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Transient dynamics of packet-like space charge in low-density polyethylene at high temperatures

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ABSTRACT

Among features observed in polyethylene-based materials under high fields, packet-like space charge are frequently reported but without complete theory explaining their formation and propagation. The present contribution reports transient dynamics of packet-like space charge in low-density polyethylene (LDPE) under multi-field coupling conditions based on pulsed electro-acoustic (PEA) method. The measurements were carried out under −125 kV/mm at 20 °C, 40 °C, and 60 °C. Space charge results reveal systematic occurrence of positive packet-like space charge in all samples generated at the anode and then moved toward the cathode. It is observed that higher temperatures contribute to the migration of packet-like space charge and field distortion. Based on the detailed injection model of packet-like space charge, it is shown that electrode injection plays a major role in the formation of positive packet-like space charge, the total amount and depth not only depend on the temperature, but also the negative charges dynamics. Packet-like space charge phenomena at different temperatures still feature NDM relationship with the nonlinear increase of migrate velocity as the rise of temperature.

1. Introduction

Charge transport under high electric field in the polymeric materials is of particular interest as charge dynamics is closely associated with field distortion, conduction current, power dissipation, physic-chemical ageing, and electrical breakdown [1–3]. It is well known that HVDC extruded power cable suffers severe space charge accumulation. Thus, design, manufacture, and long-term stability can be complicated tasks under real service conditions [4,5]. Moreover, cable insulation layer also suffers temperature gradient caused by heating due to Joule losses originating from the conductor [6]. Carrier mobility, conductivity, and electrical strength of polymeric dielectrics strongly depend on the temperature, while the transient charge dynamics completes in a very short period at high temperatures, which requires high-speed and dynamic measurement technology of space charge in solid dielectrics.

Under high fields, packet-like space charge, consisting in a pulse of net charge that remains in the form of pulse as it cross the insulation, could be observed in dielectrics and study on the mechanism of formation, transport, accumulation, and dissipation of packet-like space charge is of great significance [7–9]. In order to investigate the transient dynamics of space charge under the conditions of pre-breakdown and polarity reversal, several research groups have been focusing on the high-speed space-charge measurement technology since 90's last century [10–12]. However, the main limitation occurred in this technology is the controversial between the short acquisition interval and long-period continuous measurement. In this article, we put up with a new system design and balanced these two aspects according to the test requirements. Finally, a 1 ms acquisition interval and 10 min-longest continuous space charge measurement system was developed successfully.

The aim of the article is to investigate the extent of transient packet-like space charge behavior injected from the electrodes into low-density polyethylene (LDPE) at high temperatures. For this purpose, millisecond-level space charge measurements were carried out under high fields at different temperatures. The main results, consisting of packet-like space charge dynamic track, field distortion, and quantitatively injected amount, are discussed here.

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2. Experiment details

2.1. Material and sample preparation

LDPE pellets were purchased from Sigma-Aldrich (CAS 9002-88-4) with melt index of 25 g/10min, density of 0.925 g/ml (25 °C), and melt point of 116 °C. LDPE films with a thickness of 200 ± 10 μm were prepared via hot-press method using polyimide films as substrates under the conditions of 140 °C, 5 min, and 10 MPa, for the following space-charge measurements. When the hot-press process finished, LDPE films were transferred into ice water (about 0 °C) to obtain a relatively high annealing rate as soon as possible, resulting into the fast non-isothermal crystallization. In order to avoid the influence of moisture, all samples were subsequently dried in a vacuum oven overnight at 70 °C and then stored in a drier.

2.2. Space charge measurement system

An advanced millisecond (ms) short-interval space charge measurement system based on pulsed electro-acoustic (PEA) method was developed for the observation of transient dynamic process of space charge in LDPE samples [13]. A 9 μm β-polyvinylidene fluoride (PVDF) film was adopted as the piezoelectric sensor, which possesses the operating frequency range of 0–500 MHz. The voltage-withstanding ability of PEA unit could reach ±60 kV DC with a new design of insulation structure of high voltage electrodes. Temperature was conditioned via an oven up to 70 °C. The main parameters of solid-state high voltage pulse generator were 1 kHz, 250 V, and 4.5 ns.

In this work, due to the applied DC electric fields were chosen from −75 kV/mm to −125 kV/mm, PEA system has a relatively good signal-noise ratio. Thus, the average number of original PEA waveforms could be reduced from hundreds or thousands to just 10, or even less, for the subsequent data processing using an advanced digital oscilloscope. By updating the digital oscilloscope with a 500 MB storage module, the measurements with 1 ms high-speed acquisition interval could be continuously carried out for 10 min at least. Moreover, the newly developed PEA system is also able to measure external current simultaneously as well as space charge. A thin alumina layer (Al_2O_3) was used for the separation of space charge and external current signals due to its insulation property and similar acoustic impedance compared to aluminum electrodes.

During the space charge measurement, polarization time was set 2 min and depolarization time 1 min. The temperatures were selected as 20 °C, 40 °C, and 60 °C. Each group was tested twice at least (see Fig. 1).

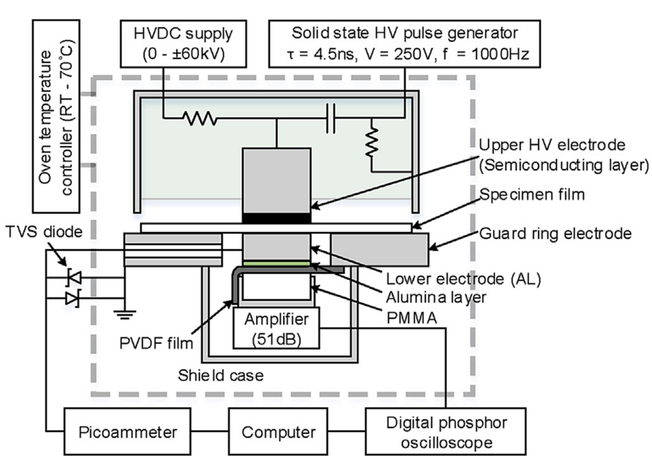

Fig. 1. Millisecond-level measurement system of space charge and conduction current.

3. Results

3.1. Transient dynamics of space charge at 60 °C

Fig. 2 presents the transient dynamics of space charge in LDPE samples at 60 °C under different nominal fields. In order to describe the detailed process, the polarization process is divided into three different time scales, namely 0–1s, 0–5s, and 0–2 min. Comparing Fig. 2a-1, 2b-1, and 2c-1, both positive and negative charge velocities decrease as the rise of field within 1s, and packet-like space charge is only observed under −125 kV/mm. Furthermore, the injection depth of negative charges seems to be suffer more from the variation of applied field. It is worth mentioning that charges of both polarities already accumulate in the vicinity of electrodes at 1s under −75 kV/mm in Fig. 2a-1. As the polarization time goes on, heterocharges near anode play a dominant role in the sample gradually shown in Fig. 2a-2.

When the electrical stress is raised to −100 kV/mm in Fig. 2b-1, it is obvious that large amounts of positive and negative charges inject extrinsically from both electrodes, then moves towards and meet with each other within 5s. In addition, several waves of negative space charges migrating from the cathode to the anode were observed in the first minute. In Fig. 2c, a positive packet-like space charge generates from anode under −125 kV/mm with the continuously increasing amplitude and leaves positive charges behind it. Only a small amount of negative space charges is observed near the cathode within 1s, which is quite different with the other two groups. As the packet continues to migrate towards the cathode, the field in front of it is enhanced and thus trigger the severe injection of negative charge, which can be seen in Fig. 2c-2 and 2c-3. After the decrease of positive space charge through recombination and extraction process, negative packet-like space charge generates, which could be conclude that the formation threshold of negative packet-like space charge is higher than that of the positive one.

3.2. Packet-like space charge phenomena at different temperatures

Fig. 3a, b, and 3c show the packet-like space charge evolution under −125 kV/mm at 20 °C, 40 °C and 60 °C, respectively. It can be seen that a positive packet-like space charge generates and moves towards the cathode in all groups. In addition, the amplitude of packet-like space charge grows larger during the migration. The difference on migration characteristics is also observed with varying temperature. Although the migration rate of these charge packets increases with temperature, the amplitude decreases. Moreover, injection of negative space charge could be observed as the rise of temperature and field distortion, and negative packet-like space charge even appears after the dissipation of positive charge packet accumulated near the cathode at 60 °C.

4. Discussions

4.1. Effect of temperature on the carrier mobility

Polyethylene is regarded as excellent electrical insulating material because of low carrier mobility and high trap concentration [14]. However, there insulation properties also lead to the formation and accumulation of space charge under DC fields and subsequently the severe distortion of internal electric field, which would strongly influence the conduction, breakdown, and ageing [15].