Estimation of the Conductivity of Water-treed Regions in Polyethylene

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***Abstract*—Electrical conductivity of the treed regions in a water-treed low density polyethylene (LDPE) sample has been estimated by using an equivalent numerical 3D model. Numerical calculations have been performed with FLUX3D software and the modeling results have been compared with the experimental data obtained from current measurements using a Keithley 6517 electrometer.**

Two cases have been considered for the conductivity of the treed regions: constant and having linear variation with the depth.

Even in the most simple case in which the treed region is considered to be homogenous, the numerical model gives a reasonable fit with the experimental data. Thus, by considering for treed regions a conductivity of 10^{-14} S/m, the computed intensity of the current passing through the sample is $1.1 \cdot 10^{-14}$ A, having the same order of magnitude as the measured current.

***Index Terms*—Polymers, water trees, conductivity, numerical modeling.**

I. INTRODUCTION

The initiation and the development of water trees in polymeric insulation are very complex phenomena. Many simplified models were proposed in order to explain water-treeing process and/or to estimate the electrical properties of water trees [2, 3], but there is not yet a general model or theory to answer these questions by treating globally these phenomena. In this paper we present the preliminary results of a study focused on the simulation of the electrical behaviour of water trees developed in plane additive free LDPE samples. The numerical models considered in this study were elaborated with the FLUX3D package, a powerful tool for electromagnetic field analysis based on the finite element method.

In a first approach the purpose of the modeling is the obtaining of qualitative results corresponding of global quantities (current intensity, capacity, resistance) which can be validated by the experiments. Then, by using the models one could estimate the electric behaviour of the polymeric insulation with water trees without performing measurements which are in most cases energy and time consuming.

II. EXPERIMENTAL

Disks of 0.5 mm thickness and 24 mm diameter were made by compression moulding from pellets of LDPE without additives, manufactured by BOREALIS Group.

On one face of each sample, small needle-like defects were created, as initiation sites for water trees. In order to obtain a uniform distribution of the initiation sites, these needle-like defects were created by pressing a sheet of abrasive paper (P240) on one face of the sample, for 2 min at 50 MPa [1, 7].

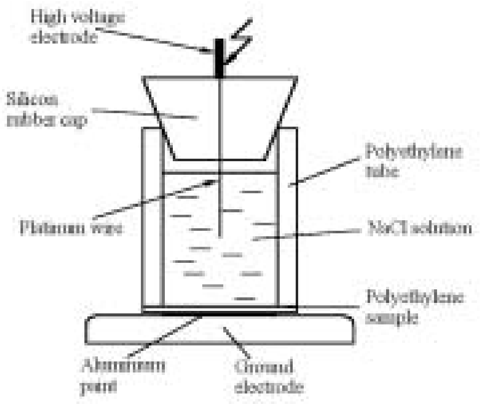
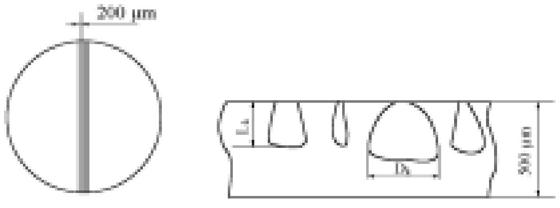


Fig. 1. Cell used to produce water trees.

Water trees were grown in cells (Fig. 1) realised by sticking the sample on a polyethylene tube, using LOCTITE 401 after an adequate surface treatment. The electrolyte was a NaCl solution of concentration $c = 0.1$ mol/l. Groups of five cells were fixed in a cell-holder and water trees were grown by applying the samples an electric field of 4 kV/mm, 5 kHz, for 25 hours. Then, the samples were dyed in order to facilitate the measurements of water tree lengths.

The average length for a sample was determined as the average of the water trees lengths measured on the three slices of 200 μm thickness microtomed from the sample (Fig. 2). From the measurements of the water tree dimensions performed on ten samples the following results were obtained:



(a) (b)

Fig. 2. (a) Slices for measuring water tree dimensions; (b) Water tree length L_k and diameter D_k as measured on a slice.

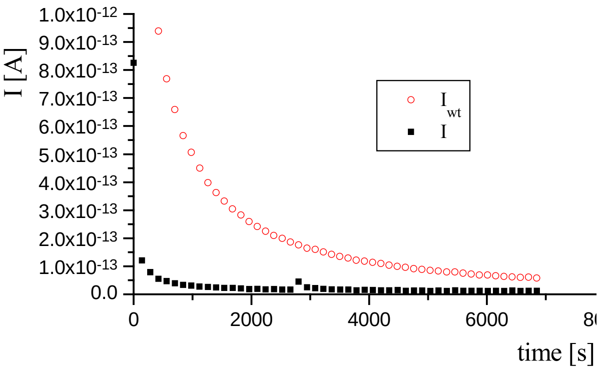


Fig. 3. Variation of the current through a sample before (I) and after (I_{wt}) water tree developement.

average number of water trees on a slice $N = 32$, average water trees length $L_m = 200$ μm and average water trees diameter $D_m = 100$ μm.

The currents through samples were measured before and after water treeing as well (Fig. 3). The measurements have been performed by applying the sample a d.c. step voltage of 1000 V, the current variations being recorded for 120 minutes.

The setup used for current measurements consist of a KEITHLEY 6517 electrometer connected to a measuring cell (of LEMD type) and a PC-Pentium for measurement control and for storing and managing the results. Ten samples were tested by the above described procedure and the average currents at $t_m = 120$ min have been compared with the currents resulting from modeling.

III. NUMERICAL MODEL

The problem has been modeled in the steady-state conduction regime. The irrotational character of the electric field allows the use of the electric scalar potential V, the equation to be solved being simply:

$$\operatorname{div}(\sigma \operatorname{grad} V) = 0 \tag{1}$$

The steady-state conduction model has been implemented by means of the finite elements based package FLUX3D. The 3D model represents a disc sector of radius $r = 3$ mm and angle $\alpha = 22.5°$ of the whole active disc sample of radius $R = 12$ mm (Fig. 4).

According to the uniqueness theorem, the potential of the conductors have to be imposed. The boundary conditions imposed to the model are: on the upper disc sector the Dirichlet condition $V = 1000$ V and on the lower disc sector the Dirichlet condition $V = 0$ V, on the side surfaces null Neumann condition, and the rotational periodicities have been taken into account.

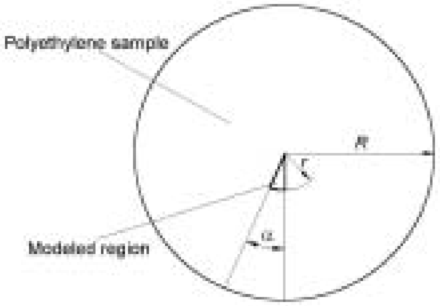


Fig. 4. Region of the sample modeled with FLUX3D

The water trees have been considered as cylinders [1], with an uniform repartition on the sample surface. The cylinders were considered identical, having the dimensions (L_m and D_m) of an average water tree defined using the experimental data presented in the previous section. The discretisation mesh (Fig. 5) was obtained by extrusion and it contains 94099 nodes and 69069 volume elements (tetrahedrons and prisms). The conductivity assigned to undamaged polyethylene (considered homogenous) was 10^{-17} S/m. For the conductivity of the cylinders representing the treed regions we have imposed a value, we have solved the problem and we have compared the resulting current with the current experimentally determined. Then we have alterated the conductivity of the treed region and we computed again the current. From this iterative process two different type of variation were retained: constant at 10^{-14} S/m and linear increase with the depth in the range $10^{-15} \div 10^{-13}$ S/m.

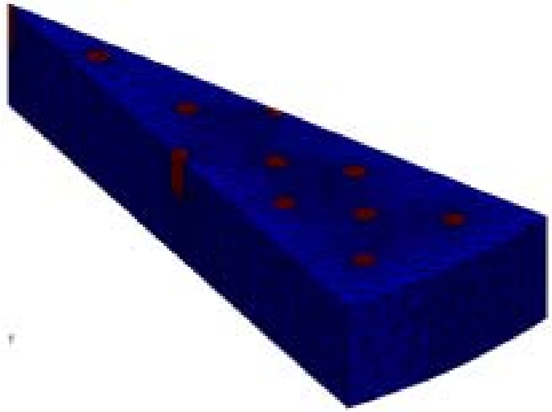


Fig. 5. Discretisation of the 3D model of the sample with water trees.

Figure 6 shows current density repartition, for constant

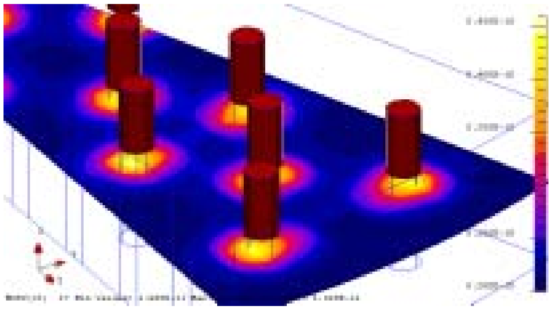


Fig. 6. Current density in a cross-section.

conductivity of the treed regions, in a cross section of the model used for computing the current intensity through the sample. The current through this cross section is $i = 0.43\cdot10^{-16}$ A, and consequently, the current through the entire sample is:

$$I = \frac{2\pi R^2}{\alpha r^2} i = \frac{4\pi(12\cdot10^{-3})^2}{22.5\cdot\frac{\pi}{180}(3\cdot10^{-3})^2}\cdot 0.43\cdot10^{-16} = 1.1\cdot10^{-14}\ \text{A}, \qquad (2)$$

having the same order of magnitude with the average value experimentally determined $I_{wt} = 1.5\cdot10^{-14}$ A.

For the linear increase with the depth of the treed region conductivity the current i was $0.437\cdot10^{-16}$ A, being very close (a difference of 1.6%) to that obtained for constant conductivity of the treed region.

IV. CONCLUSION

The preliminary results presented in this paper show that it is possible to estimate the water tree conductivity by using 3D models. Thus, the treed regions behave as insulators but they are about 10^3 times less resistive than the undamaged polyethylene.

The proposed model will be enhanced by taking into account the charge at the tree front and other types of variations of the tree conductivity with the depth. Also, other electrolyte types and concentrations will be analysed and we will study the variation of the numerical results for different tree lengths and/or different tree diameters for the same volume of the treed regions. The improved model would allow us, on the one hand, to obtain information on the nature or the concentration of the salt of the electrolyte, and on the other hand to estimate the dimensions of water trees developed in cable insulation or in opaque samples in which water trees can not be observed.

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