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Investigation of Electrical Treeing in Perspex Material

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ABSTRACT

Perspex material, does not only belong to a big family of polymers, but it is also used for large number of electrical and non-electrical applications. This paper investigates the aging mechanism of Perspex material under high electric field. Electrical treeing phenomenon is studied using Perspex samples with electrodes of a pin-to-plane configuration. The growth of electrical tree in Perspex is measured and analyzed with the aid of an advanced microscope, equipped with a high resolution camera and connected to a personal computer. A number of distinct stages are assigned to characterize the electrical tree development. The area occupied by the tree channels is calculated using equal-area squares. This approach is employed to measure the growth rate of electrical trees under dry and wet conditions. Finally, the tree construction, shape and growth speed are studied and analyzed to distinguish between treeing phenomenon under wet and dry conditions of fabricated Perspex specimens.

Keywords: *Perspex, tree, microscope, wet , dry.*

INTRODUCTION

The application of strict social distancing requirements and the need for a cheap material to make a physical barrier between adjacent persons have led to an exponential increase in the use of Perspex in parallel with the spread of Covid-19 and the attempts to contain it. Perspex is sometimes called "plexi glass", "acrylic glass" or poly (methyl methacrylate) (PMMA). It is a transparent plastic, durable, hard and stiff material. It is widely used for several applications including rear-light and instrument groups of vehicles, appliances and lenses of glasses. It has a good tensile and flexural strength. Table I illustrates detailed information on chemical composition and physical properties of the Perspex round bar [1].

Table 1: Physical properties and chemical composition of Perspex

Properties	Composition/Values
Chemical Formula	$(C_5O_2H_2)_n$
Melting Point	160°C
Boiling point	200°C
Density	1180kg/m³

Perspex is available in the form of cast sheets with surface roughness of $3x10^{-5}$cm or less [1]. It is also similar, in glass transition temperature, to many polymers such as polyester. Perspex has an outstanding resistance to outdoor environments, including ultraviolet radiation [2]. Therefore, acrylic molding and extrusion compounds are frequently used in applications requiring retaining extreme clarity under severe weathering and other environmental exposures. This property has enabled Perspex to replace glass in all applications where temperature is below 90°C and where a low chemical resistance is required. Electrically, this material possesses very good properties including a low electrical conductivity. However, the dielectric property of this material is not very high, compared with polyethylene, XLPE and PVC. Therefore, cast sheets of Perspex are mainly used for distribution boards and lighting accessories.

A number of works [3,4] have been conducted to investigate the mechanical properties of Perspex and to study its dielectric response to electric field, whereas, the detailed studies focusing on treeing process are relatively limited. Some of these studies have concentrated on the treeing analysis associated with discharge luminous image and discharge magnitude in each phase angle area [5,6,7]. Other works have focused on breakdown mechanisms and tree measurement using impulse voltages at different rise times [8,9]. On the other hand, an experiment was carried out to characterize the directly grounding tree in Perspex located at the end of a coaxial cable [10].

The present work attempts to study the treeing process in Perspex using power frequency ac voltage. Several sets of identical samples were tested for dry and wet conditions. The tree growth and the time to breakdown are measured at regular intervals. The tree shape, dimension and construction are investigated using a microscopic system. The obtained images were photographed using a high resolution camera, mounted on a microscope with high magnification factor. Finally, the microscope is connected to a personal computer as shown in Fig. 1.

EXPERIMENTAL SETUP

New Perspex material was obtained in the form of solid sheets of 50cm x 50cm x 0.6cm. A sufficient number of slabs with dimensions of 5cm x 5cm x 0.6cm each, were cut. To create a pin-to-plane configuration, a 0.5mm-tip needle was inserted into the specimen. The grounding lead is connected to the sample via aluminum foil facing the needle tip at 1mm distance as shown in Fig. 2. This arrangement facilitates the test repetition and reduced the experiment time. The tests were performed in a clean area under controlled conditions. The temperature was 22±3ºC and the relative humidity was 35±5%. To conduct the experiment, a fully-controlled 25kV testing transformer was used to test the specimens under various conditions.

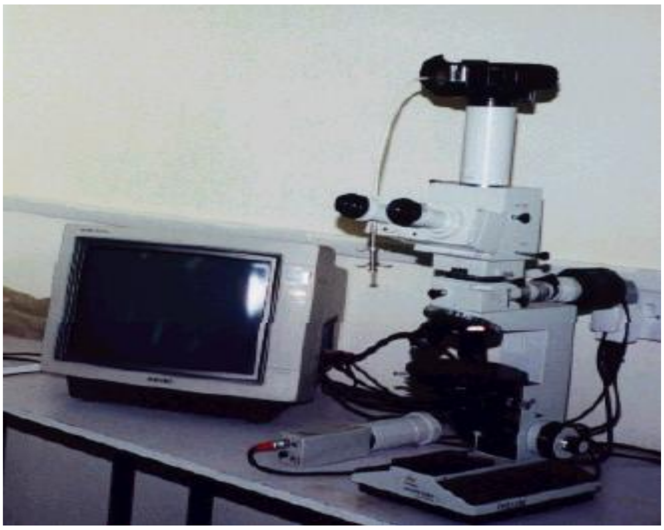


Figure 1: Treeing photography system

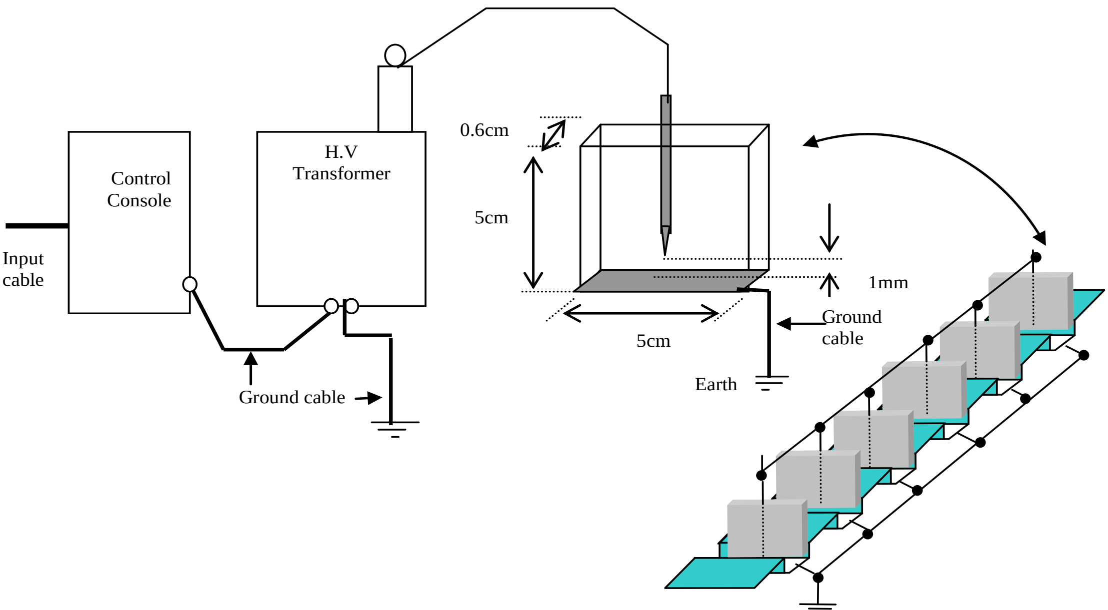


Figure 2: Sample configuration and test setup.

Before conducting the test, Perspex samples were divided into three equal groups; dry, wet with distilled water and wet with ionized water. Groups of wet samples were initially allowed to absorb water for one week (168h) before being exposed to high voltage test. The samples were then exposed to an AC voltage of 11kV(rms) for regular intervals of time (1h).

RESULTS

The transparent characteristics of Perspex were used to detect and trace the trees in the examined specimens. It was found that the tree branches grow in vertical and horizontal directions towards the earth electrode. The description of growth stages is achieved by recording the tree expansion in a systematic way.

Dry samples

To specify the tree development in dry Perspex specimens, the horizontal (along X-axis) and vertical (along Y-axis) channels were measured at equal time intervals. The horizontal component of the tree consists of all horizontal extensions of the branches on both sides of the main direction of the tree, whereas, the vertical component considers only the straight-up expansions directed towards the earth electrode. Figure 3 demonstrates the growth process from the moment of tree initiation to breakdown. For most of the tree life, the horizontal growth was slightly higher than that the vertical one. However, just before the breakdown to occur, the vertical growth was remarkably increased above the horizontal component.

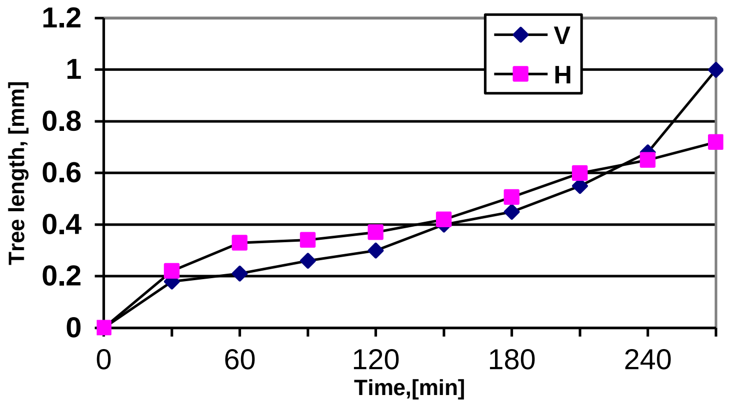
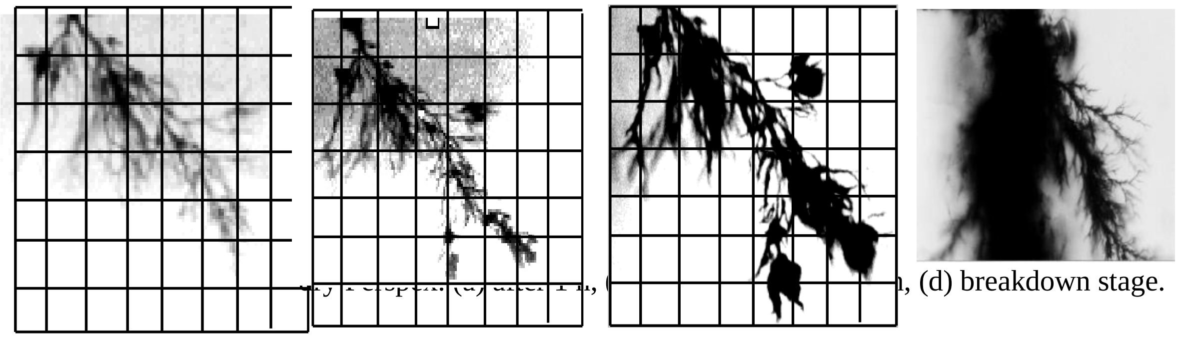


Figure 3: Vertical and horizontal tree growths for dry Perspex samples

By comparing the tree growth in the horizontal and vertical directions, three distinct stages are considered. The primary stage characterizes the first hour of tree development. In this phase, the horizontal growth is higher than the vertical one. In the second stage, the vertical growth was significant, compared with the horizontal one which was increasing at a constant rate. The third stage starts when the tree front approaches the earth electrode.

Although the total horizontal growth is higher than that of the vertical one, the latter is more effective in causing breakdown. However, not all horizontal channels grow in the same direction, but many of them abruptly go to the earth electrode. Therefore, the insulation area surrounded by the horizontal and vertical channels, is considered. This is achieved by dividing the area located between the pin tip and the earth plate into treed and non-treed sections. The treed section, enclosed by the outer branches, includes the area of the tree itself, whereas, the remaining space outside the tree frame is the non-treed area. Figure 4 shows samples of trees, depicted at a magnification of 300 times.

(a) (b) (c) (d)



, (d) breakdown stage.

The above images, overlaid on a grid of squares, are used to describe the stages of tree development. The squares containing branches determine the effective area of tree. However, the area shown in the above figure does not include the total width of the sample, which is far larger (50mm) than the vertical distance between the pin and earth electrodes (1mm). By counting the increment of tree-contained squares, it is possible to measure the growth progress and the actual area of tree. The time variation of treed area for dry samples is shown in Fig. 5, whereas, Fig. 6 illustrates the change in the actual area of the tree, expressed as a percentage of the treed section. The actual tree area consists only a small portion of the total insulation area between the pin and earth electrodes.

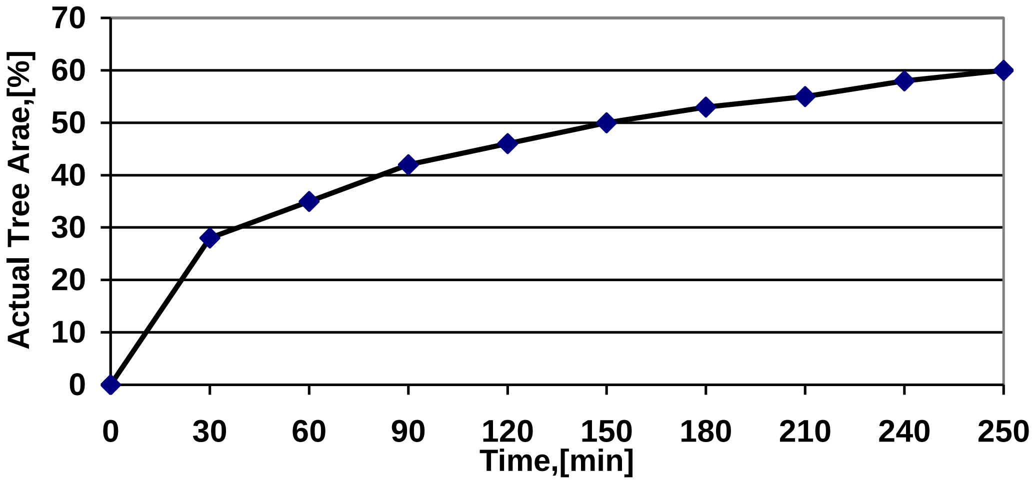


Figure 5: Variation of treed area related to the space between pin and ground electrodes.

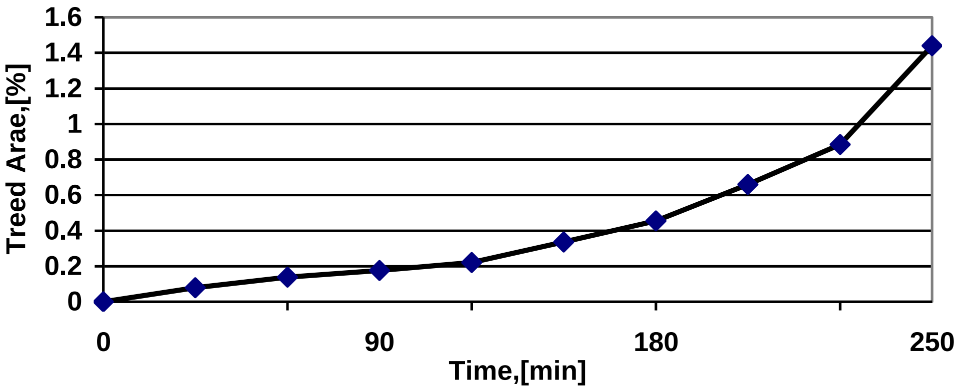


Figure 6: Variation of actual tree area related to the treed area

The branches of dry tree are short and thick. Initially, they have a brown colour, turning into black in the final stage of growth. Moreover, the horizontal and vertical tree expansions are relatively slow and limited within a narrow zone of treed section. However, they move perpendicularly towards the earth electrode in a constant rate.

Wet samples with deionised water

In this part of study, the samples were exposed to distilled water for one week before being subjected to high voltage supply. During this time, a sufficient quantity of water is absorbed and distributed inside the examined sample. The results showed that an active growth occurs in horizontal and vertical directions. However, the tree elongation in the vertical direction is lower than that in the horizontal one. The difference between the two components remained constant throughout the whole life of the tree as shown in Fig.7.

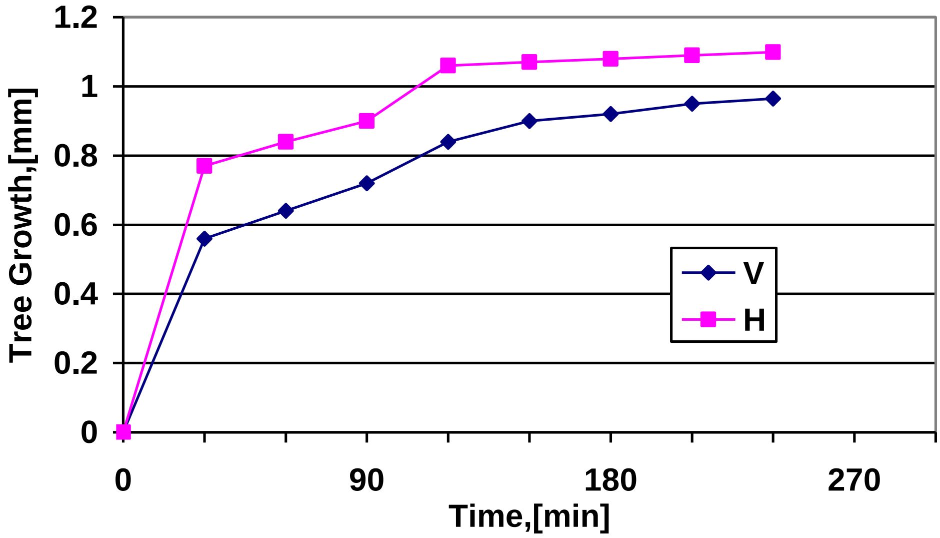


Figure 7: Vertical and horizontal tree growth for wet Perspex.

Due to the intensive and fast distribution of tree, it was difficult to contain all extensions in a single image. Therefore, to obtain a complete picture it was necessary to employ the computer facilities to integrate all images of the channels, growing in various directions, into single tree shape as shown in Fig. 8.

In comparison with dry case, the wet tree occupies wider area with a variety of routes followed by thin, long and sparse channels. The easiness of tree to grow in these conditions agrees with the findings of other researchers [12,13], who considered that the presence of water in the polymer will decrease the mechanical strength of the material and, consequently, reduce the growth resistance, making the tree extension much easier.

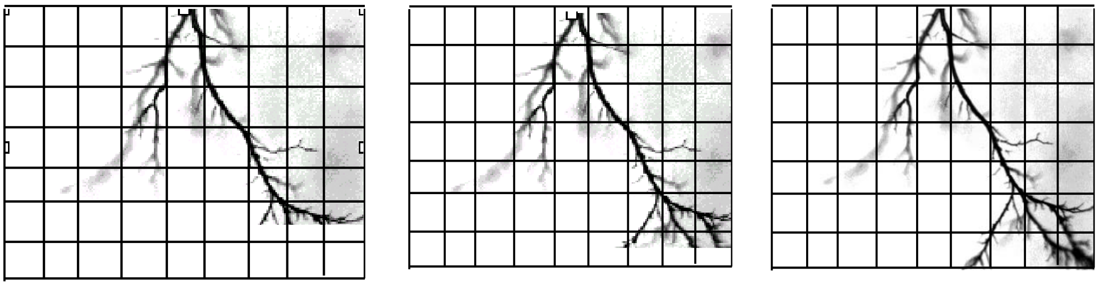


Figure 8: Tree growth stages in wet Perspex using distilled water.

Figure 9 shows the time variation of treed section, whereas, Fig.10 illustrates the percentage change of the actual tree area. In both illustrations, the increase in the treed and actual tree areas is much higher than that of the dry test shown in Figs. 5 and 6, respectively. Nevertheless, in general, the increase of the above parameters in the first hour of the tree growth is considerably higher than that of the subsequent hours of tree life.

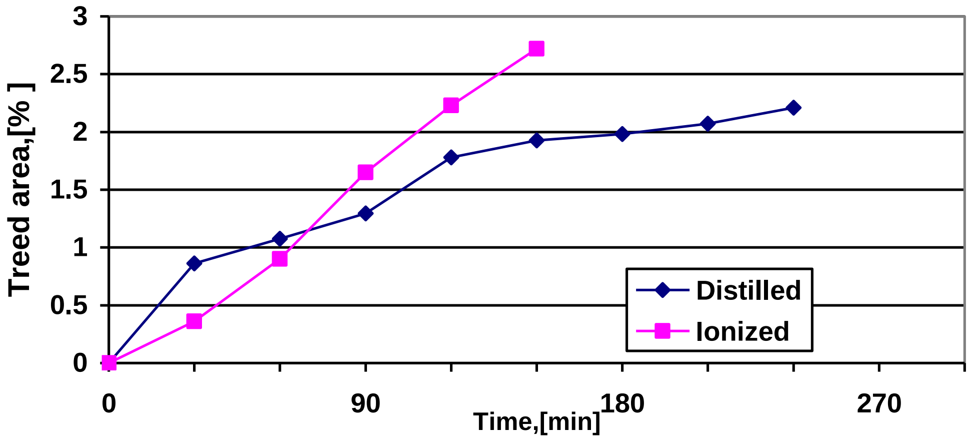


Figure 9: Variation of wet treed area related to the total space between the pin and ground electrodes

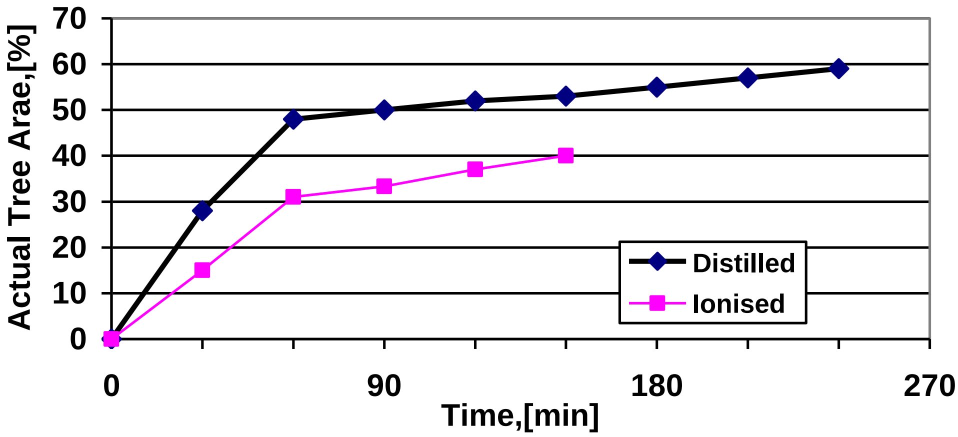


Figure 10: Variation of actual tree area related to the treed section

Wet samples with ionized water

The presence of ions in absorbed water accelerates the breakdown due to the conduction activity of these ions [14-18]. This fact was clearly found here. The tree initiation and development processes were significantly faster than that obtained in the previous cases. The total time to breakdown for the samples absorbed ionized water was in the order of 164 min compared with 250 and 280 min for wet (distilled water) and dry cases respectively. Additionally, the total horizontal growth was higher than other cases as shown in Fig.11.

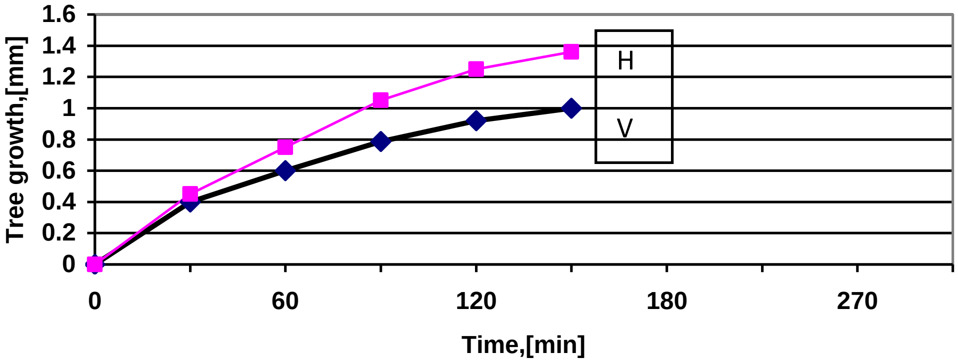
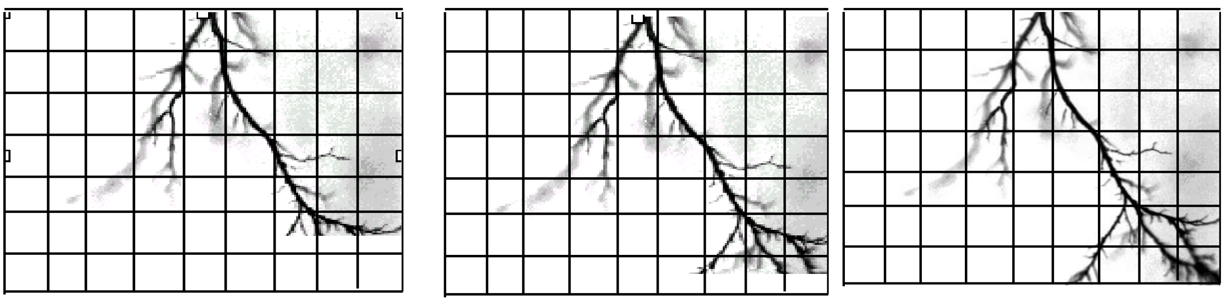


Figure 11: Vertical and horizontal tree growth for Perspex samples exposed to ionized water

Regarding the tree structure and shape, the extension is occurred in all directions with fine and interlaced channels as shown in Fig. 12. The fast growth of tree in this condition has caused an enlargement in the treed section and, therefore, an increase in the ratio of the treed section to the total area between the pin and earth electrode. The ionized water curve in Fig. 9 shows the variation of the above ratio presented in a percentage form, whereas, the ionized water curve in Fig.10 illustrates the percentage variation of the actual tree area in relation to the total treed section. Despite the notable ability of this type of trees to enclose a wide area during growing process, the actual tree space is less than that obtained for distilled water and dry cases due to a limited number and thickness of grown branches.



vet Perspex specimens using ioniz

DISCUSSION

A number of findings can be discussed concerning the tree growth and configuration. Firstly, the growth rate in similar samples is slightly different, due to the minor variations in the material structure. This can be attributed to the presence of impurities and the non-uniform distribution of these impurities inside the material. Secondly, the tree growth in wet specimens is higher than that in the dry ones. The tree area contains various voids, which are stressed by electrostriction forces associated with high electric field. With the increase in the amount of absorbed water, these stresses are magnified, causing more influence on the tree propagation. Finally, it was found that the time to breakdown was a function of the condition of the specimen. Therefore, the longest time to breakdown was associated with dry samples, followed by that of wet (de-ionized) and then by ionized samples.

Concerning the configuration, the results showed that the growth mode affects the tree shape and construction. In dry specimens, the tree was developed slowly and did not have the chance to spread widely inside the sample. Therefore, the treed section was small and the branches were concentrated around one major channel. Thus, such tree was compressed and compact. Then, these channels were gradually enlarged and darken, which refers to a material damage internally. A breakdown is initiated if one of the front branches approaches the earth electrode. Therefore, the last treeing hour was associated with a significant increase in the vertical growth compared to that in the horizontal one.

The electrical tree developed in wet (de-ionized) conditions was characterized by long, thin and fast-growing branches. Although the main direction of these branches was from the pin tip to the earth plane, many channels were randomly distributed in all directions including horizontal direction. The vertical and horizontal frames of the tree dictated the ratio of the treed region to the whole insulation area. However, the density of branches in the treed region determines the actual area of the tree. In the current case, the treed section has shown an enlargement over that of the dry one, whereas the ratio of the actual tree to the treed section remained the same in both cases. This is attributed to the fact that the tree density and dimensions were proportionally increased. Despite the remarkable growth in the horizontal direction of wet samples, the fast vertical growth was the main cause of early breakdown of these samples compared with the dry ones.

The trees in the specimens treated by ionized water were characterized by a fast growth and high density of branches. Therefore, the treed region was significantly larger than that of the dry and distilled water cases. However, the limited number of branches made the actual area of the tree relatively small compared to that of other cases.

In all studied cases, the tree branches behave like conductors, bridging the distance between the electrodes and causing the insulation to breakdown. With ionized water, the breakdown occurred earlier than that of other cases, which reveals the role of ions in increasing the water absorption and breakdown under high field. This agrees with the results obtained previously [18].

The common course of action, which the electrical trees have demonstrated in the various studied cases, was the random growth. This means that in most cases the tree does not linearly grow with time. Therefore, it is normal to note that a lateral branch can be initiated from an existing tree stem or growing branch. This newly developed branch could be in horizontal or in vertical direction.

CONCLUSIONS

Electrical tree initiation and growth have been investigated for Perspex material under different conditions. The insulation area between the electrodes was divided into treed and non-treed sections. The dimensions of the treed section are governed by the outer extensions of the tree, whereas, the actual tree area is determined by the density of branches. The adopted approach to investigate the tree growth was based on the measurement of tree elongations in horizontal and vertical directions under dry and wet conditions. The study of the relationship between water absorption and treeing process was not limited to the growth but also extended to include the tree shape and texture. Finally, the results of this paper will be of great importance for researchers in Perspex material especially with significant growth of current use of such material.

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