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Original Article

Experimental investigation and numerical simulation of electrical tree growth in polyethylene under AC voltage

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ABSTRACT

This paper reported the growth of electrical tree in low density polyethylene under AC voltage. Specimens of double needle geometry were achieved by compression molding. The evolutions of electrical tree length and discharge magnitude versus aging time were studied. The tests were carried out until dielectric breakdown of the polymer happens. Firstly, ionization of the cavities occurs inducing a rapid propagation of electrical tree. Secondly, the growth slows down resulting to the rise of gas pressure in the tree channels. The decrease in growth rate is also attributed to the increase of the electric conductivity of channel walls. This process is highlighted by the inception and the extinction of partial discharges. The presence of space charge affects the growth of tree. For the modelling of electrical tree, we have considered a model with two concentric spheres. The simulation results were validated by the experimental tests.
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1. Introduction

It is well known that electrical tree can occur in solid dielectric when it is subjected to high electrical stresses. Electrical tree is often referred to as the most important degradation mechanism in solid polymeric insulation [1-2]. Tree initiates in gas-filled voids because partial discharges take place when the electrical field exceeds the breakdown strength of the gas. In solid insulating materials, internal defects (voids, cracks, and impurities, interfacial) can be formed during the manufacturing process despite all the precautions one can take.

There are two distinct phases of electrical tree process [3]. The first one is the initiation phase, during which luminescence happens but no partial discharges are detected. The second one is the propagation phase, during which significant measurable partial discharges generate and tree grows.

Once tree starts, it usually continues to grow in the direction of the electrical field. It propagates from the points of stress concentration by partial discharges. Many authors reported electrical tree growth in solid insulating materials. Laurent and Mayoux [4] investigated growth of electrical trees and a simultaneous measurement of discharges initiated in microchannels of different types of trees which are branch-type tree, bush-type tree and, bush and branch-type tree. Densley [5] mentioned that space charges are dominant in determining the shape of tree and the time to breakdown in insulation. Arbab and Auckland [6] reported that tree growth is sensitive to applied mechanical stain and to internal strain built up owing to prolonged exposure to vibrational electrostatic forces. Some influencing parameters on the growth of electrical tree are: the nature of trapped gas [7,8], mechanical properties [5,9], insulation material morphology in the bulk [1,10], applied voltage and frequency [11] and interface [12]. Many authors have developed models of electrical tree growth [13-19].

This work reported an experimental study and simulation of electrical tree propagation in polyethylene under AC voltage. Polyethylene is the most polymers used in insulation systems because of its good electrical and mechanical properties.

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2. Materials and methods

2.1. Preparation of samples

The tests were performed on low density polyethylene used in high voltage cables. To simulate defects producing local field enhancement, samples of double needle configuration with stainless steel electrodes having 1 mm in diameter were realized. These electrodes, of Ogura-Jewel type, were first cleaned with alcohol and inspected using optical microscopy. The radius of curvature is 3 µm and 500 µm for the sharp needle and the blunt needle, respectively. The space between electrodes was fixed to 4 mm.

The samples were elaborated by compression molding: the electrodes were sandwiched between two 500 µm thick polymeric films, and then the specimens were heated to 170°C for 45 min while pressure was applied to the mold. Next, this later was subsequently cooled to room temperature. The specimens were carefully examined with a microscopy to confirm that no void existed around the tip of the sharp needle. Before the experiments, the samples were short-circuited for several days in a dry environment in order to neutralize the residual electrical charges created during the molding. The electrode arrangement is shown in Fig.1.

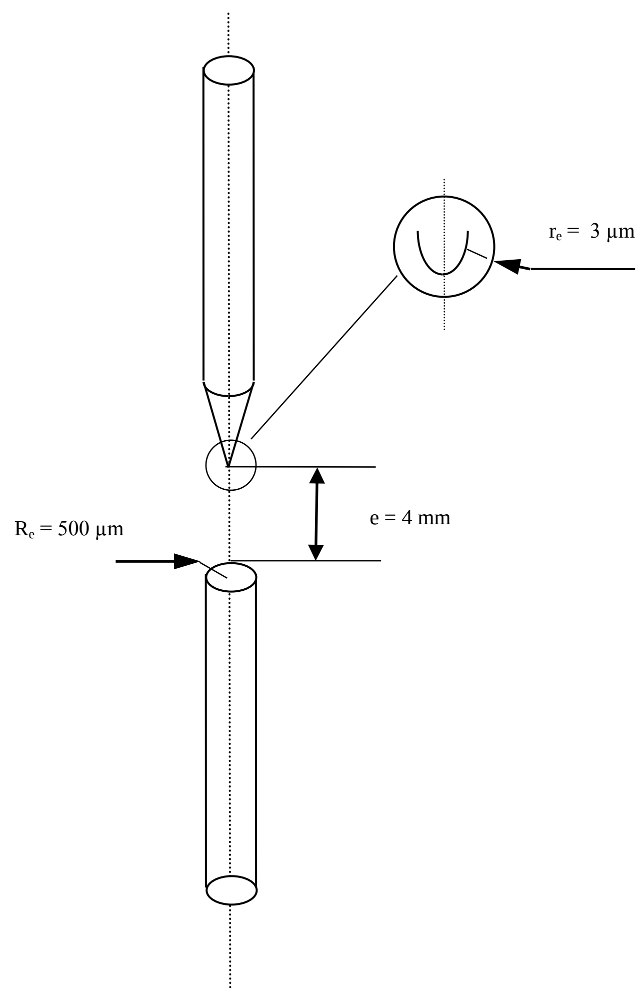

Fig 1. Configuration of electrodes, r_e being the curvature radius of the sharp needle, R_e the curvature radius of the blunt needle and e electrode space.

2.2. Experimental set-up

The prepared samples were placed in a cell and immerged in insulating silicone oil to avoid surface discharges during the experiments. These specimens were exposed to 50 Hz AC electrical field, delivered by a high voltage transformer (30 kV) connected to the measurement cell. Over cell, an optical microscopy was placed in order to measure the length of tree. The evaluation of partial discharges within tree was measured using a system of detection and measurement. This system measures the discharge magnitude larger than 1 pC. The tests were performed until the breakdown occurred. The experiments were carried out at room temperature and at different voltages: 12, 14 and 16 kV. The experimental set-up whole is given in Fig. 2.

The variation of the maximum tree length versus aging time was studied. The electrical trees are of bush – type tree. The evolution of maximum magnitude of discharges versus aging time was investigated.

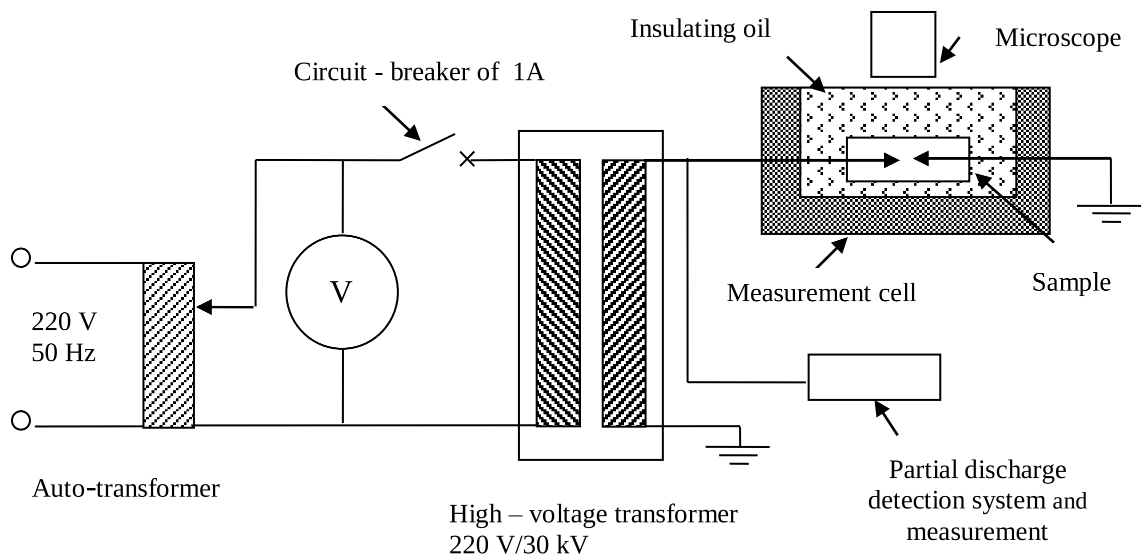

Fig 2. Experimental set-up whole.

3. Model of electrical tree propagation

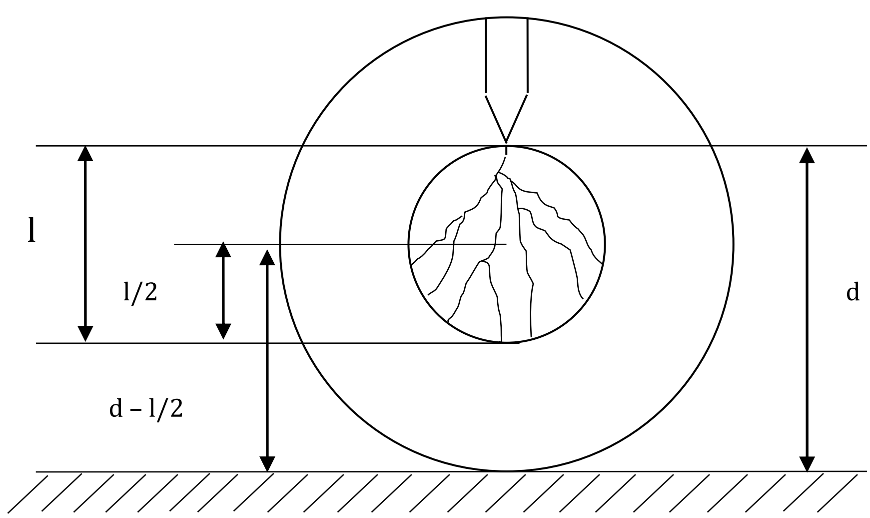

Fig 3. Representation of the model

3.1. Electrostatic pressure

The model of tree growth is based on electrostatic pressure. We assume that the interface of tree/polymer is devoid of electrical charges: the charge density of the surface is null (σ = 0). The electrostatic pressure is given by the following relationship:

$$P_e = \frac{1}{2}\,\varepsilon_0\varepsilon_r\,(\varepsilon_r - 1)\,E^2 \quad (1)$$

where:

ε_o: Vacuum permittivity

ε_r : Polymer relative permittivity

E: Applied electrical field.

If we set $K = \frac{l}{2}\,\varepsilon_0\varepsilon_r\,(\varepsilon_r - 1)$, then $P_e = KE^2$ (2)

3.2. Representation of electrical tree

The electrical tree is assumed as a sphere in the same potential than the sharp needle electrode. A concentric sphere to the first one represents the blunt needle (Fig.3).

3.3. Expression of electrical field

The electrical field was calculated by solving the Laplace' equation in spherical coordinates: $\nabla^2\phi = 0$. The length of the tree is equal to the diameter of the internal sphere. The boundary conditions are:

$$r = \frac{l}{2}, \qquad \phi(r) = U$$

$$r = d - \frac{l}{2}, \qquad \phi(r) = 0$$

with r: radius of the internal sphere and Φ electric potential.

By applying the limit conditions to the Laplace' equation, we obtain the electrical field on the internal sphere:

$$E(l) = \frac{U}{d}\,\frac{2 - \frac{l}{d}}{\left(1 - \frac{l}{d}\right)\frac{l}{d}} \quad (3)$$

with:

d: inter-electrode distance

l: tree length

U: applied voltage.

3.4. Energy balance

We assimilate the electrical tree to a conductive cavity which grows from the tip of the sharp needle to the blunt needle maintaining a spherical form. The work of the electrostatic pressure provided at the tree/polymer interface can be expressed as:

$$W = \int_{R_0}^{R} 4\pi R^2 . P_e . dR$$

with:

P_e: electrostatic pressure

R_o: initial radius of the electrical tree

R: radius of the electrical tree at time t.

The work W is transformed to kinetic energy which is given by the following formula:

$$E_C = \frac{1}{2}\rho\left(\frac{4}{3}\,\pi R^3\right)\left(\frac{dR}{dt}\right)^2$$

Here ρ is the volume mass of the polymer

Equating the expressions of work and kinetic energies, we obtain:

$$W = E_c \text{ then } \int_{R_0}^{R} 4\pi R^2 . P_e . dR = \frac{1}{2}\rho\left(\frac{4}{3}\,\pi R^3\right)\left(\frac{dR}{dt}\right)^2$$

After differentiation and arrangement we get:

$$P_e = \frac{1}{2}\rho\left[\left(\frac{dR}{dt}\right)^2 + \frac{3}{2}\,R\left(\frac{d^2R}{dt^2}\right)\right]$$

We assume that the electrical tree movement is uniform: $\frac{dR}{dt}$=constant, thus $\frac{d^2R}{dt^2} = 0$. The expression of electrostatic pressure becomes:

$$P_e = \frac{1}{2}\,\rho\left(\frac{dR}{dt}\right)^2 \quad (4)$$

3.5. Propagation rate of electrical tree

By combining (2), (3) and (4), we obtain:

$$K\left[\frac{U}{d}\,\frac{2 - \frac{l}{d}}{\left(1 - \frac{l}{d}\right)\left(\frac{l}{d}\right)}\right]^2 = \frac{1}{8}\,\rho\left(\frac{dl}{dt}\right)^2$$

with l = 2R

Then the propagation rate of the electrical tree versus the different parameters can be written as follows:

$$\frac{dl}{dt} = g\,\frac{U}{d}\,\frac{2 - \frac{l}{d}}{\left(1 - \frac{l}{d}\right)\left(\frac{l}{d}\right)} \quad (5)$$

with $g = \sqrt{\frac{8K}{\rho}}$

4. Results

4.1 Variation of electrical tree length versus aging time

Fig.4-6 show the dependence of tree length on aging time. This can be summarised as follows:

For the three voltage levels, the electrical tree grows according to two phases. We do not consider the change in slope which happens before perforation, expressing the interactions between channels and blunt needle.

- Under a voltage level of 12 kV
  During the first phase, after 67.3 min, the tree length increases to 1910 µm. This phase is characterized by a rate of 0.6 µm/s. During the second phase, the tree length rises to 3211 µm corresponding to an aging time of 200.3 min. The rate is of 0.1 µm/s. Then, the tree grows and reaches 4088 µm after 255 min thence breakdown occurs.
- Under a voltage level of 14 kV
  Firstly, the tree length rises to 2519.4 µm for an aging time of 73.2 min. In this phase, the speed is of 0.6µm/s. During the second stage, the length increases to 3094.57 µm after 164.6 min. The breakdown occurs after 200 min and the length reaches 3538 µm.

– Under a voltage level of 16 kV

At the beginning, the length increases to 1115 µm after 39.2 min with a rate of 0.5 µm/s. Afterwards, the length rises slowly to 1471.4 µm after 72.54 µm with a speed of 0.1 µm/s. The perforation occurs after 115 min and the length reaches 3360.2 µm.

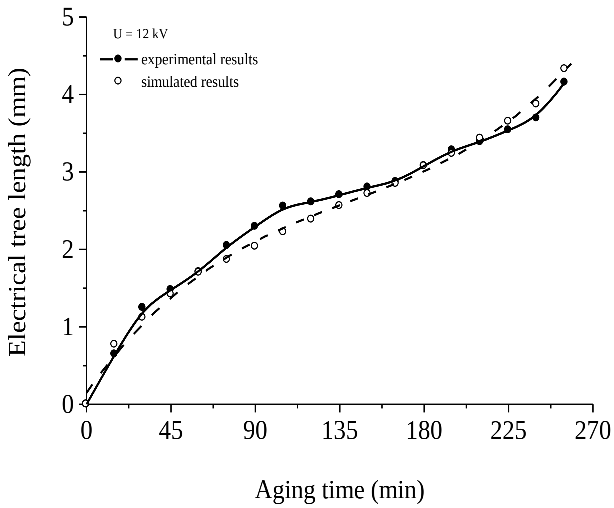

Fig 4. Dependence of tree length on aging time at 12 kV.

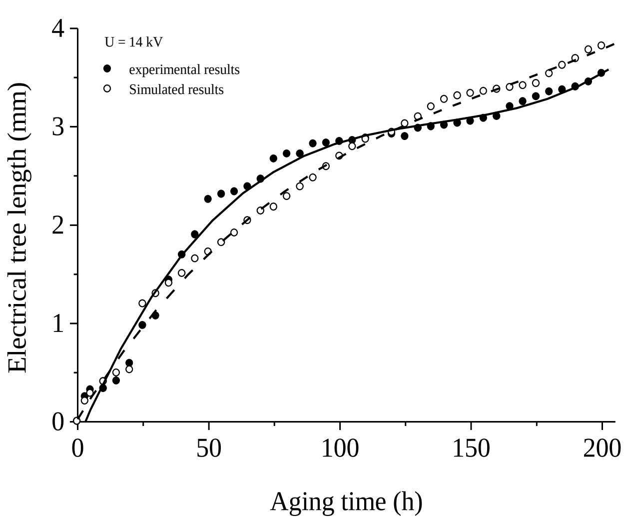

Fig 5. Dependence of tree length on aging time at 14 kV.

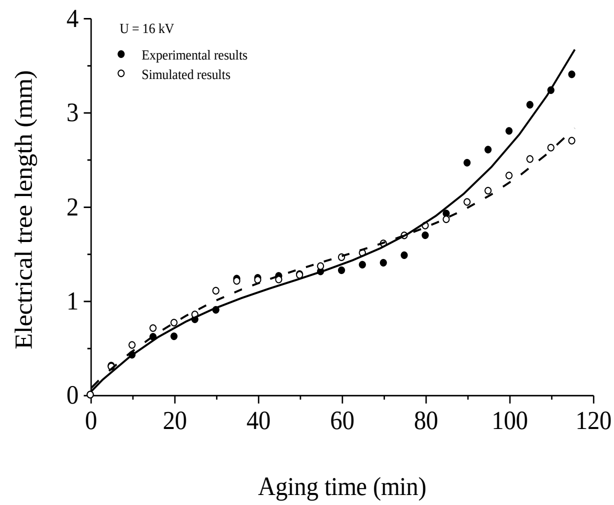

Fig 6. Dependence of tree length on aging time at 16 kV.

4.2. Variation of the discharge versus aging time

Fig.7 represents the variation of maximum discharge magnitude in function of aging time. As one can see, the curves present several minimums and maximums related to inception and extinction of partial discharges, respectively. The maximum discharge amplitude increases with applied voltage. At 12 kV, the higher peak corresponds to 598 pC after 105 min. For 14 kV, the higher peak is of 1551 pC after 190 min. At 16 kV, the higher peak is equal to 1558 pC after 60 min.

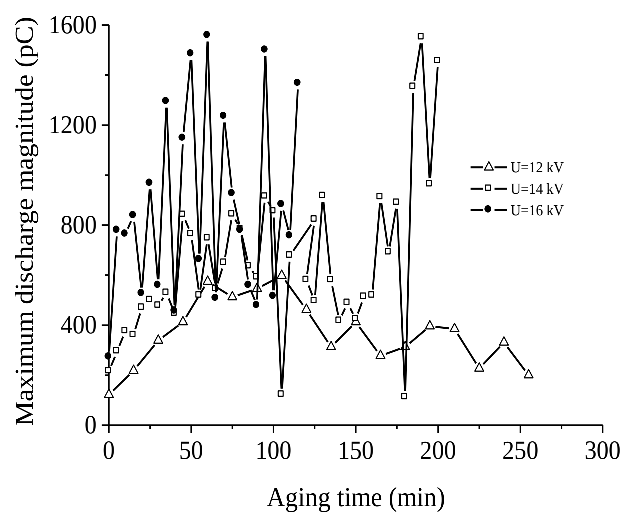

Fig 7. Variation of maximum discharge magnitude against aging time at different voltages.

4.3. Simulation of tree growth

The simulation of tree length is carried out using finite difference method. The results are presented in Fig.4-6 with discontinuous lines. Fig.8 gives an example of the simulation errors. The curves giving the variation of tree length versus aging time were successfully reproduced in computer simulation. The maximum errors are 19.26%, 23.64% and 24.61% for 12, 14 and 16 kV, respectively.

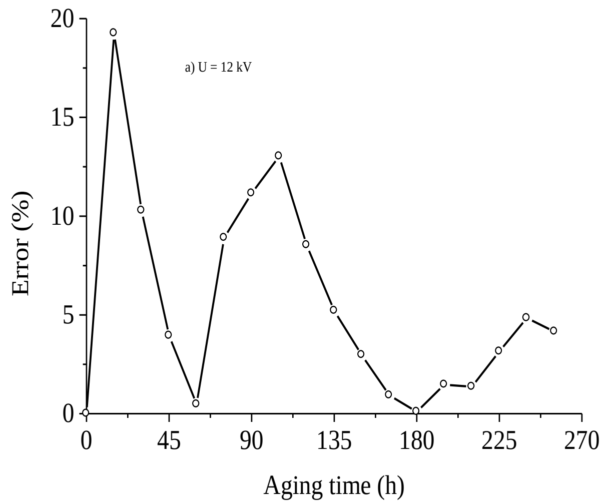

Fig 8. Errors of simulation

5. Discussion

1. When a high voltage was applied to the samples, the initiation of electrical tree happened rapidly in the tip of the sharp needle from a void, for instance.
2. Tree propagates from a site of stress concentration by successive partial discharges when the maximum effective stress at channel extremity reaches the intrinsic electrical strength of the material. Discharges erode the edge of cavity and increase slowly its size [20]. The erosion process may consist of [21]:
   - direct attack by ions produced in the discharge
   - local temperature rise by high temperature discharge gases
   - chemical reaction initiated by excited molecules and/or chemical compounds generated in the discharge

   The oxidation of the cavity wall [22] and the rise in temperature [23] have been reported. The increase in number and dimension of cavities versus aging time has been also mentioned by Dissado et al [2].
3. The actions of partial discharges lead to the decomposition of the polyethylene into gases. The gases are mainly CO, CO_2, H_2 as reported by Laurent et al [24]. Cooper et al [25] indicated that partial discharge activity was always accompanied by bursts of gaseous products, primarily H_2 and C_2H_2. Small quantities of other hydrocarbons were also observed.
4. The growth of electrical tree can be described as follows:

a) During the first phase, the available voltage U_a applied to cavities is higher than the ionisation voltage $U_{i,}$ of the discharges. Based on Pashen's curves, the inception of discharges takes place then the tree grows rapidly as one can see in the Fig.4-6.

b) During the second phase: the activity of partial discharges causes degradation thence the gas pressure increases. The voltage U_a is less than U_i. The extinction of the discharges occurs and the propagation temporarily slows down. The rise of gas pressure is reported by Loffelmacher [26] who indicates that molded needles were injected under the effect of the gas due to the polymer degradation. In this investigation, the author pointed out the relationships between electrical stress, growth rate, and internal pressure in channels and appearance of tree. The diminution of propagation speed is also allotted to interaction of existent electrical field within the channels of tree as mentioned by Bahder et al [27]. It has effect to reduce the gradients of electrical fields. When gas pressure in the tree channels has been reduced sufficiently by permeation outwards, ionisation will grow little longer or thicker as reported by Nawata and Kawamura [28]. The tree growth rate is influenced greatly by the gas evolution. The gas diffusion is a characteristic depending on the material. Self extinction of discharges is also caused by the increase in conductivity of channel walls. Indeed, the insulating wall perturbs the discharge conditions. Charges on the surface of the walls create an electrical field modifying the macroscopic field which produced the discharge [29]. Hence, the local electrical field is insufficiency to create ionisation of cavities.

5. The time to breakdown is shown to be dependent on the level of the applied voltage.
6. The electric field plays a fundamental role in the mechanisms of electrical tree. The maximum electrical field at the tip of sharp needle was calculated using hyperboloidal approximation proposed by Griac et al [30]:

$$E_{max} = \frac{2V}{r\,Ln\left[\frac{2d}{r}\left(1 + \frac{2d}{R}\right)\right]} \quad (6)$$

where V is the applied voltage; d space between the electrodes; r curvature radius of the sharp needle; R curvature radius of the blunt electrode. The calculation results of the maximum electrical field are as follows:

a) V = 12 kV, E_{max} = 7.46 MV/cm
b) V = 14 kV, E_{max} = 8.71 MV/cm
c) V = 16 kV, E_{max} = 9.95 MV/cm.

Carrier injection leads to measurable space charge effects when the local field at the surface of the injective electrode exceeds a certain value 'critical field for space charge injection'. The critical field for electron injection is reported to be ~100 kV/mm for polyethylene [31]. The values of E_{max} point out the presence of space charge which was formed due to the injection of electrons and /or holes from the sharp needle. The formation of space charge in polyethylene plays an important role in the breakdown process [32,33].

7. The evolution of maximum magnitude of partial discharges in function of aging time shows several maximums and minimums attributed to inception and extinction of the discharges, respectively. The maximum magnitude rises with voltage as indicated in Fig.7.

6. Conclusions

1. The study shows that the propagation of electrical tree is done according two phases. At the beginning of aging, ionisation of the insulating material occurs and induces inception of partial discharges. The action of discharges leads to material degradation in gases. The electrical tree grows rapidly with a propagation rate of 0.6 µm/s.
2. After several hours of aging, the gas pressure in channels rises, the discharge extinction take place thereby leading to slowdown of the electrical tree growth. The growth rate is of 0.1 µm/s.
3. Next, the gas can diffuse in bulk of the material, the pressure will be reduced and the inception of discharges appears. Later, the polymer degradation is accompanied by several repeated actions of inception and extinction of partial discharges until the dielectric breakdown occurs.
4. The electrical field calculation highlights the presence of space charge around the needle electrode. The space charge affects the process of tree propagation.
5. There is a good agreement between the experimental results and those obtained by the computer model; the maximum error is 24.61%.

Confict of Interest

The author declare that he have no conflicts for interest.

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