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Influence of Paper Properties on Streamers Creeping in Mineral Oil

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Abstract—This work presents an experimental study of second mode positive streamers propagating along mineral oil-paper interfaces. A point-plane arrangement immersed in mineral oil with the paper inclined 60 degrees to the plane electrode is used to create the liquid-solid interface. Kraft paper and a kraft fibril paper, made from cellulosic micro and nano fibrils, with higher density and lower surface roughness are used as the solid materials. High speed shadowgraphy and charge recordings are used to compare the propagation of second mode positive streamers along the mineral oil-kraft paper and mineral oil-kraft fibril paper. Streamers creeping along the mineral oil-kraft paper interface propagate mainly into the liquid, with one or two main filaments. In comparison, the streamers propagating along the kraft fibril paper show a strong reduction of the branching; these streamers consist of a single filament that propagates exactly on the solid surface. Streamers along the kraft fibril paper also have longer propagation time than for the case with kraft paper. Mutual electrostatic shielding between filaments is observed for the streamers creeping on the kraft paper. An electrostatic analysis of the influence of permittivity, density and surface roughness of the solid in the electrical properties of the streamer filaments is also performed.

Keywords—*Streamer; mineral oil; impregnated paper; interface; porosity; roughness*

I. INTRODUCTION

The electrical prebreakdown phenomena in liquids (usually called ‘streamer’) is a complex problem that involves several mechanisms, such as electronic, thermal and mechanical [1], [2]. Large number of studies in the literature have been devoted to the understanding of these mechanisms [1]–[3]. Streamer properties and characteristics are highly dependent on the liquid, electrode configurations, pressure, voltage, etc [1], [2], [4]. The large variation of the streamer parameters has made the streamer characterization complicated and today, there is no predictive models of liquid breakdown comparable with the existing ones in the field of gases [1].

Positive streamers is the type of streamers most commonly studied in the literature [1]. They have been classified according with their propagation velocities [1], [4]. The classification comprises four propagation modes. The 1st mode positive streamer with subsonic speed (<1 km/s). The 2nd mode with a supersonic velocity (≈ 2 km/s). The 3rd and the 4th modes also supersonic with velocities of approximately of 10 km/s and 100 km/s respectively.

Studies of guided and unguided second mode positive streamers creeping over liquid-solid interfaces include the characterization of some of their main electrical parameters [1]: The potential gradient across the streamer filament [5]–[7], the influence of the thickness and permittivity of the solid on the current of the streamer filament [1], [8], [9] and the influence of the solid materials on the shape of the streamer [10] are some examples. Also, the mechanism of ‘self-stabilization’ by branching of the streamer in liquids such as mineral oil and alkanes has been shown by experiments with polymeric tubes restricting the streamer branching [11], [12]. Furthermore, the spatial restriction of the streamer branching has been found to decrease the acceleration voltage [11], [12]. The acceleration voltage means the disappearance of 2nd mode streamers at higher voltages where breakdown is caused by 3rd or 4th mode streamers instead [1].

The experimental study reported in this document shows a comparison of 2nd mode positive streamers creeping along two different types of mineral oil-paper interfaces. Since 2nd mode positive streamers are the most characterized streamer mode [1], they are suitable to study in order to understand which properties of the solid influence the streamer. Kraft paper and kraft fibril paper are used as solids. Both solids are made from kraft pulp. However, the kraft fibrils are pulp fibres further treated, mechanically, in a homogenization process which produces micro and nano sized fibrils and results in papers of higher density and lower surface roughness. This means that the papers have same chemistry but differ in morphology and porosity. In order to investigate the influence of density and surface roughness of the solids on the streamer propagation, charge recordings and high-speed shadowgraphs are used. Velocity, charge, current, propagation time and features of the streamers are also reported. In order to find a correlation between the physical properties of the papers with the electrical properties of the streamer filaments, an evaluation of the model of a single streamer filament introduced in [1], [13] is also performed. This analysis presents a correlation of the circulating current across the streamer filament and its propagation velocity, capacitive coupling to the opposite electrode and applied voltage for a 2nd mode positive streamer.

II. EXPERIMENTAL SETUP

A. Setup

The experimental setup consists of a point-plane configuration immersed in mineral oil. The point electrode has a radius r_p of 2.9 μm and the plane electrode has a diameter of 100 mm. The arrangement is assembled in a test chamber. The point-plane gap distance d is 7 mm. The needle tip is located at the center of the chamber aligned with the lateral viewports. The plane electrode is covered with an impregnated kraft paper with a thickness of 100 μm to protect the system in case of breakdown.

A mineral oil-solid interface is made by placing a solid sample in contact with the point electrode. The solid sample is inclined 60 degrees to the plane electrode. Fig. 1 shows an example of a shadowgraph of the needle tip in contact with the surface of the solid sample installed.

A shadowgraph technique is used to detect streamers initiated at the mineral oil-solid interface (e.g. [1], [11], [14]–[27]). The point electrode tip is illuminated with a laser beam such that a high-speed, 8 frames shadowgraph is recorded with an intensified framing camera (SIM D8-UV, Specialized Imaging). Using a far field microscope (QM 100, Questar corporation / LaVision) the image is projected to the camera sensor. The detected image has a maximum resolution of 4.1 $\mu\text{m}/\text{pixel}$.

B. Procedure and sample preparation

The solid samples are cut into long narrow pieces of 9×100 mm. The samples are dried in a vacuum oven (5 mbar) at 105 °C. After 24 h, the temperature in the oven is reduced to 60 °C and filtered mineral oil is inserted into a glass container inside the closed oven through a feedthrough. The oil is degassed for 24 h in the vacuum oven prior to impregnation of the solid sample.

High voltage square pulses with 35 ns of rise time and 40 μs duration are applied to the point-plane arrangement. 100 measurements are performed for a fix voltage of 23.7 kV.

C. Solid samples

The solid samples are one kraft paper and one paper made from cellulosic micro and nano fibrils. The kraft paper sample is produced from an electrical grade unbleached kraft pulp (Munksjö, Aspa Bruk, Sweden) beaten (mechanically treated) for 4000 revolutions in a PFI-mill while a kraft fibril paper is made from cellulosic micro and nanofibrils produced from the same kraft pulp. The kraft fibrils are prepared, without chemical pre-treatment, by mechanical treatment first by beating the pulp for a total of 6000 revolutions in the PFI- mill followed by homogenization at a pressure of 1600 bar in a Microfluidizer M-110eh (Microfluidics Inc., USA); by three passes through a 400 μm and a 200 μm chamber connected in series followed by three passes through a 200 μm and a 100 μm chamber connected in series. Papers from kraft pulp and kraft

fibrils are produced using a Rapid Köthen sheet former (PTI, Pettenbach, Austria) according to procedures previously described in [28], [29]. All the investigated samples have a thickness of 100 μm .

The relative permittivity of the impregnated kraft fibril paper is higher than for the impregnated kraft paper (4.5 and 3.2 respectively) due to its higher density (i.e. lower fraction of mineral oil in the impregnated system).

The surface roughness of the kraft fibril paper is investigated with atomic force microscopy (AFM, Nanoscope IIIa AFM, Bruker AXS). The average roughness of the AFM measurements is defined as the root mean square of the values measured over three different areas $15 \times 15 \mu\text{m}$ in size. The surface roughness of the kraft paper is obtained from frequency analysis of a height map obtained by an OptiTopo (Innventia, Sweden) in which height map is calculated after illumination of the sample surface from low angles from two opposite directions.

Sample properties (relative permittivity, surface roughness and density) are summarized in Table 1. The thickness used for calculating the paper density are averages from 5 measurements with a disc micrometer (Absolute Digimatic Quick 227, Mitutoyo) of a stack of 3 test pieces (derived from ISO 534:2005).

Table 1. Sample Properties

Material	Relative permittivity ϵ_r	Average surface roughness (nm)	Density (g/cm^3)
Kraft fibril paper	4.5 ¹	350	1.30
Kraft paper	3.2 ¹	2000	0.80
Oil	2.2	-	0.87

¹ Measured by dielectric spectroscopy at 50 Hz (procedure described in [29])

III. RESULTS

A typical shadowgraph of the propagation of second mode positive streamer creeping along the mineral oil-kraft paper interface is presented in Fig. 1. The streamer propagation along the kraft paper interface shows three main features. First, several and small branches with filamentary appearance start to propagate from the point electrode as it is shown in Fig. 1a and 1b. The length of the branches is in the order of few hundred micrometers. Each filament has some micrometers in diameter and they widen as the streamer propagates. Second, the streamer propagation along the interface consists of either one or two main filaments with small branches Fig. 1c, 1d and 1e. Third, the filaments reach their maximum diameter as soon as the streamer stops propagating (Fig. 1f). The streamer collapse and disconnection of the branches can be observed in Fig. 1g, followed by the fragmentation of the filaments in Fig. 1h. This observation agrees with the dynamic of the filaments of second mode positive streamers reported by other authors [18], [1].

Fig. 1. Shadowgraph of second mode positive streamer propagating along mineral oil-kraft paper interface. Point plane configuration with kraft paper inclined 60 degrees to the plane electrode. $v=1.57$ km/s.

Fig. 2 shows the charge recording of the streamer propagating along the mineral oil-kraft paper interface reported in Fig. 1. The total charge injected by the streamer is about 1.2 nC. The shape of the measured charge indicates a continuous current and its value is about 1 mA. The currents of second mode positive streamer are usually composed by a continuous component with rapid superimposed pulses [30]. The charge injection to the streamer stops after approximately 1.1 μ s from the voltage rise. This defines the moment when the streamer propagation stops and it corresponds to the shadowgraph shown in Fig. 1e.

Fig. 3 shows an example of the propagation of a second mode positive streamer along the kraft fibril paper interface. The propagation of the streamer along this interface also has three main features. First, small branches with filamentary appearance propagate from the point electrode Fig. 3a, 3b, 3c and 3d. Their characteristics are similar to those in the case with kraft paper. Second, one of the branches becomes the main filament. Its propagation consists mainly by one filament. The main filament continues its propagation exactly on the paper surface (as seen in Fig. 3e) and possible branches from this filament are strongly reduced. The main filament increases its diameter as the streamer propagates. 78% of the measurements with kraft fibril paper showed the propagation of the streamer as a single filament along the interface. This behavior of the streamer is not observed in the case of the kraft paper. Third, the streamer reaches its maximum propagation and the process of collapsing, disconnection and fragmentation of the streamer starts (Fig. 3g). Fragments of the main filament remain on the solid surface during the fragmentation process (Fig. 3h).

The charge recording for the streamer propagating along mineral oil-kraft fibril paper in Fig. 3 is shown in Fig. 4. The charge recording shows a linear increase with a maximum injection of charge of 4.8 nC. The injection of charge stops after 5.2 μ s when the streamer propagation ends. The shape of the charge recording also suggests that the streamer current is composed mainly of a continuous component of about 1 mA.

Fig. 2. Charge recordings of second mode positive streamer propagating along mineral oil-kraft paper interface.

Table 2 shows the average values for 100 measurements of the streamer parameters with the kraft paper and the kraft fibril paper. The streamer average velocity is estimated from the streamer length measured in the shadowgraphs and its respective time. The propagation time is assumed as the instant when the streamer charge injection stops. The reported charge in Table 2 corresponds to the average of the maximum charge injected to the streamer when it stops propagating. The average current is obtained from the slope of the charge recordings. No damages of the papers are observed, by optical microscopy, after the streamer propagation.

Table 2. Streamer parameters

Material	Velocity (km/s)	Propagation time (μ s)	Number of filaments	Charge (nC)	Current (mA)
Kraft paper	1.52 ± 0.2	1.78	2	1.73	0.9
Kraft fibril paper	1.63 ± 0.3	4.56	1	4.83	1.1

IV. DISCUSSION

The comparison of the cases with kraft paper and kraft fibril paper show two significant observations. First, the streamer propagating with kraft paper have several branches and the streamer propagation has place more into the liquid far from the solid surface. Second, the streamer branching is drastically reduced (almost to a single filament) when it

Fig. 3 Shadowgraph of second mode positive streamer propagating along mineral oil-kraft fibril paper interface. Point plane configuration with kraft fibril paper inclined 60 degrees to the plane electrode. $v=1.68$ km/s.

propagates along the kraft fibril paper; the streamer propagation mostly takes place on the solid surface as a single filament and propagates longer than with kraft paper.

The branches of the streamer creeping along the kraft paper propagate along the interface but with a distance from the solid surface. Please note that the presence of the kraft paper restricts the volume where the streamer can propagate and force the filaments to propagate on the solid, as compared with a case without any solid. The existence of two main filaments with multiple branches in the streamer propagation produces a reduction of the electric field at the head of the filaments due to mutual electrostatic shielding [1], [11], [31], [32]. At atmospheric pressure, the existing potential gradient E_s across the streamer filaments during its propagation is the main mechanism responsible of its stopping [1]. This potential gradient also contributes to the reduction of the field at the streamer head until it is lower than the critical electric field E_c (i.e 850 MV/m in mineral oil [33]) for its propagation [1], [6]. Thus, the mutual electrostatic shielding and the increasing potential gradient across the streamer filaments lead to a significant decrease of the streamer propagation time as reported in Table 2. The mean value of the streamer propagation time with kraft paper is 1.78 μ s which is about 40% of the propagation time with kraft fibril paper.

The streamers propagating along the mineral oil-kraft fibril paper interface have less branching than those propagating with kraft. Their propagation is mainly guided by one single filament. The presence of the kraft fibril paper also limits the volume where the streamer can propagate. Since the streamer propagation consist mainly of one single filament, no reduction of the field at the head of the filaments due to mutual electrostatic shielding exists [34]. Thus, the stopping of the streamer is caused by the existing potential gradient across the filament responsible of decreasing E_c during its propagation [1], [5]. This absence of the mutual electrostatic shielding leads to an increase of the streamer propagation time as it is reported in Table 2. Due to its longer propagation time, the total injection of charge of the streamer is also larger than for the case with kraft paper as shown in Table 2.

Fig. 4 Charge recordings of second mode positive streamer propagating along mineral oil-kraft fibril paper interface.

When a streamer filament is propagating close to a solid surface, an intensification of the field at the streamer head can occur [1], [7]–[9], [35], [36]. In consequence, the branching of the streamer can be altered [36], [9]. Also, the thickness and permittivity of the solid affects the capacitive coupling of the streamer to the opposite electrode (capacitance per unit of length) [1], [10], [37]. Thus, the differences in streamer branching between the cases with kraft paper and kraft fibril paper could be attributed to differences in permittivity and surface properties of the two solids. Kraft paper is an impregnable network of fibers where the transition between the oil and the impregnated paper is not well-defined [38]. Kraft paper has a large surface roughness (2000 nm) which is comparable with the size of the head of the streamer filaments (μ m size [1], [35]) as it is reported in Table 1. When a streamer filament is propagating close to the kraft paper interface, two possible scenarios could occur. One possible scenario is that the streamer is attracted to the solid surface due to intensification of the field between the filament head and the solid surface. This intensification is related to the permittivity mismatch between the mineral oil and the solid [39]. The electric field distribution at the head of the filament is highly modified as it is shown with an electrostatic simulation in Fig. 5a. A second possible scenario is that the intensification of the electric field between the head of the filament and the solid surface is reduced when the streamer reaches a hole filled

Fig. 5 Electric field distribution of streamer propagating along mineral oil-solid interfaces (normalized scale). a) Case with low surface roughness. b) Case with surface roughness comparable to the streamer head size.

with oil on the solid surface. In this case, the distribution of the field at the head of the filament becomes more symmetrical as it is shown in Fig. 5b. Thus, the next segmentation of the filament can take place either along the solid surface or into the liquid. The propagation of streamers along the surface of the kraft fibril paper, which has lower surface roughness (350 nm) than kraft paper, follows mainly the first scenario described above.

The velocity of the streamer propagation with kraft paper and with kraft fibril paper is presented in Table 2. Considering the scatter of the data, no significant difference is observed between the respective velocities. Since the streamer velocity is the same with kraft paper and with kraft fibril paper, it is possible to conclude that the streamer velocity is independent of the field across the filament and at the filament head. This conclusion is in agreement with the experimental results in [6] showing that the field intensification at the streamer head due to surface roughness and permittivity mismatch of the solids in the experiment does not influence the streamer velocity for the applied voltage. In small gaps, the velocity of second mode positive streamers is usually almost constant in a large range of applied voltages [34], [40]. Also, the field at the filament head is in the range of $6 - 10 \times 10^8$ V/m. An increment in the velocity of the streamer implies a change of propagation mode to 3rd mode streamer propagation [1], [4]. The 3rd mode is ten times faster than 2nd mode propagation [1], [35], [4]. Third mode propagation has been observed in small gaps and those streamers have fields at the filament head of $15 - 30 \times 10^8$ V/m [1], [41]. Thus, the intensification of the field at the filament head at the applied voltage for both paper interfaces does not reach such electric field magnitudes as to change the propagation mode. Thus, the velocity of streamers can be considered independent of the surface roughness and permittivity of the solid surface for the applied voltage level.

It is important to highlight that the permittivity of the kraft paper and kraft fibril paper is related to their respective densities. The denser the paper, the higher is the concentration of polarizable groups [42]. Thus, kraft fibril paper with higher density than kraft paper has higher electrical permittivity (Table 1). A solid with high electrical permittivity increases the capacitive coupling of the streamer filament to the opposite

electrode [1], [10]. This increment of the capacitive coupling of the streamer filament results in an increment of the circulating current inside the streamer filament [1], [13]. The influence of the capacitive coupling on the electrical properties of a single streamer filament can be explained with the ‘macroscopical’ model introduced in [1], [13]. It defines that the current of a streamer filament can be written as [1]:

$$i = v \frac{dC}{dx} V \quad (1)$$

The capacitive coupling is shown as the capacitance per unit of length dC/dx of a streamer filament during its propagation. i is the current across the filament, v is the velocity of the streamer filament and V is the voltage applied. The increment of i when dC/dx increases, means that E_s decreases. This affirmation agrees with a large number of experiments [1], [7]–[10], [36]. Thus, the permittivity of the solid affects the potential gradient E_s across the streamer filament which is the main stopping mechanism [1], [6], [9].

Using the values in Table 2 and (1), it is possible to calculate the capacitance per unit of length of the streamer filament for each solid case. The current per filament is higher for the case with kraft fibril paper which has the highest permittivity. The current is 1.1 mA and the streamer mainly consists of a single filament. This means that E_s is lower for the case with kraft fibril paper and leads to a longer propagation time 4.56 μ s. The capacitance per unit of length of the streamer filament with kraft fibril paper is 28.5 pF/m. For the kraft paper, the mean injected current is 0.9 mA and the streamers mainly consist of two filaments. Assuming that the filaments are similar, a current of 0.45 mA is injected for each filament. Since kraft paper has lower current per filament, E_s is higher in its streamer filaments. The capacitance per unit of length of each filament is 12.5 pF/m. This leads to a shorter propagation time 1.78 μ s. Thus, streamer filaments propagating along mineral oil-kraft paper interface have lower capacitive coupling and shorter propagation time compared to those ones propagating with kraft fibril paper.

Notice that the total average current injected by streamers is very similar in both cases, with kraft paper and with kraft fibril paper. This seems to be independent of the number of branches of the streamer for the conditions of this experiment. Similar features has been reported in [13]. The average of streamer current does not change significantly for streamers consisted of one to three branches.

V. CONCLUSIONS

Streamers propagating along a mineral oil-kraft paper interface propagate with a distance from the solid surface. Their propagation takes place mainly into the liquid. The streamers are mainly composed by two main filaments. The mutual electrostatic shielding between both filaments leads to the decrease of its propagation time and the charge injected.

For the case with the kraft fibril paper, the streamer propagation occurs exactly on the paper surface. The streamer consists mainly of a single filament. The streamer propagation time is longer with kraft fibril paper than with kraft paper. Due

to the longer propagation time, the final injection of charge is larger than in the case with kraft paper.

Streamers propagating with kraft paper with two main filaments have similar average of injected current than those propagating with kraft fibril paper (with only one main filament). Assuming the both filaments of the kraft paper are similar, the current per filament is lower for the kraft paper case than with kraft fibril paper. This difference is attributed to their difference in electrical permittivity (which is dependent on density) that produces different capacitive coupling of the streamer filaments during their propagation.

Despite their branching differences and current across the streamer filaments, the streamer propagates with same velocity in both solid cases. The streamer velocity is independent of the potential gradient and current across the streamer filament for the applied voltage.

The surface roughness of the solid is correlated to the streamer branching. Due to the high electrical permittivity and low surface roughness of the kraft fibril paper, streamers propagating along the surface have a constant intensification of the field at the head of the streamer filament. This constant field intensification leads the propagation of the streamer exactly along the interface. For solids with high surface roughness as kraft paper, the propagation of the streamer along the interface has two scenarios. The first scenario is when the streamer is attracted to the solid surface due to intensification of the field between the filament head and the solid surface. The second scenario is when the streamer reaches a hole filled with oil on the solid surface, the intensification of the electric field between the head of the filament and the solid surface is reduced. Thus, the next segment of the streamer filament can have place either close to the solid surface or move into the liquid.

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