THE EFFECT OF SPACE CHARGE ON PARTIAL DISCHARGES INCEPTION VOLTAGE IN AIR GAPS WITHIN HIGH DENSITY POLYETHYLENE

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ABSTRACT

Partial discharges (PDs) which can occur in embedded voids in solid dielectrics depend on many factors, among them space charge which can seem to be one of the most relevant. As a matter of fact, under certain high voltage operating conditions, trapped or low-mobility electrically charged species within the insulation can give rise to space charge build up. These charges may have been the product of earlier PD events but they can also be the result of charge transport from the electrodes towards defect which can be contained within the insulation.

This paper deals with the relation between space charge and partial discharges phenomena due to electrical stresses. Both simulation and experimental evidences of relations between partial discharge inception voltage (PDIV) and charge accumulation are investigated. PDs in trapped air-filled gaps between two adjacent insulated tapes made of high density polyethylene (HDPE) were measured. An amount of space charge is introduced on the cavity surface by negative direct current application (DC). An alternative current of increasing magnitude was then applied until PDs were initiated and observed. The voltages at which PDs initiate are measured for samples with and without space charge. It was shown that the larger the amount of space charge, the lower PDIV. Simulation results are in good agreement with those obtained from experiment.

1 INTRODUCTION

Partial discharges, in insulation systems, are caused by local defects such as foreign particle inclusions, voids or heterogeneities in surface, giving rise to a large variety of physical phenomena. Electrical overstress caused by such defects is, to a large extent, controlled by similar physical processes and contributes to insulation degradation and breakdown [1]. The process depends upon many factors such as the type of gas in the void and the gas pressure [2, 3], the surface properties of the void, the trapped charge on the cavity walls, the size and shape of the void [1], the dielectric constant of the surrounding medium and the environmental conditions [4]. Partial discharges and the way they affect insulation have been a rewarding subject for many researchers. The advent of powerful hardware has led to an extensive exploration and development of pattern recognition techniques.

Numerous studies have been carried out to develop further a better understanding of the build up of trapped space charge within solid dielectric materials. During operation and under certain conditions, a trapped or low-mobility charge in the insulator bulk tends to increase the space charge quantities. These charges will be captured in the interfacial areas between the crystalline and amorphous parts. Therefore, a high electric field appears and will be able to produce the partial discharges phenomenon and thereafter insulator premature degradation [5].

In this paper, and in order to show the influence of space charge on PDs inception voltage a space charge has been created on one side of the cavity realized in high density polyethylene model samples. A quantitative analysis of the electric field distribution in the material and within the cavity has been and the PD-activity has been experimentally investigated.

2 SPACE CHARGE IN INSULATING MATERIAL

Dielectrics are rarely homogeneous at microscopic level. They may be considered as a composite of amorphous and crystalline regions. Ieda [6] has shown that the interface between amorphous and crystalline regions is host to hopping sites of the order of 0.3 to 0.4eV.

In general, the conductivity of amorphous and crystalline regions will differ, as will that of the interface region between them. Of course the electric field distribution will be moderated by the field-dependent conductivity of all the regions in series. Thus, the microscopic inhomogeneity of the conductivity should give rise to substantial space charge at microscopic level. The other issue is that space charge on a nanoscopic scale is distributed in three dimensions around inhomogeneities [7].

Space charge formation is a major issue for DC systems, but most high voltage systems in electrical engineering operate under AC, not DC. However recent work [8, 9] demonstrated the presence of space charges in polymeric cable insulation materials under AC conditions. Under AC excitation, space charge tends to be less an issue, except around microscopic stress enhancements where space charge oscillates during each half AC cycle, resulting in hot electrons and photon emission from carrier recombination; both of them degrade the dielectric. Such phenomena can only occur within microscopic geometries, as the power density would cause thermal runaway in a macroscopic volume. In [5] Space charge in PE after ac ageing at 50 Hz has been investigated.

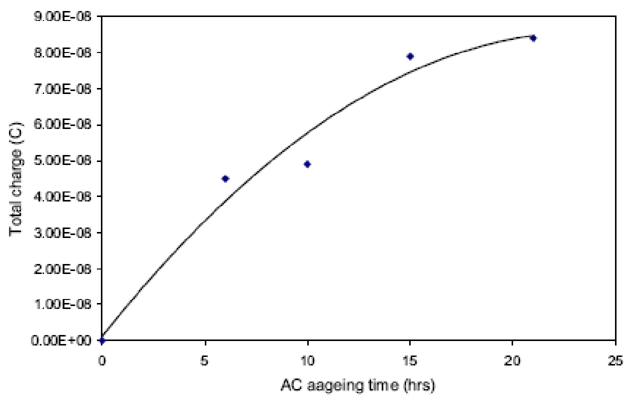


Figure 1 : Relationship between the total charge and ageing time at 50 kV/mm [5]

3 SPACE CHARGE AND PARTIAL DISCHARGE

Partial discharge and space charge are closely related; one affects the other. Charges trapped within material in shallow trapping sites at the boundary between dielectric and cavity serve as initiatory electrons. These charges may have been deposited by earlier PD events but they can also be the result of charge transport from the electrodes towards the cavity. The nature of these trapping sites is not quite clear; i.e. the trap depth and trap density can be estimated [10, 11] but to the authors' knowledge estimations have never been verified by experiment. In order to understand and describe why and how the PD mechanism changes as a result of the cavity aging. Measuring the trap distribution is a challenging task. Moreover, the properties of the cavity surface change as a result of PD activity. Last but not least, the PDs also act as a source of charge injection into the dielectric. Part of the charge involved in the discharge process is trapped at the cavity surface and part of the charge migrates deeper into the dielectric [12]. Very little literature [11] is available on measurements of space charge injected by discharging cavities. It would therefore be of great interest to study simultaneously the PD activity in a cavity and the space charge profile in the dielectric. The results of such a study could give some idea on the relation between PD and breakdown.

3.1 Experimental procedure

Model sample and configuration

The geometrical characteristics of the samples under study are given in figure 2.

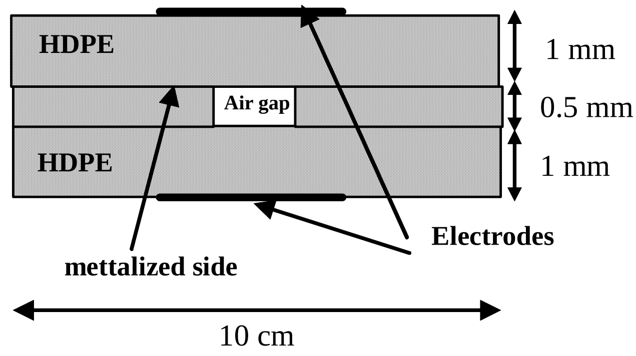


Figure 2 : Transverse section of the sample.

The sample is composed of a 500µm-thick air gap dividing two 1 mm-thick HDPE slabs. These dimensions are calculated from Paschen's curves in order to reach the partial discharge inception voltage for an applied voltage of some kV. External removable grips ensure the attachment of the three slabs together. Gold electrodes (thickness: 0.9µm and diameter: 3 cm) are deposited on both external sides. A metallized layer is deposited on the lower side of the sample higher part.

As shown in figure 3, this configuration enables us to introduce a controlled charge quantity in the sample volume by applying a negative DC voltage through the metallized wall of the cavity. Then AC voltage of increasing magnitude is applied until PD is initiated.

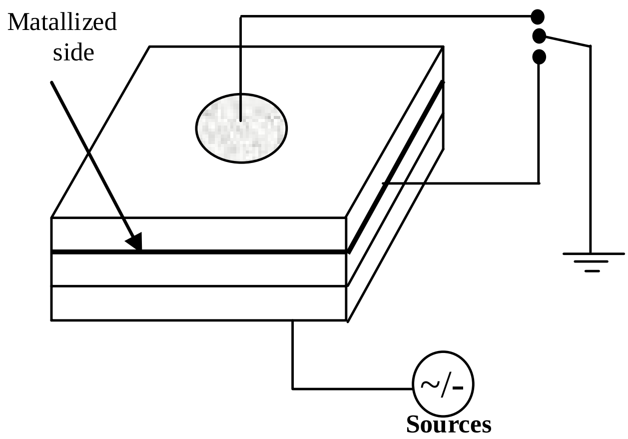
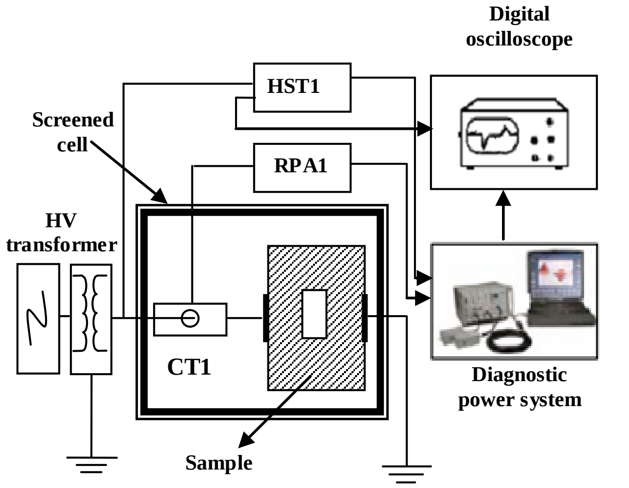


Figure 3: Configuration of the sample including the two supply voltage sources

3.2 Experimental Setup

Partial discharges activity is measured using the experimental set up showing in Figure 4.



RPA1: Preamplifier

CT1: Current and isolation transformer serve to pick up partial discharge signals.

HST1: Voltage divider

Figure 4: Experimental set up including sample and PD detection system

It is composed of a 30kV transformer, a measuring cell, a partial discharge detection system (Power Diagnostix System). This instrument transmits the pulses associated with the discharges and representing their amplitude and phase in a three dimensions. Special care is taken to reduce external noise and corona effects. A filter is used to reduce the noise carried by the network. Screened cell (Faraday cup) is used to avoid any electromagnetic interference.

4 SPACE CHARGE AND ELECTRIC FIELD DISTORTION

It is known that space charges in the material are usually distributed randomly in three dimensions. For this reasons a bulk, containing a constant space charge amount, is introduced in different positions as shown in the figure 5.

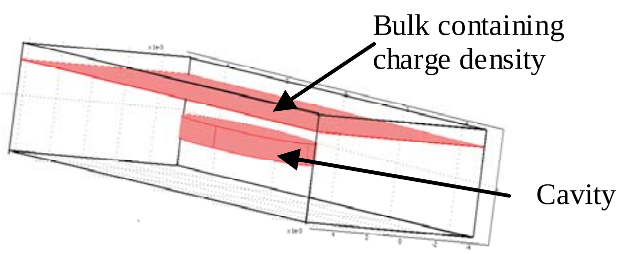


Figure 5: Position of the charge density compared to the cavity position.

The effect of the distance separating space charge and cavity, on the electric field distortion is investigated using Comsol Multiphysics software. The numerical resolution of electric potential and electric field distribution in the insulation and within the artificial cavity is achieved. Figure 6 shows that distance has an important effect on electric field distortion. The electric field increases with decreasing distance, reaching a maximum for a charge density deposited directly on cavity side (zero distance). The field increases by 70 % compared to the case where there is no space charge.

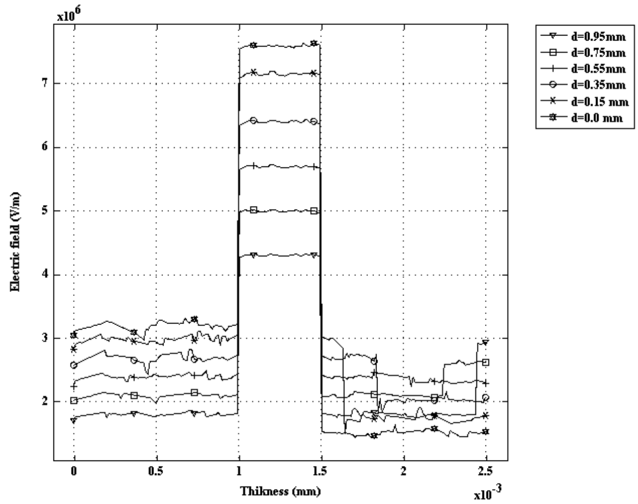


Figure 6: Electric field distribution in the sample as a function of distance which separates space charge and the cavity

Likewise, figure 7 shows clearly that the electric field in the cavity is more reinforced when the distance which separates space charge and the cavity decreases; as a result, partial discharges are more probable. The same remark applies for the electric potential.

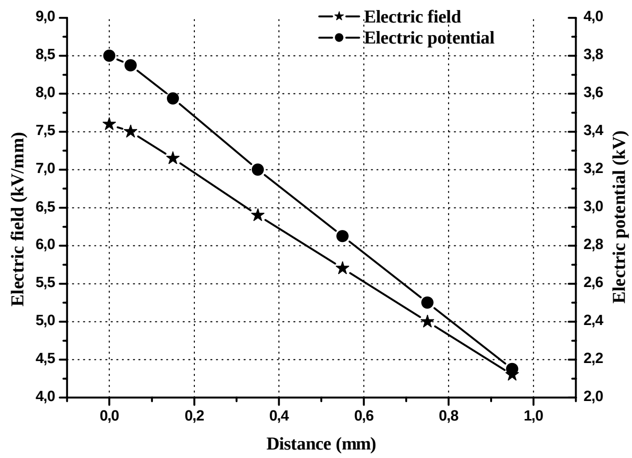


Figure 7: Electric field and electric potential distribution within the cavity as a function of the distance.

It is shown that the electric field is more reinforced if the charge density is closer the cavity or deposited on the cavity wall; this unfavourable situation leads us to consider the case when a space charge of variable density is distributed on cavity surfaces. Initially, a time a controlled DC voltage is applied to part of the sample under study as indicated in Figure 8.

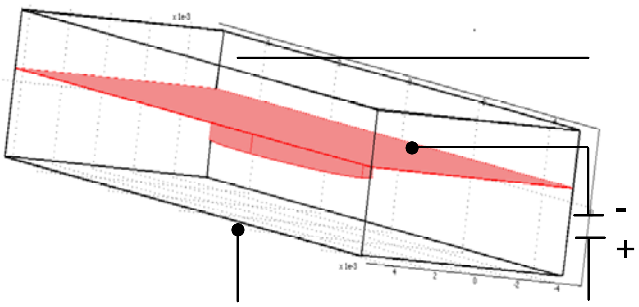


Figure 8: Application of controlled negative DC voltage

The upper metalized face of the cavity is connected to the ground, which enables polarization of the sample and thereafter the formation of a surface density of electric charges on the cavity walls. For a DC voltage of 7 kV, Figure 9 shows an example of the charge density distribution on the cavity wall.

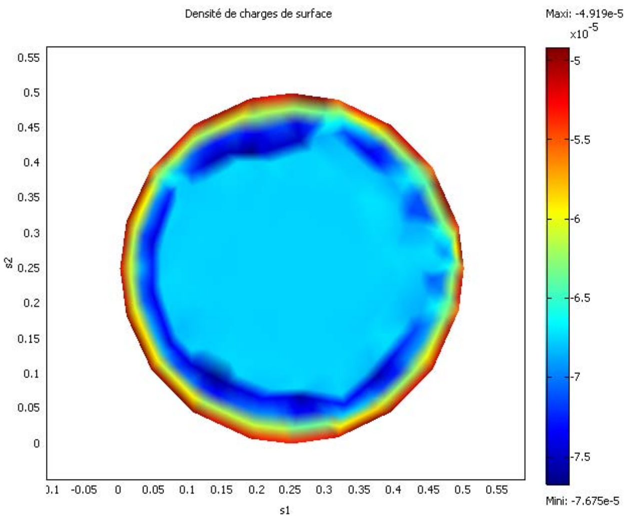


Figure 9: Charge density distribution on the cavity wall.

Figure 10 shows the results obtained by simulation, indicating that the deposited charge density increases when the applied DC voltage increases.

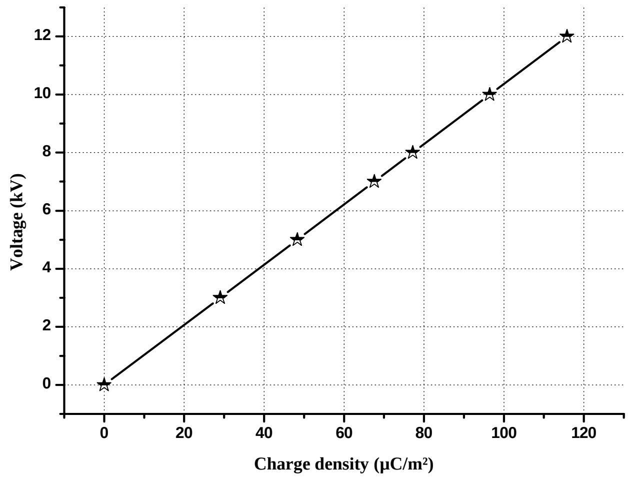


Figure 10: Applied DC voltage as a function of charge density

As was shown earlier, by applying a variable DC voltage, a variable amount of charge density could be created on wall cavity. For this reason, a quantitative analysis of the electric field and the electric potential distribution in the material and within the cavity is performed. For increasing charge density, Figure 11 shows that electric potential is affected and reinforced within the cavity, and that the potential difference in the cavity increases.

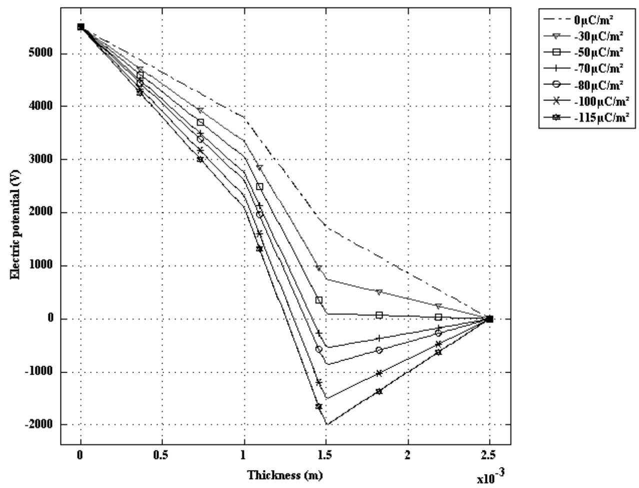


Figure 11: Electric potential distribution within the sample as a function of charge density

The electric field and electric potential within the cavity were calculated. Figure 12 shows that both electric field magnitude and electric potential are affected. These two electric quantities increase when the space charge density increases

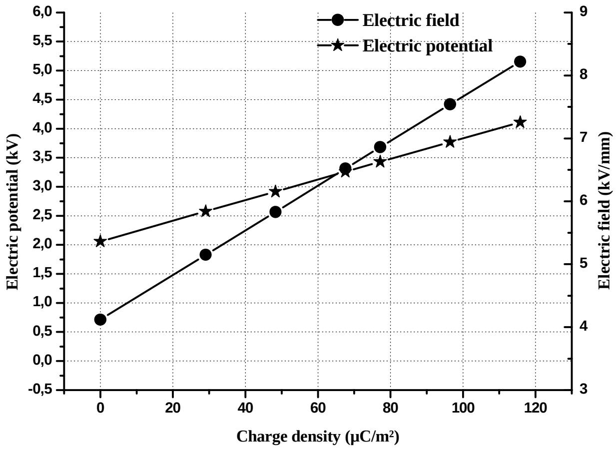


Figure 12: Electric field distribution within the cavity as a function of charge density

5 PARTIAL DISCHARGE MEASUREMENT

PDs activity is investigated experimentally in order to show how the main PD characteristics are influenced by the field and potential distorsion. For both cases, in the presence and in the absence of charge density, the pulse shape, pulse phase distribution, PDs magnitude and PDs number are recorded. The discharges inception voltages were measured (voltage rising rate about 0.5kV/s). A sufficient number of measurements were made in order to verify the reproducibility and to find an average value.

Preliminary measurements were made and on a virgin sample, free from any electrical treatment. In this case, partial discharges are detected for an applied voltage of approximately 5.5 kV, which corresponds to a potential difference in the cavity of about 2.1 kV. This value matches the breakdown voltage of a 0.5 mm air interval according to Paschen curve.

Figure 13 shows that the PD signature is slightly asymmetrical in phase of the applied voltage. The number of positive PD is higher than the negative ones. In this case, the asymmetry may be due to a space charge produced by an earlier partial discharge. Under an alternating voltage, the polarity of the local field changes periodically. The reduction of the local field for a voltage polarity leads to an increase in the field on the opposite polarity. The next discharge, on the half wave of opposite polarity, appears with a weaker tension.

Immediately after space charge creation, PD activity is recorded during the first 10s of polarization. Under such conditions, it may be considered that a part of the introduced space charge (which has been deposited on metallized cavity side) may affect the PD activity. In fact, Figure 14 shows that the space charge effect is certainly the modification of the pulse-height and the pulse phase distribution. There is no discharge in the opposite polarity and the distribution is not symmetrical. These changes are attributed to the surface cavity.

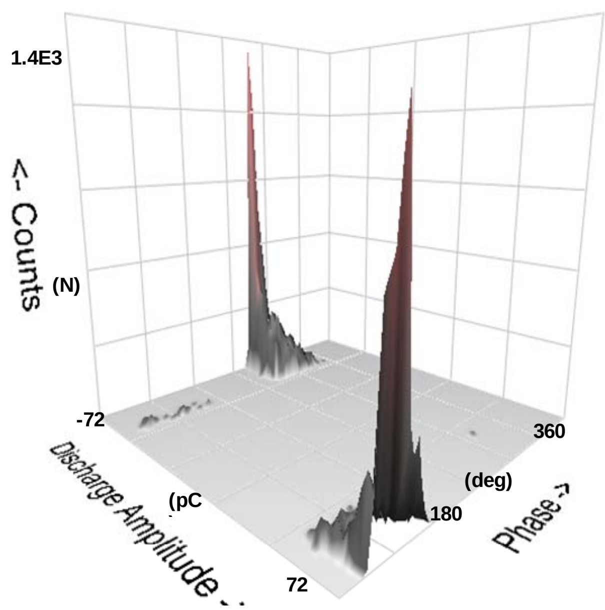


Figure 13: Partial discharge pattern before the application of a DC voltage.

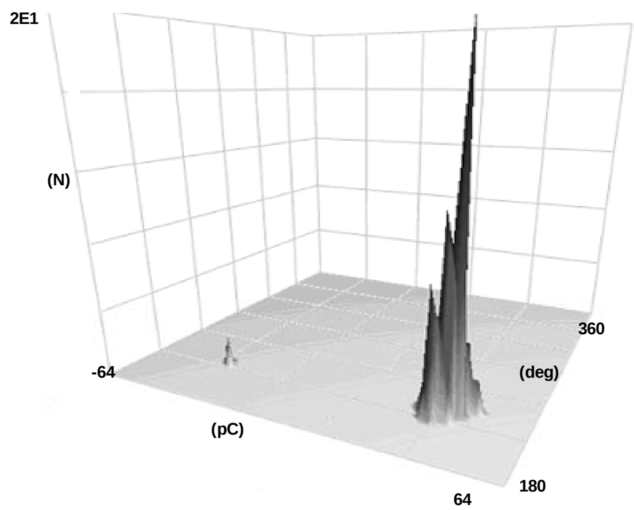


Figure 14: Partial discharge pattern with space charge.

When the polarity of the AC voltage is positive, space charge creates an additive field, thus the number of pulses becomes higher. On the contrary, during the negative polarity of the applied voltage, the charges create an opposite field so the partial discharge appears with higher applied voltage. This charge effect can only be observed in the very first seconds of polarization. But when this space disappears, PD activity during the two polarity of the voltage must become symmetrical.

In order to validate experimental results, it is important to compute the PD threshold voltage by introducing the charge density values already calculated (Figure 10).

In a past section, it was shown that the ample without space charge case and for our sample dimensions the potential difference in the cavity which will produce PD is approximately 2.1 kV. This value corresponds to an applied voltage equal to 5.5 kV (figure 11). Therefore, taking account of this value which is maintained constant, and for various values of charge density, the PD threshold voltage was calculated. Figure 15 and 16 show that the potential difference and electric field in the cavity are constant for different charge density values and different applied AC voltage.

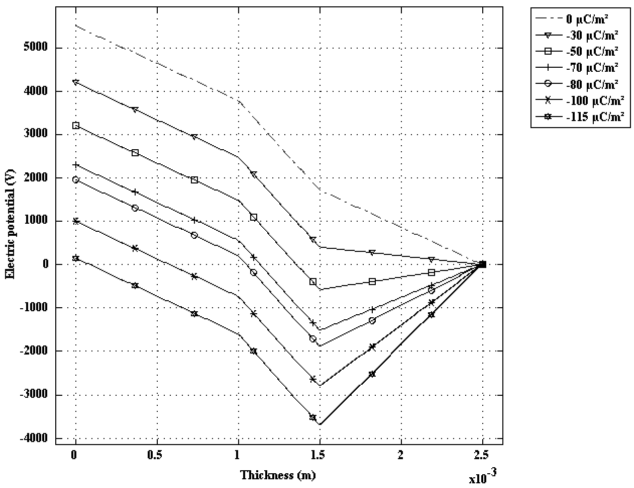


Figure 15: Electric potential distribution within the cavity as a function of charge density

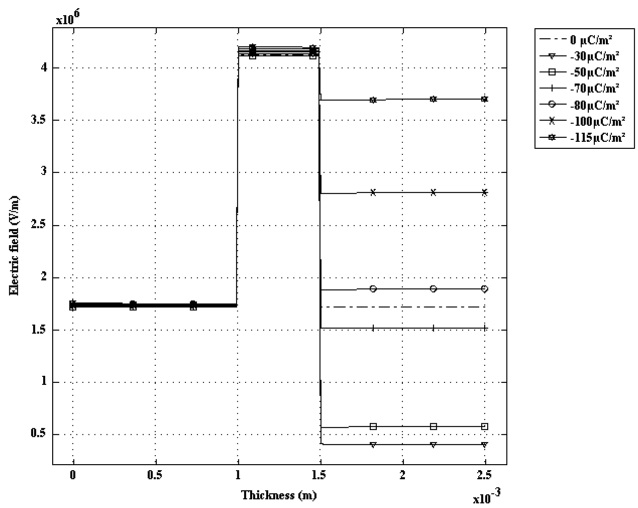


Figure 16: Electric field distribution within the cavity as a function of charge density

For increasing values of charge density and to have a potential difference equal to 2.1 kV and constant electric field equal to 4.2 kV/mm, is necessary to apply a lower voltage. Further more, as shown in Figure 17, the discharge inception voltage decreases from a value close to that of a virgin sample when charge density increases.

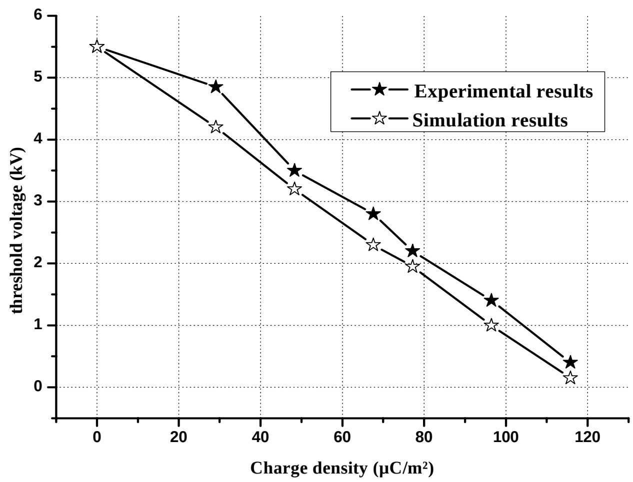


Figure 17: Threshold voltage of PD ignition as a function of charge density

The simulation results are in good agreement with the experimental one. The larger the space charges quantity the lower the PDIV. PD is strongly influenced by field modification due to space charge. However, space charges modify the field in the cavity; space charge field in the dielectric could be created and the field was reinforced, so partial discharges are more probable.

6 CONCLUSION

The relation between space charge and partial discharges phenomena due to electrical stresses are investigated. This paper presents both simulation and experimental evidences of relations between PDIV: partial discharge inception voltage and charge accumulation. PDs in trapped air-filled gaps between two adjacent insulated tapes made of high density polyethylene were measured. An amount of space charge is introduced on cavity surface by polarization then an AC voltage of increasing magnitude was applied until PDs was initiated and observed. The voltages at which PDs initiate are measured for samples with or without space charge.

It was shown that distance has an important effect in the electric field distortion. The electric field in the cavity is reinforced when the distance decreases. In fact a maximum of field is reached for a charge density closer to the cavity, so partial discharges are more probable. Furthermore electric field is more reinforced for important values of charge density. According to charge polarity, charge creates an additive field, and on the contrary, during the opposite polarity of the applied voltage, the charges create an opposite field.

It was shown that the larger the space charge amount, the lower the PDIV. Both the numerical analysis and the experimental results show that PD is strongly influenced by field modification. Computation results by simulation are in good agreement with the experimental ones.

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