space charge distributions at different layers of the corona charged sample (8 kV and 2 min corona charging).

PEA measurement generally shows the resultant (net) charge. Since both positive and negative charge injections appear to occur, it is believed that the negative charge measured at the interface is a resultant of positive and negative charge. To verify our belief, space charge measurements were performed on both top and bottom layers of the corona charged two-layer LDPE separately. To limit the charge lost, care has to be taken when separating the two layers. Two fresh 50  $\mu\text{m}$  LDPE films were attached to both sides of each layer. The results are shown in figure 10. From these charge distributions it is evident that negative charge is present at the top surface of the bottom layer (bottom layer curve) and positive charge at the bottom surface of the top layer (top layer curve). The amount of negative charge is greater than that of positive charge, so overall it shows a negative charge peak (two-layer curve). The more negative charge observed is consistent with the higher potential observed in figure 6. The revelation of both positive and negative charges at the interface between the top and bottom layer is a clear indication of bipolar charge injection. The injected charge carriers will tend to move across the sample under the influence of the electric field. The interface between the two layers can trap both positive and negative charge carriers due to various traps generated by surface states. In this instance, positive charge tends to move upwards and is therefore trapped by surface states on the bottom surface of the top layer while negative charge is trapped by surface states on the top surface of the bottom layer. This suggests that the interface acts as a barrier. The PEA results may also indicate that it is easier for charge carrier to exit from the bulk than to enter the bulk. These results are significant as they indicate more energy is required for charges moving into the bulk. The revelation of positive charge is also important.

#### 4. Conclusions

Surface potential decay of corona charged LDPE has been studied using both conventional surface potential measurement and space charge measurement (the PEA technique). The following conclusions may be drawn.

The sample thickness plays a crucial role in surface potential decay. The potential decay of the thicker sample is much slower than that of the thinner sample. In the corona

charged multilayer film, potential measured from the bottom layer implies that the surface electric charge can inject into the bulk and be trapped at the interface of two-layer films.

The PEA technique is a new and useful tool to study charge dynamics in corona charged polyethylene films. This technique provides an alternative way for investigating the charge decay process and it allows monitoring charge migration through the bulk of the corona charged film. Therefore, it is an excellent complement to the surface potential measurement. By combining both surface potentials of two-layer LDPE and space charge measurements, direct evidence has been found to support that the bulk transport process is accountable for the surface potential decay.

Space charge in two-layer LDPE films clearly demonstrates that bipolar injection has taken place in corona charged LDPE films. Any future theory and model have to take this fact into consideration.

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