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Effect of Pressure on the Electrical Treeing and Discharge Characteristics of Epoxy Resin

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***Abstract*—The move towards more electric aircraft (MEA) is driven by the need to tackle the increasing level of greenhouse gas emissions in the aviation sector. MEAs operate at low-pressure, high-altitude environment, where the increase in operating voltage will make the insulation system more susceptible to defects. Electrical treeing and the partial discharge (PD) associated with it, is one of the pre-cursors leading to untimely failure of solid dielectrics. This work investigates the influence of air at 0.2 bar and 1 bar on the propagation of electrical trees and the PD activity in an epoxy resin needle-plane sample under 6 kV$_{RMS}$. It was found that a pressure of 0.2 bar usually inhibits the tree propagation when compared to 1 bar. The permeation process of a test sample under 0.2 bar air led to short branches of tree growth along the chamfer edge of the needle tip.**

Keywords—electrical treeing, low pressure, partial discharge

I. INTRODUCTION

Polymers are essential for the electrical insulation of high voltage systems. Understanding their failure mechanisms can be challenging due to the increased complexity of operating conditions and presence of defects that are likely to occur during manufacturing and installation processes. These defects will lead to a higher electric field, a higher possibility of PD and the initiation and propagation of electrical trees. The move towards electrification of transportation systems is partly to reverse the ever-increasing trend of greenhouse gas emissions globally, with the aviation sector accounting for 3% of these emissions [1]. Therefore, there is an increased interest in developing MEAs in the aerospace sector, which will require voltages up to 3 kV and to be operated at pressures as low as 0.17 bar [2, 3]. As the operating voltage of future electric aircraft continues to increase, the insulation thickness within the aerospace electrical systems (i.e. cable) will increase too, leading to an increased likelihood of electrical treeing phenomena as observed in high voltage power cables for ground applications. The different types of stresses, such as thermal, electrical, and mechanical, can lead to insulation degradation and the subsequent component failure. Under voltages above 1 kV, electrical stress is the critical factor in defining the selection of material and insulation thickness [4].

Several studies reported the role of pre-existing gases on tree initiation in polyethylene and XLPE. In [5], it was reported that the partial discharge inception voltage (PDIV) of a polyethene sample in SF_6 was higher than samples initiated in air, nitrogen, and argon. Results in [6] show that fluorinated gases with high dielectric strength can significantly improve PDIV for twisted wires when compared to air using sine wave and square wave. An increase in gas pressure can significantly elevate the PDIV almost linearly for the twisted wire sample. It was demonstrated in [7] that samples immersed in air take less time to initiate than samples in SF_6, nitrogen or vacuum. This suggests that the gas can permeate into the tree channels and play a role in the subsequent discharge and treeing activity. The studies outlined above show that immersing the sample in different gases and pressures could lead to different results [6, 7]. So far, most studies on treeing and PD behavior have been performed in atmospheric air, not representative of the aerospace environment. There is limited literature on polymer degradation and treeing behavior below the atmospheric pressure. This work is to determine the combined effect of the high-voltage and low-pressure conditions on the development of PD and treeing in epoxy resin samples surrounded by air at pressures below 1 bar, to understand the potential issues caused by these operating conditions.

II. EXPERIMENTAL DETAILS

A. Sample Preparation

To generate a divergent electric field that aids electrical treeing propagation, a point-to-plane electrode configuration was used. The detailed sample preparation is described in [8]. In short, a tungsten needle of 1 mm diameter and 3 µm tip radius was inserted into an epoxy resin block and the distance between the needle tip and ground was 2 ± 0.3 mm. Finite element analysis was used to simulate the electric field at the needle tip, which was equal to 79.5 kV/mm. To ensure the same starting conditions for all tests, samples were initiated in atmospheric air at voltages between 7-12 kV$_{RMS}$. The voltage was increased if no tree inception was observed, but as soon as some tree growth around ~50 µm was seen, the voltage was stopped so the incepted tree length is kept small before the tree propagation experiment.

B. Gas Handling

The samples were assembled in a 5-liter acrylic pressure vessel rated up to 3 bar for the tree propagation test under different air pressures. All pressure values mentioned in this paper are in bar absolute. Samples tested in atmospheric air were directly energized in the pressure vessel without gas handling. Gas handling was required for filling air at 0.2 bar. After placing the sample in the pressure vessel, the vessel was vacuumed down to below 0.1 mbar for 10 minutes, then filled with 0.2 bar air. The test setup was left to settle for a day to allow the gas to permeate the epoxy sample and uniformly distribute within the pre-incepted tree channels.

C. Experimental Setup and Test Procedure

PD measurements were performed in accordance with IEC 60270 and using the test circuit shown in Fig. 1. Before energization, the PD test system was calibrated using an input signal of 50 pC and the PD threshold was set to 1 pC. The

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acrylic vessel is discharge-free up to 7 kV$_{\text{RMS}}$ at 0.2 bar and up to 10 kV$_{\text{RMS}}$ at atmospheric pressure. Therefore, the test voltage was chosen as 6 kV$_{\text{RMS}}$ for all pressures for result comparison. The setup was first energized at 1 bar for 2 hours and the PD activity was monitored using an Omicron MPD 800 system. The sample was taken out and imaged using an optical microscope to measure the final tree length and width, before being reassembled and permeated into 0.2 bar air until the next day, when it was energized for 2 hours and then imaged again. This process continued until either the tree reached the ground plane, or it stopped propagating. The test sequence was performed on three samples.

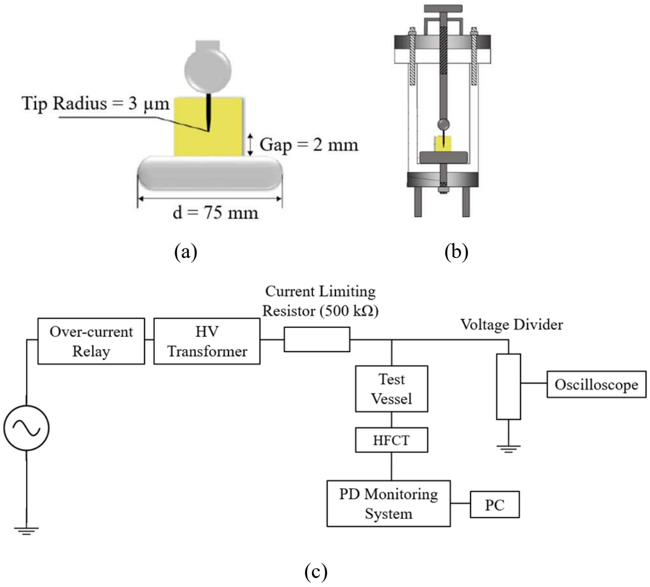


Fig. 1 (a) Sample dimensions, (b) test vessel and (c) experimental circuit.

III. RESULTS & ANALYSIS

A. *Treeing Behavior*

Optical images of the propagated electrical trees after 2 hours under 6 kV$_{\text{RMS}}$ are shown in Figs. 2-4. At 1 bar, the tree propagates with dark branch-type channels, whereas at 0.2 bar, short branches have formed around the needle tips and previously propagated trees. The tree growth at each stage of energization is shown in Table I.

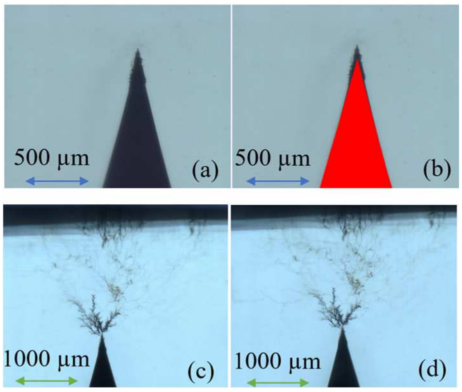


Fig. 2 Sample 1 after testing at 6 kV$_{\text{RMS}}$ in: (a) 0.2 bar air for 2 hours, (c) 1 bar air for 2 hours and (d) 0.2 bar air for 18 hours. (b) shows the needle geometry overlaid on (a) for clarity.

Reasons behind the different number of tests performed on each sample are: (i) For sample 1, the tree has already propagated to the ground plane after test no. 3, so an additional test could have led to a breakdown, which was not the purpose of this experiment; (ii) For sample 2, there was no modification in the tree morphology or PD activity after test no. 5; and (iii) No additional test was performed in sample 3 after the tree propagated under 0.2 bar (test no. 4), since it was different from behavior exhibited in other tests under 0.2 bar.

The samples had trees pre-incepted prior to being energized under 6 kV$_{\text{RMS}}$ for 2 hours. Therefore, the tree growth region for the samples tested at 1 bar belongs to the next stage of tree propagation, referred to as a “fast-forward tree growth” by [9]. It is characterized by dark branches growing from the initial pre-incepted tree, associated with an increase in the PD magnitude during this tree growth period.

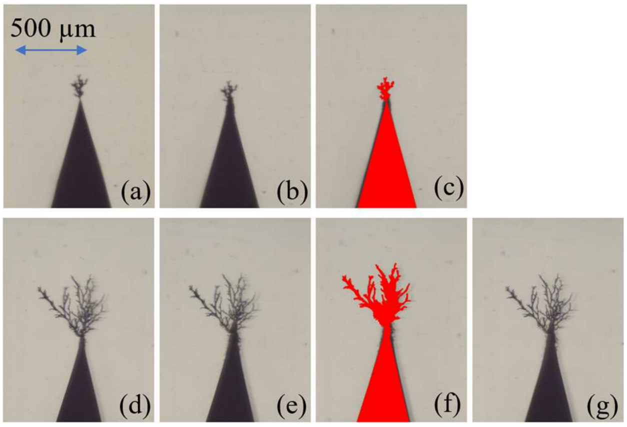


Fig. 3 Sample 2 after testing at 6 kV$_{\text{RMS}}$ in: (a) 1 bar air for 2 hours, (b) 0.2 bar air for 2 hours, (d) 1 bar air for 2 hours, (e) 0.2 bar air for 2 hours, and (g) 1 bar air for 2 hours. (c) shows figure (a) overlaid on (b), while (f) shows figure (d) overlaid on (e).

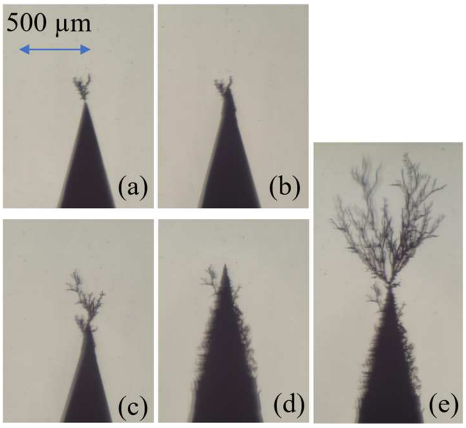


Fig. 4 Sample 3 after testing at 6 kV$_{\text{RMS}}$ in: (a) 1 bar air for 2 hours, (b) 0.2 bar air for 2 hours, (c) 1 bar air for 2 hours, (e) 0.2 bar air for 2 hours. (d) shows the sample after overnight permeation under 0.2 bar air without any voltage energization.

The fast-forward tree growth stage is followed by the region of fine tree growth [9], which can be difficult to image using the optical microscopy. However, it is assumed that this region occurred in the present tests due to the period of consistently high PD activity followed by low, almost non-detectable PD activity. One electrical tree that showed different characteristics to the rest is the one propagated at 1 bar during test no. 2 for the first sample, shown in Fig. 2(c). While the other trees only show the propagation of dark branches, this test shows fine tree growth at the extremities of the dark branches, which extend the tree in both length and width. The next tree evolution stage is also seen with the darkening of the fine tree branches [9]. However, the 2-hour test time was not enough to commence the growth of reverse trees, which is the final tree growth stage before the sample failed [9]. This sample was then energized under 0.2 bar for 18 hours, with no change to the tree geometry or PD activity.

TABLE I. SUMMARY OF TREE GROWTH AND PD ACTIVITY OF ALL TESTED SAMPLES

Test	Air Pressure (bar)	PD Activity	Tree Growth	Tree Length (μm)
Sample 1, Test 1	0.2	No	No	326.4
Sample 1, Test 2	1	Yes	Yes	2061.2
Sample 1, Test 3	0.2	No	No	-
Sample 2, Test 1	1	Yes	Yes	167.9
Sample 2, Test 2	0.2	No	No	234.5
Sample 2, Test 3	1	Yes	Yes	428.1
Sample 2, Test 4	0.2	No	No	651.5
Sample 2, Test 5	1	No	No	-
Sample 3, Test 1	1	Yes	Yes	199.9
Sample 3, Test 2	0.2	No	No	282
Sample 3, Test 3	1	Yes	Yes	568
Sample 3, Test 4	0.2	Yes	Yes	1953.2

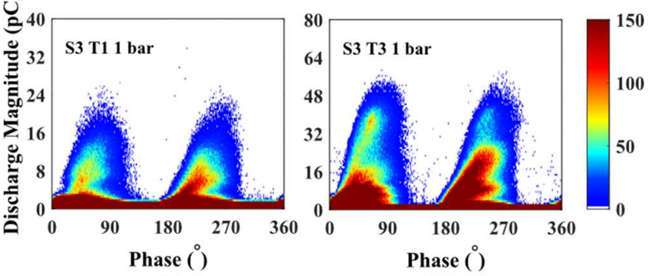
Note that after overnight permeation in 0.2 bar air, the needle was surrounded by short branches along the chamfer edge even before the voltage application. To verify this observation, after test no. 3 was performed on sample 3 at 1 bar, the sample was permeated with 0.2 bar air overnight. The following day, the sample was taken out to ambient pressure and imaged. As it can be seen in Fig. 4(d) compared to Fig. 4(c), the sample exhibits an elongation of the needle tip and short branches formed under 0.2 bar air without energization. The short branches are an irreversible characteristic of the material, as it does not disappear or change after the sample is left at 1 bar air for several days. When a voltage of 6 kV_{RMS} is applied on the sample with short branches around the chamfer edge of the needle, the tree does not change in length or width. For figure clarity, some images of the trees grown at 1 bar were overlaid on images obtained post-permeation at 0.2 bar.

It is now clear that the low-pressure condition influences the material properties. To check if high pressure conditions, like those encountered in gas-insulated equipment, also influence the material, 9 samples in different stages of their tree growth process were left under 8 bar CO_2 for two weeks. They did not exhibit any change in the material or the tree morphology when they were imaged. Therefore, this highlights a low-pressure effect on the material condition at the needle tip that is not seen at higher pressures.

B. *PD Activity*

In general, there was PD activity for the samples tested at 1 bar, and no PD recorded for the samples tested at 0.2 bar. This can be explained by the fact that, during energization, the pressure increases in the pre-incepted tree channels. When the sample is settled under 0.2 bar, it is harder to hold the high pressure, therefore the local stress is lower, and it is more difficult for discharges to occur. Additionally, the low-pressure results in less intense PD activity, below the detection level of the equipment. For the low-pressure tests, PD activity was only observed for the test that showed tree propagation at 0.2 bar, namely sample 3, test no. 4. Examples of PRPD patterns for certain test conditions are shown in Fig. 5.

All samples exhibit PD activity have symmetrical clusters in both half cycles of the PRPD pattern corresponding to the polarity of the applied voltage, i.e., positive discharges in the positive half-cycle and vice versa. This is typical PD behavior reported for tree propagation process [10]. At the same time, superimposed turtle-like and wing-like clusters can be seen on the PRPD pattern. "Turtle-like" refers to smaller magnitude clusters, below 15 pC, resembling the shape of a parabola, and "wing-like" corresponds to higher magnitudes, above 15 pC, visually resembling an open parabola [11]. Turtle-like patterns relate to discharges occurring in voids or short branches, where PD can readily propagate from one side of the defect to the other, resulting in discharges of similar magnitude [11]. This pattern can be seen as the lower magnitude cluster in Fig. 5(a). Wing-like patterns form when the discharges occur in longer, narrower channels and correspond to the higher PD magnitudes recorded. These can be seen on top of the turtle-like cluster in Fig. 5(a). Additionally, in Fig 5(b), two wing-like patterns of different magnitudes can be observed which are related to simultaneous tree growth occurred in two branches of different lengths [11].



(a) (b)

Fig. 5 PRPD patterns after 2 hours energization at 6 kV_{RMS} for sample 3 at 1 bar for (a) test no. 1 and (b) test no. 3.

For the samples showing PD activity at 1 bar, most of the PD activity is concentrated in the first 30 minutes of the test, related to the period of quick propagation of tree branches. Then, the PD activity was low with only a few bursts at higher magnitudes. This period of reduced PD activity is linked to the growth stagnation of the main tree branches, but fine channels can still propagate during this period with no detectable PD [11]. Fig. 6 shows an example of the PD magnitude evolution with time for sample 2, test no. 1.

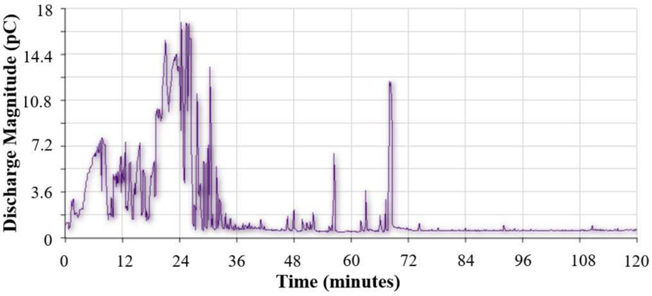


Fig. 6 PD magnitude evolution with time for sample 2, test no. 1 tested at 6 kV_{RMS} under 1 bar air for 2 hours.

Fig. 6 displays the PD magnitude trend in the early stages of tree growth as observed by other researchers [10]. During the first 30 minutes of testing, the magnitude and intensity of discharges sharply increase as the tree extends in length. For the next 5 minutes, the PD activity reduces with a reduced level of tree growth, before both processes cease for the remaining duration of the test, except a few short bursts of PD activity.

IV. DISCUSSIONS

The short branch growth occurred at 0.2 bar can be associated with the theory of filamentary electromechanical breakdown proposed by Fothergill [12]. This model suggests that a crack can propagate through the solid dielectric material due to the mechanical stress generated by the electrostatic forces between the tip of the crack and the opposite electrode. Additionally, epoxy resin is brittle at room temperature [13], aiding the solid tungsten needle to push into the polymer and extending the needle tip. This can be clearly seen on Fig. 4(d) with a new needle tip visible further away from the previously propagated tree geometry, while the extremities of the previous tree are still visible on the sides of the new tip. This could be due to the externally applied mechanical stresses, low-pressure in this case, which was found to lead to an increase in the size and number of microvoids forming in the solid dielectric [10]. Furthermore, volatile contents such as water molecules could escape from the epoxy surface due to the low-pressure condition overnight, leading to local changes in strain at the needle tip area, with the epoxy tending to shrink. Since this occurs in a very small area, the strain cannot easily be redistributed to the bulk of the epoxy and this mismatch leads to localized material cracking.

Due to the short test duration, the electrical trees at 1 bar did not fully propagate across the solid dielectric. In fact, the growth length is small, less than 200 μm for each individual test on samples 2 and 3 (less than 10% of the gap between needle tip and plane). The tree evolution belongs to the stage of fast-forward propagation, proven by the stagnation of tree growth after 30 minutes of energization, as shown in Fig. 6. This is also supported by the PD activity captured during the test, where high discharge magnitudes correspond to the fast growth of dark tree branches and low discharge magnitudes belong to the region of fine tree growth [9, 11]. At the early fast-forward propagation stage, space charge injection influences the sample behavior as follows: During the negative half-cycle, electrons are emitted from the needle electrode, and they become trapped in the polymer. During the positive half-cycle, some electrons are freed from the particle traps and drift back into the needle while some remain in the dielectric. This leads to a region of space charge around the needle tip which can extend a few tens of μm into the solid material and after several cycles the treeing channels will start forming into the low-density space charge zone [14, 15]. This effect is mainly seen in the trees grown at 1 bar after the fine branch growth has occurred during permeation. The next tree will propagate from the new “needle tip” and not from any of the lateral branches. This new needle tip will lead to a new region of space charge buildup from where the new tree is initiated and then propagates through the dielectric.

V. CONCLUSIONS

This work reports the influence of low-pressure on the treeing propagation process and material changes occurred at the needle tip in two cases: permeation of the sample in 0.2 bar air or AC electric stress at 0.2 bar and 1 bar. The results show that permeating the test sample into 0.2 bar air leads to the extension of the needle tip towards the ground plane and fine branch growth around it, suggesting a mechanically driven deterioration of the material even without energization. However, the electrical trees do not propagate under 0.2 bar during testing, but electrical trees can initiate and further propagate from the newly generated needle tip when the sample is once again energized at 1 bar. The trees propagated at 1 bar show typical tree growth characteristics, with fast-forward tree growth associated with consistent PD activity followed by fine tree growth with no detectable PD.

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