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Propagation of negative streamers along mineral oil-solid interfaces

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Abstract— This paper introduces an experimental study on the propagation of negative streamers along mineral oil-solid interfaces. A standard type of impregnated paper and different polymeric films (made of PET, PTFE and PVDF) are selected as solid materials immersed in mineral oil. The effect of the solid material on the streamer propagation along the interface formed with transformer oil is studied. Streamer velocities classified as first mode propagation point cathode are reported. Voltage gradient of the streamer channel and its stopping voltage are calculated for all the cases. Comparison of streamer charge and stopping length propagation are reported.

Keywords—Streamers, creeping discharges, mineral oil, impregnated paper, .

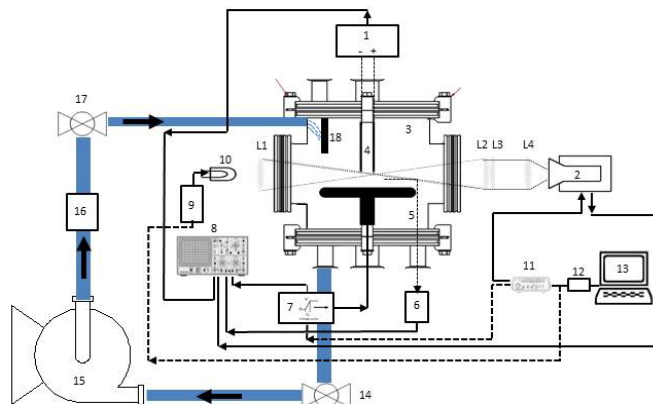
I. INTRODUCTION

The development of tailor-made materials provides new possibilities to improve the dielectric performance of electrical insulations systems. Unfortunately, there is a lack of understanding about which characteristics need to be modified in order to make a material suitable for electrical insulation applications. The analysis of the streamer propagation at liquid-solid interface has a relevant importance for the understanding of the streamer properties [1,7,8]. The present work is intended to present the results of streamers propagating along the interface of different solid materials with mineral oil. The comparison of these results contributes to the understanding of the materials properties that affects the streamer propagation; namely voltage gradient of the streamer channel, stopping length, velocity, total charge accumulation and others. In this study an impregnated paper and three polymeric films are selected to compare the influence of the material permittivity in the streamer propagation.

II. EXPERIMENTAL SETUP

Figure 1 introduces the complete experimental setup to study the prebreakdown processes in mineral oil in the presence of solid interfaces under a needle-plane configuration. It consists of a vertical needle with tip radius of $2.9 \mu\text{m}$ and gap distance of 5 mm to the plane electrode. The volume of the test chamber is $6 \times 10^{-3} \text{m}^3$ and it is half-filled with mineral oil. The solid material is in an inclined position (30 degrees) respect to plane (see section II.D). Square positive voltage pulses are applied to the plane electrode.

Fig. 1 Sketch of the experimental setup. (1) Differential amplifier, (2) high speed camera, (3) test chamber, (4) probe-plane and point-plane configuration, (5) fiber optic, (6) photomultiplier, (7) high voltage pulse source, (8) oscilloscope, (9) xenon lamp power source, (10) xenon lamp, (11) signal generator, (12) USB data acquisition device, (13) computer, (14) and (17) valves, (15) magnetic pump, (16) particles filter, (18) heating rod



A. Measurements

The streamer propagation is studied based on the following measurements:

- Injected charge
- Light emission
- Shadowgraphs

The streamer charge measuring system consists of an integrating circuit with a known capacitor connected to the needle electrode to integrate the streamer current. When the applied voltage rises, a large displacement current circulate in the needle electrode superposed to the streamer current and resulting in an undesired voltage level of the current integration. The problem is avoided by using a differential measurement, based on an additional blunt probe electrode to integrate the displacement current [2]. Then a differential amplifier is used to subtract the signals from the needle electrode and probe electrode signals. A full description of the measuring system is presented in [1].

The streamer light emission measuring system consists of an optical fiber installed 5 mm away from the point electrode and facing the needle tip. The optical fiber drives the light signal outside of the test chamber until the photomultiplier sensor, Figure 1.

In addition, a single frame shadowgraph of each streamer is obtained by aligning a light beam from a Xenon lamp, the needle tip and the camera (with an accuracy of $\pm 0.15\text{mm}$) through a set of lenses L1, L2, L3, L4. The optical arrangement is focused to detect a $730 \times 730 \mu\text{m}^2$ image close to the needle tip (20x magnification).

B. Transformer oil preparation

The test chamber is capable to degas and filter the oil pumping it through a filter with pore size of $2 \mu\text{m}$. A continuous flow of oil through the chamber, pump and the filter is kept on during 24 h at 60°C and 6 mbar. Once the filtering and degassing process is finished, the chamber is cooled down to room temperature ($\approx 23^\circ\text{C}$) and filled with dry air up to atmospheric pressure. All tests are performed at atmospheric pressure.

C. Solid sample preparation and assembly

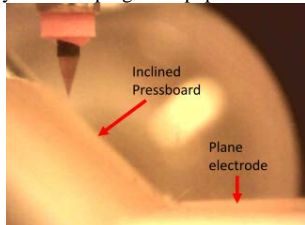
Different polymers are chosen for the solid interface in addition to the impregnated paper, which is the reference material in the insulation system of power transformers (Table I). Polyethylene terephthalate PET ($\text{C}_{10}\text{H}_8\text{O}_4$)_n is selected as a polymer with the same permittivity as the impregnated pressboard but with different surface morphology and chemical composition. Polytetrafluoroethylene PTFE (C_2F_4)_n is chosen as a material to match the permittivity of the oil at the interface. Polyvinylidene fluoride PVDF ($\text{C}_2\text{H}_2\text{F}_2$)_n is tested as a material with a large permittivity mismatching with transformer oil. The tested paper or films are cut into long narrow pieces of $8 \times 100 \text{mm}^2$.

TABLE I. SAMPLES CASES

	Thickness (mm)	Permittivity	Density (g/cm^3)
Impregnated paper	0.17	3.0	0.7
PET	0.1	3.0	1.3
PTFE	0.1	2.0-2.1	2.2
PVDF	0.1	8.4	1.76
Oil	-	2.2	0.87

All samples are preheated at 120°C for 24 h in order to remove all the absorbed moisture and then impregnated with filtered and degassed transformer oil at 60°C and 6 mbar for 24 h. The impregnation process is presented in [1]. The solid piece is installed on a holder mounted on two precision mechanical stages that allow rotating the strip piece with a precision of 2.4 arcmin per revolution of the micrometrical screw control and it moves along an axis direction with a precision of 0.5 mm per revolution of the micrometrical screw control. This assembly permits to install the strip piece sample touching the point electrode tip (as shown in Fig. 2).

Fig. 2 Assembly of the impregnated paper in inclined position



III. PROCEDURE

Series of square high voltage pulses with 35 ns in rise time and $50 \mu\text{s}$ width are applied to the plane electrode. The multi-level test method with voltage levels ranging between 11.5 and 22 kV and steps of about 0.6 kV is used. In order to detect changes in the solid samples or the oil during the experiment, all the tests for each level are partitioned into four different randomized series of 10 shots each. All the results presented at each level correspond to the average of 40 measurements. The waiting time between voltage shots is 1 minute.

IV. RESULTS AND DISCUSSION

Figure 3 presents a typical oscillogram recorded for a streamer propagating in mineral oil without any solid (the oscillograms for the cases of oil-solid interface are very similar in shape). Curve *a* corresponds to the exposure time of the high speed camera recording the picture up to the last charge injection step. Curve *b* is the streamer light emission recorded with the photomultiplier (in arbitrary units). Notice that this signal presents a continuous component that is typical of the light emission at the head of negative streamers propagating in oil [11]. The streamer charge is shown in curve *c*, which shows the typical propagating steps of negative streamers. These steps are strongly correlated with the light pulses [7]. The magnitude and frequency of the light pulses increase with voltage. These pulses appear after a short period (about $2 \mu\text{s}$) after the start of the voltage.

Fig. 3 Oscillogram of streamer propagating in transformer oil

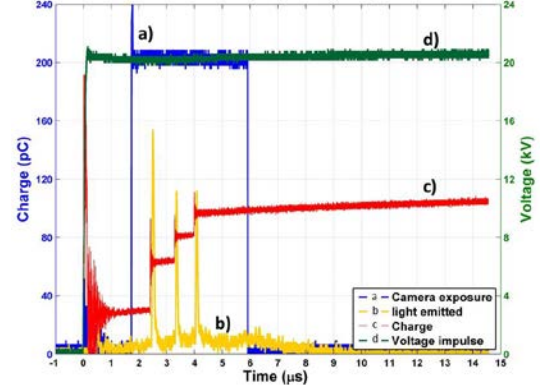
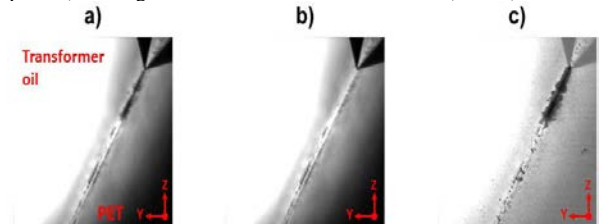


Figure 4 shows a typical example of the frame images recorded with the camera a) when the streamer is propagating along the oil-solid interface and b) in the next frame 25 s after the voltage has dropped (no streamer). The shadowgraph of the streamer is then intensified by making the digital difference and filtering between these two frames (Fig. 4.c).

Fig. 4 Example of the frames recorded for a streamer propagating along the mineral oil-PET interface. a) frame taken during the streamer propagation. b) following frame 25 s after the voltage is dropped and the streamer has collapsed. c) The digital difference between the frames a) and b).



Typical shadowgraphs of the propagation of streamer for negative polarity along the oil-solid interfaces studied are shown in Fig. 5. These time-integrated shadowgraphs show the streamers at their stopping length. The structure of the streamer is in general a single filament for the cases of the oil-solid interfaces and an ionized gas cavity of irregular shape for the case in oil. Differences of the morphology of the filament streamer in thickness and length are appreciable for the different tested interfaces. Notice that the pictures presented in Fig. 5 have two parts. First part show clearly where the solid interface edge starts and second part (filtered picture) shows a detail of the streamer edge in contact with the solid interface.

Fig. 5 Shadowgraphs of streamers propagating along the different solid-liquid interfaces at 21kV. a) Transformer oil-PTFE interface, b) Transformer oil-PET interface, c) Transformer oil without solid interface, d) Transformer oil-PVDF interface and e) Transformer oil-Pressboard interface

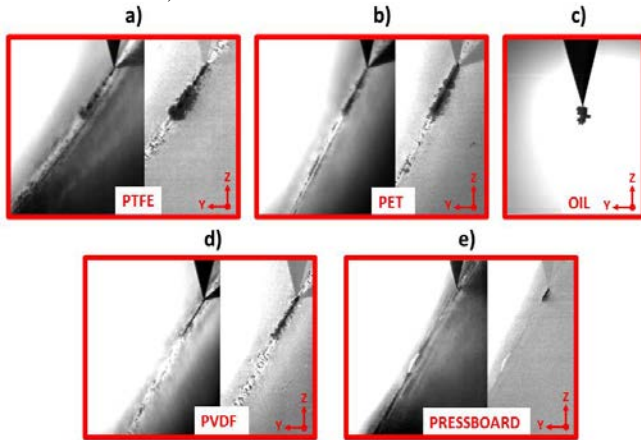


Figure 6 presents the streamer stopping length estimated from the shadowgraphs as a function of the applied voltage. A linear correlation is observed for all the considered cases. This indicates a constant potential gradient along the channel of the streamer as proposed in [7]. The mean value of the potential gradient (E) calculated as the slope of the best fitting lines of the experimental data is reported in the legends for each curve. Interestingly, this mean potential gradient is similar for all the polymers considered, despite of their large differences in permittivity. This results shows that the permittivity of a polymeric interface does not have a significant influence in the potential gradient in the streamer channel. For the case with the impregnated paper interface (with the same composite permittivity as PET), the potential gradient is about two times larger. Assuming that the permittivity of the impregnated paper does not affect the streamer potential gradient either, this difference can be attributed to the different surface morphology and chemistry compared with the polymeric films. For streamers propagating in oil without interface, the potential gradient is slightly larger than with the pressboard interface.

According with [8] streamer propagation stops when the electrical potential of the channel tip reaches a specific value. It is possible to estimate the stopping voltage value from the intersections of the curves with the voltage axis in Figure 6. It is circa 14.7 kV for PTFE and about 12.2 kV for the other cases. It is interesting that even when the streamer is propagating along surfaces with different permittivity and chemistry, the stopping voltage condition of the channel tip is

the same. Nevertheless it is not possible to conclude that this voltage condition is independent of the oil-solid interface case because PTFE presents a different value.

Fig. 6 Average streamer length for point cathode at transformer oil and transformer oil-solid interface for materials presented in section III.

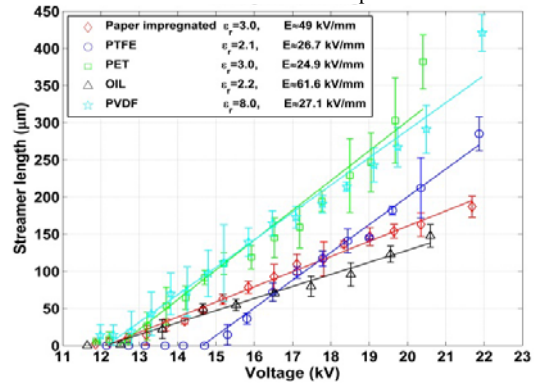


Figure 7 presents the streamer velocity as a function of the applied voltage for all the cases. The velocity reported is calculated with the maximum streamer length measured from the pictures and the time when the last streamer charge injection is detected. All velocities reported range between 10 and 280 m/s. These streamers can be classified as slow streamers according with [9,10]. These are first mode propagation point cathode streamers, typically observed in short gaps at low voltage and tip radius around 1 μm . Those streamers consist of vaporized liquid with low conductivity. Notice that all the velocity curves have two major parts. A first part where the velocity increases linearly with the voltage and a second part with a rather constant velocity (this assumption is valid only for the range of voltage applied). For much higher voltages an increment in the velocity and changes of mode propagation is expected. It is possible to estimate that the transition between the linear and the constant part of the velocities curves occurs when the streamer length is about 100 μm for all the polymers cases and about 75 μm for the case of the impregnated paper and without interface.

Fig. 7 Average streamer velocity for point cathode at transformer oil and transformer oil-solid interface for materials presented in section III.

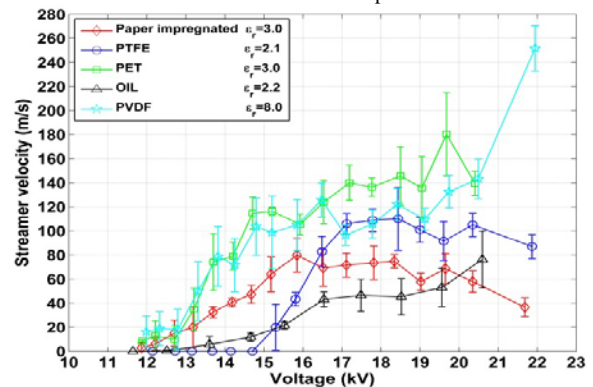


Figure 8 presents the final streamers charge as a function of the applied voltage. The increment of the streamer charge with the applied voltage presents an exponential correlation. This result is similar to the streamer charge and voltage correlation reported in [7]. Notice that the total amount of charge is different for each case and the charge tends to increase with the

permittivity of the oil-solid interface case. The streamer channel presents a voltage gradient, but still can be considered rather conductive. According with [7] the electric charges exist at the interface of the gaseous channel and the liquid. In this case a large part of the charges distributed along the streamer channel is in contact with the solid, see Figure 5. It increases the possibility of accumulation and deposition of charges on the interface.

Fig. 8 Streamer charge average for point cathode at transformer oil and transformer oil-solid interface for materials presented in section III.

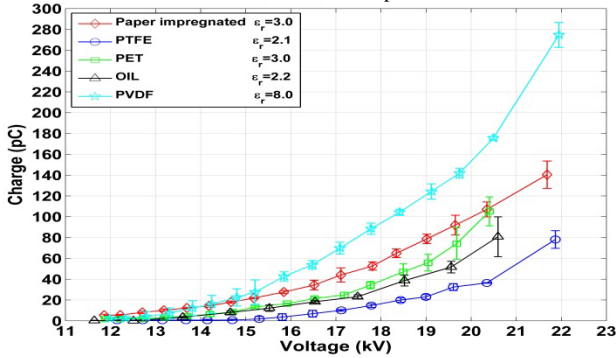
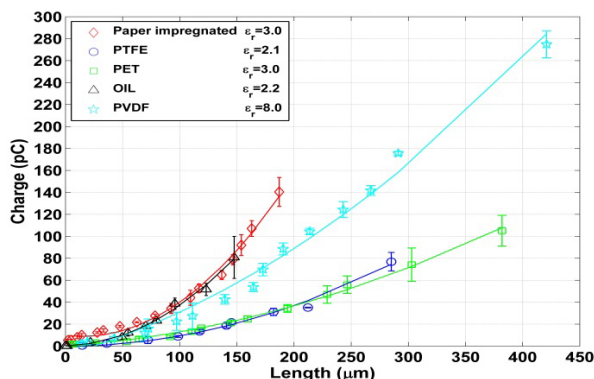


Figure 9 presents the streamer charge as a function of the stopping length. Notice the strong quadratic correlation for all the cases. It is important to highlight that this nonlinear dependency is typical for negative first mode streamers. In these conditions the streamer propagates in the range of 0-400 μm from the tip electrode with a slow velocity and the streamer charge ranges between 0-300 pC. This nonlinear dependency has been reported for the first 350 μm of what? in [5], which is comparable with the results presented here in Figure 9. Notice that linear correlation between the streamer charge and the stopping length reported in [4,11] correspond to longer streamers propagating in 2nd, 3rd and 3rd+2nd cathode modes.

It is interesting to observe that Figure 9 shows that the streamer charge per unit length depends of the type of oil-solid interface. The cases of oil impregnated paper and transformer oil without interface present similar values. The polymeric interfaces of PTFE and PET present similar and the lowest values of charge per unit of length. The result for the PVDF interface is in between these two groups. Notice that a large permittivity of the solid material (as in the case of PVDF) does not result in a drastic change in the streamer charge per unit length.

Fig. 9 Streamer charge as a function of the streamer length for point cathode in transformer oil with and without solid interface.



V. CONCLUSIONS

The creeping discharges propagating along different solid interfaces reported in this study are classified as first mode propagation point cathode streamers. All the streamers propagate in mineral oil but in contact with the solid interface. The voltage gradient of the streamer channel and its stopping voltage are calculated for all the cases. The estimated potential gradient of the streamer channel has been found to be weakly influenced by the permittivity of the solid material. The stopping voltage condition of the channel tip is the same for the cases in without interface and with impregnated paper, PET and PVDF interfaces. However, it is different for the PTFE interface. The total streamer charge increases for all the cases when the applied voltage increases. A nonlinear correlation between the charge and the length of the streamers is found, which is typical of the streamers propagating short distances ($\leq 400 \mu\text{m}$) from the point electrode tip. The total injected charge is found to increase with the permittivity of the solid interface.

REFERENCES

- [1] D. Ariza, M. Becerra, R. Hollertz and C. Pitois, "Measurements of the charge of streamers propagating along transformer oil-solid interfaces" 2014 IEEE International conference on dielectric liquids ICDL Bled, Slovenia, June 30 - July 3, 2014.
- [2] L. Dumitrescu, O. Lesaint, N. Banifaci, A. Denat, and P. Notinger, "Study of streamer inception in cyclohexane with a sensitive charge measurement technique under impulse voltage," Journal of Electrostatics, no. 53, pp. 135-146, 2001.
- [3] L. Hestad, G. Berg, S. Ingebrigtsen and L.E. Lundgaard, "Streamer injection and growth under impulse voltage: A comparison of Cyclohexane, Midel 7131 and Nytro 10X", 2004 Annual Report Conference on Electrical Insulation and Dielectric Phenomena, pp 542-546, 2004.
- [4] G. Massala and O. Lesaint, "Positive streamer propagation in large oil gaps", IEEE Transactions on dielectrics and electrical insulation, Vol. 5 No. 3, June 1998
- [5] S. Ingebrigtsen, L E Lundgaard and P-O Åstrand, "Effects of additives on prebreakdown phenomena in liquid cyclohexane: II. Streamer propagation" Journal of physics D: Applied physics, 40 (2007) 5624-5634.
- [6] N. V. Dung, H. K. Hoidalén, D. Linhjell, L. E. Lundgaard, M. Unge, "Effects of spatial restriction on streamers in white oil" IEEE International conference on liquid dielectrics, Bled, Slovenia, June 30-July 3, 2014.
- [7] P. Atten and A. Saker, "Streamer propagation over a liquid/solid interface" IEEE Transactions on electrical insulation, Vol. 28 No. 2, April 1993
- [8] A. Saker and P. Atten, "Properties of streamer in transformer oil", IEEE Transaction on dielectrics and electrical insulation, Vol. 3 No. 6, December 1996.
- [9] O. Lesaint, "Propagation of positive discharges in long liquid gaps", International conference on conduction and breakdown in dielectric liquids, Rome, Italy, July 15 - 19, 1996.
- [10] S. Ingebrigtsen, "The influence of chemical compositions on streamer initiation and propagation in dielectric liquids", Thesis for the degree of philosophiae doctor, Trondheim, October 2008.
- [11] A. Saker, O. Lesaint and R. Tobazeon, "Propagation of streamers in mineral oil at large distances", IEEE conference on Electrical Insulation and Dielectric Phenomena, 1994, Arlington, TX.
- [12] P. Rain and O. Lesaint, "Prebreakdown phenomena in mineral oil under step and ac voltage in large gap divergent fields", IEEE Transactions on dielectrics and electrical insulation, Vol. 1, No 4, August 1994.