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Positive streamers: inception and propagation along mineral-oil/ solid interfaces

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Keywords: electrical discharge, streamer propagation, streamer inception, liquid/solid interfaces, mineral oil, positive streamer

Abstract

This paper presents an experimental characterization of the prebreakdown phenomena in liquid/ solid interfaces. The characterization is devoted to the 2nd mode positive streamers initiated and propagated along interfaces of mineral-oil and solids with different chemical composition and physical properties. Polymers of low density polyethylene (LDPE), polyethylene terephthalate (PET), polytetrafluoroethylene (PTFE) polyvinylidene fluoride (PVDF) and papers made of kraft paper and a kraft fibril paper (made from cellulosic micro and nano fibrils), lignin-free paper and paper with high lignin content (referred to as k107 kraft paper) are used as the solid to study their influence on the streamer inception and propagation. The streamers are initiated at the interface by applying steps of voltage to a point-plane electrode arrangement with a solid (dielectric barrier) into the gap. The solid is placed diagonal to the oil gap and near to the point electrode. Shadowgraphs, charge and light intensity recordings are obtained during the inception and propagation of the streamers. Thus, estimations of the streamer length, velocity, current and average charge, are also presented. A time delay has been observed before the initiation of the streamer. This delay is probably correlated to the initiation process and formation of the gaseous phase of the streamer near to the interface. The threshold propagation voltage of the 2nd mode streamers at mineral-oil/solid interfaces is shown to be independent of the interface. However, the inception voltage is highly influenced by the interface. Additionally, the observed characteristics of streamers propagation (e.g. current, length, velocity, etc) along the tested interfaces cannot be fully explained by a capacitive coupling effect (permittivity mismatch). This open a discussion for the possibility that properties of the solid such as chemical composition, wettability and surface roughness can influence the streamer propagation.

1. Introduction

The electrical prebreakdown in liquids, usually referred to as 'streamers', is a complex phenomenon that involves several electrical, mechanical and thermal mechanisms [1, 2]. Several studies have been devoted to their understanding to improve the electrical insulation systems of high voltage components that use dielectric liquids [1–3]. In particular, the study of the prebreakdown in liquids has been done mainly on positive streamers because they are the most likely to cause breakdown [2]. The propagation of positive streamers have been classified in propagation modes according to their velocities [2, 3]. That is, 1st mode positive streamer with subsonic speed ($<1 \text{ km s}^{-1}$), 2nd mode positive streamer with a supersonic velocity ($\approx 2 \text{ km s}^{-1}$) and 3rd and the 4th modes with velocities of approximately of 10 km s⁻¹ and 100 km s⁻¹ respectively [2].

The initiation mechanisms of the positive streamers still remains unclear [2]. The high initiation fields obtained from experimentation (e.g. 8.4 MV cm⁻¹ cyclohexane [4]) suggest that mechanisms as impact ionization are possibly involved in the initiation process [5]. However, the dependency of the streamer initiation

field on the hydrostatic pressure suggests the existence of a gaseous phase (cavity) as precursor of the streamer inception [2, 6, 7]. The origin of this gaseous cavity is unclear. Nevertheless, some authors proposed a process of mechanical cavitation to be responsible of this cavity formation [7].

On the other hand, the propagation of positive streamer has been widely characterized. In particular, the propagation of 2nd mode positive streamer has been reported under different experimental conditions such as voltage, pressure, electrode configuration, etc [4, 6, 8]. It has been shown that the propagation and growth of the streamer filaments requires the continuous formation of a gaseous phase which depends on the hydrostatic pressure [9, 10]. The dynamics of the streamer filament comprises creation, expansion, implosion and collapse, followed for the presence of rebounds [10]. This dynamic has been shown to be in agreement with the dynamics of a cavitation bubble modelled by Rayleigh [2, 10]. Parameters of the streamer such as propagation time and length are depended on the hydrostatic pressure [9]. Thus, the increase of the hydrostatic pressure results in a shorter streamer propagation. This effect is attributed to the enhancement of the potential gradient along the filament. Such consideration takes in account the streamer conductivity due to a gas discharge mechanism [9].

A wide characterization of the inception and propagation of 2nd mode positive streamers have been performed by several authors along liquid/solid interfaces [11–15]. Different studies report the influence of the thickness and permittivity of the solid on the current, charge and shape of the streamer filaments [11, 15–21], the existence of a potential gradient across the streamer [8, 13, 14], the accumulative effect of multiple streamers initiated at a liquid/solid interface and the influence of the chemical composition of the oil [15, 21, 22], etc. All these studies highlight the importance of the bulk properties of the solid material (i.e. permittivity and thickness) since it influences the capacitive coupling of streamers to the opposite electrode [19]. However, there is no clear understanding about the effect of the properties of the solid (e.g. chemical composition, surface roughness, porosity, etc) on the development of positive streamers along liquid/solid interfaces. Moreover, there is currently no predictive model that can describe the inception and propagation of positive streamers [2] due to the lack of understanding of the physical mechanisms involved in these processes, especially when liquid/solid interfaces are present.

In order to contribute to the further understanding of the inception and propagation of 2nd mode positive streamers, an experimental study is performed to investigate the streamers along different mineral-oil/solid interfaces. Thus, the same mineral-oil is used in combination with 8 different solids. Those are, four polymeric films and four papers which are cellulose-based material widely used in the electrical insulation system of power transformers and high voltage impregnated cables [23]. The comparison between the solids helps to investigate and better understand what properties of the solid (e.g. permittivity, composition, surface roughness, etc) and of the interface (e.g. surface energies) can influence the streamer inception and propagation. This contributes to improve the knowledge to reengineer new materials with better electrical insulation performance capable to disable the streamer inception and propagation. The comparison of the studied liquid/solid interfaces is done by performing measurement of the stopping length, average injected charge, average current, emitted light and velocity of streamers together with shadowgraphs. It is shown that the characteristics of 2nd mode streamers such as shape, branching, average charge, average current, propagation time, velocity and inception voltage are strongly influenced by the properties of the interface (e.g. surface energies) and specific properties of the solid such as permittivity and surface roughness.

2. Experimental setup

The experimental setup has been described previously in detail in [24]. Figure 1 shows a schematic of the experimental setup. It consists of a point-plane configuration installed into a test chamber filled with mineral oil. The tip of the point electrode (made of tungsten) has a radius of curvature r_p of 2.9 μ m. The point-plane electrode gap distance *d* is 5 mm and the diameter of the plane electrode is 100 mm. The plane electrode is covered with an impregnated paper (100 μ m thick) to prevent breakdown.

The solid sample to be tested is assembled in an angle of 20° to the plane electrode and near (~30 μ m) to the point electrode as shown in figures 2 and 3. Each solid sample has a length of 100 mm, a width of 25 mm and a thickness of 100 μ m. The point electrode and the solid sample are totally immersed in the oil (see figure 2).

A shadowgraphic system is used to detect streamers propagating along the different mineral-oil/solid interfaces. The tip of the point electrode is illuminated with the light beam of a xenon lamp. Thus, the shadow image of a streamer is projected on the sensor of a non-intensified high-speed camera (Photron—FASTCAM SA3) by using a configuration of lenses aligned with the light beam and the camera. See figure 1. The positioning of the solid sample respect to the light beam has been disposed in two configurations. In the first configuration, the solid surface is parallel to the light beam as shown in figure 3(a). Thus, it is possible to observe the mineral-oil/solid interface as shown in figure 2. In the second configuration, the solid sample is rotated 90° as shown in



Figure 1. Experimental setup. (1) Test chamber (filled with oil), (2) Point and probe electrode, (3) Plane electrode, (4) Charge measuring system, (5) High speed camera, (6) Xenon lamp, (7) Xenon lamp power source, (8) Optical fiber, (9) Photomultiplier, (10) Valve, (11) Pump, (12) Particle filter, (13) Valve, (14) Heating rod, (15) High voltage pulse source, (16) Oscilloscope, (17) Signal generator, (18) Data acquisition device, (19) Computer, (20) Vacuum pump.





Table 1	L.Sample	e properties :	and parameter	rs of the streamer	inception.
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Material	Relative permit- tivity ϵ_r	Average surface roughness (nm)	Density (g cm ⁻³)	t_d (ns) max/min	E_2^i (kV cm ⁻¹)	$V_2^i(\mathrm{kV})$	V ₂ (kV)
LDPE	2.2 ^a	30	1.30 ^a	210/155	14.5	17.10	16.2
PET	3.0 ^a	3	1.92 ^a	230/140	13.4	15.10	15.6
PTFE	2.0-2.1 ^a	130	2.20 ^a	330/146	14.8	17.50	16.0
PVDF	8.4 ^a	360	1.76 ^a	260/139	17.1	16.30	15.6
Kraft fibril	4.5 ^b	350	1.30	330/133	14.1	14.90	15.6
Kraft paper	3.2 ^b	2000	0.80	240/137	15.8	17.60	16.0
Lignin free paper	2.5 ^b	~2000	0.65	250/135	14.4	16.70	15.6
κ107 Kraft paper	3.0 ^b	~2000	0.59	230/151	15.3	17.20	16.0
Oil	2.2 ^b	—	0.87 ^a	_	_	—	—

^a From supplier.

 $^{\rm b}$ Measured by dielectric spectroscopy (procedure described in [26]).

figure 3(b). This positioning allows observing the branching of the streamer on the solid surface of transparent polymers such as PET, LDPE and PVDF.

The experimental setup includes a streamer charge measuring system. It consists of a differential amplifier and a third probe electrode (radius tip of 500 μ m). See figure 1. The streamer charge measuring system rejects the displacement current on the point electrode during the rise of the voltage pulse. Thus, the system only integrates the current of the streamer with a passive integrator circuit. The measuring system has a maximum sensitive of 0.1 nC. The schematic circuit of the streamer charge measuring system is presented in [24].

A photon detection system is also included in the experimental setup. An optical fiber with diameter of 2 mm is placed 20 mm away from the point electrode. The aperture of the optical fiber faces the point electrode and the incident photons are transmitted to a photomultiplier sensor. See figure 1.

3. Solid samples

Four papers and four polymeric films are studied; cf the overview given in table 1. The paper samples are kraft paper, kraft fibril paper, lignin-free paper and k107 paper. The kraft paper is chosen as a cellulose-based material widely used in the electrical insulation system of power transformers [23]. It is prepared from an electrical grade unbleached kraft pulp (Munksjö AB, Aspa Bruk, Sweden) composed of 75 wt% cellulose, 15 wt% hemicellulose and 3 wt% lignin [24]. The pulp is beaten (mechanicallyreated) for 4000 revolutions in a PFI-mill. The kraft fibril paper is also made from same kraft pulp. However, the pulp is beaten for a total of 6000 revolutions in a PFI- mill and then homogenized at a pressure of 1600 bar in a Microfluidizer M-110eh (Microfluidics Inc., USA) obtaining cellulosic micro and nanofibrils prepared without chemical pre-treatment. Both, kraft fibril and kraft fibril papers, are prepared using a Rapid Köthen sheet former (PTI, Pettenbach, Austria). The procedure is described in [25, 26]. The kraft paper and the kraft fibril paper are produced from the same pulp therefore they have the same chemical composition. However, they differ in their surface roughness and permittivity ($\epsilon_r = 3.2$ and $\epsilon_r = 4.5$ respectively) [27]. Thus, studying these solids allows possible detection of the influence of the surface roughness and permittivity on the streamer propagation.

The lignin-free paper is made from a lignin-free dissolving pulp (lignin-free sulphite softwood dissolving pulp) supplied by Aditya Birla Domsjö Fabriker AB, Domsjö, Sweden. An additional paper sample referred to as k107 kraft paper is made of a laboratory-prepared never-dried unbleached softwood kraft pulp with a kappa number of 107 (meaning a lignin content of approximately 15 wt %) supplied by SCA Research AB in Sundsvall, Sweden. Both pulps are also beaten for 4000 revolutions in a PFI-mill and the papers are prepared using a Rapid Köthen sheet former. The lignin content influences the quality of the paper, namely the mechanical properties, density and permittivity. Thus, the lignin-free paper ($\epsilon_r = 2.5$) and the k107 kraft paper ($\epsilon_r = 3.0$) with high content of lignin are also tested to detect possible influence of the material composition (i.e. lignin content) on the streamer propagation.

The polymer films investigated are low density polyethylene (LDPE ET311201), polyethylene terephthalate (PET ES301400), polytetrafluoroethylene (PTFE FP301300), and polyvinylidene fluoride (PVDF FV301300). All samples are supplied by Goodfellow Cambridge Ltd, Huntingdon, England. Their relative permittivity and surface roughness are presented in table 1. LDPE and PTFE with relative permittivity of $\epsilon_r = 2.2$ and $\epsilon_r = 2.1$ respectively, are solid materials that match the permittivity of mineral oil. Thus, it is possible to compare

different properties of the liquid/solid interface such as the surface energies affecting the streamer propagation. Additionally, PVDF with a relative permittivity of $\epsilon_r = 8.4$. has been selected as an extreme case of permittivity mismatch with mineral oil. Furthermore, both, PTFE and PVDF have fluorine atoms in their elementary structural unit meaning a high electron affinity [24]. Thus, the comparison of PTFE and PVDF with the other samples may allow the detection of possible influence of the fluorinated content of the solid in the streamer propagation. PET with relative permittivity of $\epsilon_r = 3.0$ has been selected to match with the permittivity of the impregnated kraft and k107 kraft paper samples.

An atomic force microscope (AFM, Nanoscope IIIa AFM, Bruker AXS) is used to measure the surface roughness of the polymer films and the kraft fibril paper. The average roughness of the AFM measurements correspounds to the root mean square of the values measured over three different areas ($15 \times 15 \mu$ m). An 3D optical profilometer (OptiTopo, RISE Bioeconomy, Sweden, formerly Innventia AB) is used to measure the surface roughness of the kraft paper. The surface rougness of the polymers is sumarized in table 1. The surface roughness is not measured for the lignin-free paper and the k107 kraft paper. However, it is expected that they have a similar surface roughness as the kraft paper. All the investigated samples have a thickness of 100 μ m.

4. Preparations and testing procedure

The mineral oil (Nitro 10X supplied by Nynas AB, Stockholm, Sweden) is filtered and degassed before the electrical test. The filtering and degassing process is performed inside the test chamber for 24 h under a pressure of 5 mbar and a temperature of 60 °C. Figure 1 shows the filtering and degassing arrangement of the experimental setup. A vacuum pump is used to reduce the pressure inside the chamber while a heating rod increases the temperature of the oil. After the mineral oil is filtered and degassed it is cooled to room temperature. A detailed description of the preparation procedure and the experimental setup is in [24].

The solids samples are dried under a pressure of 5 mbar and a temperature of 105 °C to reduce their moisture content before they are assembled. This process is performed for 24 h in a vacuum oven as shown in [24].

After the mineral oil is degassed and the solid sample is assembled, the electrical test is performed. The electrical test is randomized with four series of measurements at each voltage. The procedure of one series of measurements can be described as follows: square high voltage pulses with 35 ns of rise time and duration of 40 μ s are applied to the point-plane configuration. The period of the voltage pulses is 60 s. The peak voltage ranges between 13 kV and 25.5 kV with steps of 1 kV approximately and it is selected randomly. 10 measurements are performed for each voltage level. Note that 40 measurements have been taken per voltage level after four series. This procedure allows the detection of possible conditioning of the samples, the point electrode or the oil during test. Figure 1 shows the high voltage pulse source connected to the plane electrode and the computer that controls the electrical test.

5. Second mode positive streamers at liquid/solid interfaces

5.1. Streamer shadowgraphs

Figure 4 shows the typical shadowgraph of 2nd mode positive streamers propagating along oil/solid interfaces of mineral-oil and LDPE, PET, PVDF and PTFE. The shadowgraphs show the streamers at their maximum propagation length. As it can be seen, the streamers have a filamentary shape and propagate along the interface with several branches on the solid surface as shown in figures 4(b), (d) and (f). Additionally, figures 4(a) and (c) show that some branches of the streamers propagating along interfaces with LDPE and PET stick out from the interface and propagates into the liquid. In contrast, the streamer always propagates in contact with the solid surface for the interfaces with PVDF and PTFE.

Figure 5 shows the typical shadowgraphs of 2nd mode positive streamers along the different mineral-oil/ paper interfaces. It is observed that the streamers do not propagate in close contact with the solid surface for the cases with lignin-free paper, k107 kraft paper and kraft paper. Only some branches contact the solid surface. Similar observation has been reported for creeping discharges over impregnated pressboard [15, 28]. In contrast, the streamers propagate in close contact with the solid surface in the case with kraft fibril paper. The low surface roughness and the high permittivity of the kraft fibril paper are the main parameters of the solid that can promote the propagation of streamers in close contact with the solid surface, as reported in [27].

5.2. Streamer charge and light intensity recordings

Figure 6 shows a typical example of charge and light recordings of 2nd mode positive streamers along mineraloil/solid interfaces. A delay t_d is detected before the injection of the charge of the streamer starts. t_d is counted from the moment when the voltage rises (at 10% of the peak value of the voltage) and the time when the first injection of charge and light pulse are detected. The maximum and minimum detected values of t_d are reported



Figure 4. Shadowgraphs of 2nd mode positive streamers propagating along different mineral-oil/polymer interfaces. (a) LDPE, (b) LDPE (camera alignment rotated 90° as shown in figure 3(b)), (c) PET, (d) PET (camera alignment rotated 90° as shown in figure 3(b)), (e) PVDF, (f) PVDF (camera alignment rotated 90° as shown in figure 3(b)), (e) PTFE. The solid surface is inclined 20 degrees to the plane electrode, V = 24.6 kV. d = 5 mm, $t_r = 35 \text{ ns}$, $r_p = 2.9 \mu \text{m}$.





in table 1. It is observed that t_d is influenced by the voltage. t_d decreases as the voltage is increased. Similar observations of t_d has been reported for slow streamers [7, 29]. t_d is always detected even for voltages at 100% inception probability.

Figure 6 shows that a continuous injection of charge is detected during a period of t_p . This injection of charge is associated to the continuous current of the streamer during its propagation. Note that t_p is the propagation time. During the period t_p , the light recordings consist of several pulses superimposed to a continuous component of light. The detected pulses are usually associated to re-illuminations of the streamer channel while the continuous component is associated to a constant emission from the streamer head [30]. The maximum injection of charge is reached after the period t_p when the streamer propagation stops.





Figure 7 shows the measurements of the streamer propagation time as a function of the voltage for each case. t_p is longer for the cases with PTFE, PVDF, PET and kraft fibril paper. In contrast, t_p is shorter for the cases with LDPE, lignin-free paper, kraft paper and k107 kraft paper. Note that t_p , is not correlated with the permittivity of the solid. For instance, the cases with PTFE ($\epsilon_r = 2.1$) and PVDF ($\epsilon_r = 8.4$) have the largest propagation time despite their differences in permittivity. This can also be observable for the case with PET $\epsilon_r = 3.0$) and the cases with kraft paper ($\epsilon_r = 3.2$) and k107 kraft paper ($\epsilon_r = 3.0$) which differ in propagatn time.

5.3. Average current and charge injection

The average streamer current is calculated with the slope of the charge recordings during the streamer propagation time t_p . The average currents arsummarized in figure 8. The current results are classified in three groups. The cases with PVDF, PTFE and PET have the highest average current. The cases with k107 kraft paper, kraft paper and kraft fibril paper have the lowest average current. The cases with LDPE and lignin-free paper are grouped together in between these two groups.

Figures 9 and 10 shows the average injection of charge of the 2nd mode positive streamers along mineral-oil/ solid interfaces. The average streamer charge shows an exponential correlation with the voltage. Notice that the cases with the largest average injection of charge also have the largest average current and propagation time as the cases with PTFE, PVDF and PET. The cases with LDPE and lignin-free paper have a high average current but





their propagation time is short, resulting in a low injection of charge. The cases with kraft fibril paper, kraft paper and k107 kraft paper have short propagation time and low average current leading to a low injection of charge.

5.4. Inception and threshold propagation voltage V2 of 2nd mode streamers

The initiation (V_2^i) and threshold propagation (V_2) voltages of positive filamentary streamers have been widely characterized by several authors in setups with point-plane configuration under step voltages and small gaps [2, 4, 6]. It has been shown that the radius of curvature of the tip r_p and the voltage define the inception conditions of the positive filamentary streamers. For tips below a critical radius of curvature r_c , the itiation voltage V_2^i is independent of r_p and filamentary 2nd mode streamers are only observed above a well-defined threshold V_2 [2, 31]. For tips with $r_p > r_c$, the initiation voltage V_2^i . increases as r_p is increased and is larger than V_2 [4]. The value of r_c vary with the tested liquid (e.g. 3 μ m for pentane and 6 μ m for cyclohexane [6]).

According to [2], the threshold propagation voltage V_2 can be obtained from plots of thend mode streamer stopping length as a function of voltage. The intersection of the fitting curve with the voltage axis (zero length) indicates the threshold propagation voltage V_2 . Figures 11 and 12 show the streamer stopping length of the here reported streamers propagating along different mineral-oil/solid interfaces as a function of the voltage. It is interesting that the plots of all cases intersect the voltage axis approximately at the same value ($V_2 \sim 15.9$ kV). Notice the linear correlation between the streamer length and the voltage. This linear correlation indicates a





constant potential gradient along the streamer channel [2, 8, 13, 14, 19, 32]. The estimates of the potential gradient (E) are presented in the legend of the figures.

For the here reported experiments, the inception voltage of filamentary streamers is determined by counting the number of streamers detected at each voltage level. V_2^i is the inception voltage at 50% inception probability. Figure 13 shows the streamer inception probability of 2nd mode positive streamers at different mineral-oil/solid interfaces. Observe that the inception probability increases from 0 to 100% within a voltage interval of about 6 kV for all materials. This is typical for streamers initiated under positive polarity [29].

The streamer inception voltage V_2^i is summarized in table 1 for each case. Note that the obtained inception voltages V_2^i are different to the threshold propagation voltage V_2 obtained from the plots of the streamer stopping lenght versus voltage. The lowest inception voltages V_2^i are observed for the cases with kraft fibril paper and PET. That is, 14.9 kV and 15.1 kV respectively. A statistical t-test with a confidence level of 99.5% shows that these inception voltages are statistically similar.

On the other hand, the highest inception voltages correspond to the cases with LDPE, PTFE, k107 kraft paper and kraft paper. The inception voltages are 17.1 kV, 17.2 kV, 17.5 and 17.6 kV respectively and are found to be statistically similar. The cases with PVDF (16.3 kV) and lignin-free paper (16.7 kV) are statistically different and between the results of those two groups.





5.5. Streamer velocity

Figures 14 and 15 show the average streamer velocity of the streamers propagating along the studied mineraloil/solid interfaces. The estimates velocities are comparable with the typical velocities of 2nd mode positive streamers propagating free in the liquid bulk reported by other authors [2, 3]. Since the velocity of sound is approximately 1.4 km s⁻¹ in the used mineral-oil, not all the detected streamers can be classified as supersonic streamers. However, all detected streamers are observed to be filamentary as reported in section 5.1.

6. Discussion

6.1. Streamer initiation and threshold propagation voltage V2

The estimation of V_2 based on the plots in figures 11 and 12 shows that the threshold propagation voltage for all here reported cases is 15.9 \pm 0.3 kV. This means that V_2 is a parameter only related to the nature of the liquid and independent of the properties of the interface.

Furthermore, the threshold propagation voltage V_2 , obtained also with probability plots, is equal in magnitude to the inception voltage of positive filamentary streamers V_2^i only for tips below the critical radius of curvature ($r_p < r_c$) as reported in [2, 6, 9, 33, 34]. In contrast, the inception voltage of positive filamentary streamers V_2^i is higher than V_2 for the condition of $r_p > r_c$ [33]. Thus, the here results reported in table 1 shows



that the threshold propagation voltage V_2 is different to the inception voltages V_2^i for some cases of streamers initiated at mineral-oil/solid interfaces. Base on a statistical analysis (confidence level of 95%) [35], it is obtained that V_2 and V_2^i are statistically similar for cases with PET, PVDF, kraft fibril paper and lignin-free paper, while V_2 and V_2^i are statistically different ($V_2 < V_2^i$) for cases with LDPE, PTFE, k107 kraft paper and kraft paper. Since V_2 is a parameter related to an ionization potential in the liquid and independent of r_p [2, 33], the obtained differences between V_2 and V_2^i reported in table 1 can be attributed to a variation of r_c due to the proximity to the liquid/solid interface. Thus, the condition turns to be $r_p < r_c$ for streamers propagating along PET, PVDF, kraft fibril paper and lignin-free paper while the condition is $r_p > r_c$ for cases with LDPE, PTFE, k107 kraft paper and kraft paper.

The results in table 1 show that the presence of the interface can influence the streamer inception process by increasing V_2^i while the threshold propagation voltage V_2 reminds unchanged. The explanation of this observation is unknown, especially because the inception process and mechanisms involved in the initiation process of 2nd positive streamers still remains unclear [2]. Certainly, an initial electric field E_2^i is required to initiate the inception process but not criteria has been stablished yet to know the role of E_2^i in the inception process. The high initiation fields obtained from experimentation (e.g. 8.4 MV cm⁻¹ cyclohexane [4]) suggest impact ionization as possible mechanism involved in the initiation process. But the conditions in which charge multiplication can have place, i.e. if it happens in the liquid or low density phase, remain unclear since the dependency of the streamer initiation field on the hydrostatic pressure suggests the existence of a gaseous phase (cavity) involved in the early stage of the initiation, triggering the streamer inception [2, 5–7]. The origin of this gaseous cavity is still unclear. Nevertheless recent works have postulated a process of mechanical cavitation as responsible of this cavity formation [7].

The lack of an inception criterion for the 2nd mode positive streamers makes complicated to understand the influence of the presence of the liquid/solid interface to the streamer initiation. Only few assumptions can be done. During the inception process, the presence of the interface can produce intensifications of the electric field at the tip due to the permittivity mismatch between the solid and the liquid. Also, charges can accumulate on the solid surface producing an effect of double layer formation leading to modifications of the field at the tip by space-charge accumulation. These field modifications can probably influence V_2' but it is unclear how significant they are to the inception process and they are not possible to be identified in the results reported here. Furthermore, note that is not possible to reach a reasonable comparison of the initiation fields for positive streamers incepted at mineral-oil/solid interfaces. The initiation field at the tip is shown to be variable. This means that for a fixed radius tip ($r_p = 2.9 \ \mu m$) the field initiation changes by changing the solid as shown in table 1 (E_2^{t} is estimated using finite element software [36] and the corresponding initiation voltages detected in figure 13). Additionally, the initiation field is not correlated with the increasing or decreasing of permittivity of the solid. For instance, the cases with PET and k107 kraft paper with similar permittivity have different initiation fields. The cases with PVDF and lignin-free paper have similar inception voltage despite their large difference in electrical permittivity. This means that the case with PDVF did not lead to an early initiation voltage despite the large field intensification due to its large electrical permittivity. This indicates that the inception process is not only conditioned by the field at the tip but also to the interface.

From the results presented in section 5. it is not possible to clearly identify a mechanism involved in the streamer initiation at mineral-oil/solid interfaces. However, a well-notable time delay t_d is observed in all the cases. This time delay is probably correlated to the conformation of a low density phase [7]. Notice that t_d decreases by increasing the voltage but still, it is always detectable even under 100% inception voltage probability for all the cases. After t_d a well-notable light emission is correlated to the change in the slope of the charge recordings corresponding to a current injection in the range of few mA (e.g. 2 mA see figure 8) defining the instantaneous streamer inception [7]. Such a current can only flow in a gaseous phase [2].

6.2. Streamer propagation

When a streamer propagates along a liquid/solid interface, its capacitive coupling to the opposite electrode can be enhanced by the solid. This capacitive coupling usually influences the streamer stopping length [12]. The higher the dielectric constant of the solid, the longer the streamers are [19]. The increase of the capacitive coupling of the streamer enhances its current and decrease the voltage drop along each filament [2]. Thus, according to [2], the relationship between the current *i* across a single streamer filament and its capacitive coupling can be described as:

$$i = v \frac{dC}{dx} V \tag{1}$$

where *v* is the streamer propagation velocity, dC/dx is the capacitance coupling (per unit of length) of the streamer and *V* is the applied voltage.

Nevertheless, the results reported in section 5.4 for the stopping length and the potential gradient of the measured 2nd mode streamers cannot be explained by a capacitive coupling effect [12]. Figures 11 and 12 show that the maximum stopping length is observed for the case with PTFE that has the lowest dielectric permittivity. In contrast, the case with PVDF (highest permittivity) has the shortest stopping length. Additionally, cases with PET, LDPE and kraft fibril paper have similar stopping length despite their differences in permittivity. Similar issue is observed for the cases with kraft paper, lignin-free paper and k107 kraft paper. These observations show that the capacitive coupling (i.e. dC/dx proportional to the permittivity of the solid) is not the parameter that mainly influences the streamer stopping length and consequently the streamer potential gradient.

Additionally, the cases with kraft paper, kraft fibril paper, and k107 kraft paper have similar average streamer current despite their differences in permittivity as shown in figure 8. Notice that these cases also have similar propagation velocity (figure 15). Thus, equation (1) is also unsuitable to predict this observation.

Furthermore, the obtained results show that the cases with lignin-free paper ($\epsilon_r = 2.5$) and k107 kraft paper (high lignin content and $\epsilon_r = 2.5$) have similar average streamer velocity and stopping length. Surprisingly, the average streamer current and the average streamer charge are higher for the case with lignin-free paper which has lower electrical permittivity. This observation cannot be explained by the capacitive coupling effect. Note that the main difference between lignin-free paper and k107 kraft paper is their lignin content. Thus, the obtained results suggest that the chemical composition of the solid material can also influence the propagation of streamers. In this case, the low lignin content in the solid enhanced the injection of charge to the streamer during its propagation. The influence of the chemical composition of the solid can also be observed for streamers propagating along interfaces with PTFE and LDPE. Note that they have similar permittivity and low surface roughness. However, the propagation characteristics of 2nd mode streamers is very much enhanced for the cases with PTFE. This observation also suggests that the chemical composition of the solid interface influences the streamer propagation. Nevertheless, there is not a clear understanding of the mechanisms involved in the streamer propagation and their relationship to the chemical composition of the interface. Thus, further experimental and theoretical research are needed to be performed in this area.

6.3. Influence of the oil/solid interface on the streamer propagation

A thermo-mechanical model for the propagation of the 2nd mode filament streamers has been proposed in [2, 10]. In this model, the head of the streamer is considered as a moving source of thermal energy. Due to the high electric field at the filament head (e.g. 10 MV cm^{-1}), electrical mechanisms as impact ionization can occur, creating charges and leading to the superheating of the liquid [2]. The fast injection of energy into the liquid generates a shockwave at the filament head followed by the continuous generation of the gaseous phase [10]. This model implies that temperature and pressure of the gas phase are not in equilibrium with the liquid. Thus, temperature and pressure are maximum at the filament head and decrease behind the head and along the filament [2].

If the described thermo-mechanical model is extended to streamers propagating along liquid/solid interfaces, the understanding of the relationship between the energy needed to generate a gaseous phase in the liquid/solid interface and the streamer propagation mechanism becomes pertinent. This energy is related to the

surface tension of the liquid and the work of adhesion of the interface. The higher the work of adhesion, the higher the energy required to generate a cavity is [37, 38]. Thus, it is likely that the continuous development of a vapor phase (produced by superheating of the liquid and/or hydrodynamic cavitation [10]) takes place at the interface (and not into the liquid phase) if the solid is not perfectly wet. Thus, streamers should prefer to propagate (and branch) exactly at the interface in contact with the surface of not perfectly wet solids.

In order to investigate this hypothesis, the contact angle θ of the here used mineral oil and the solid samples is measured and summarized in table 2. The contact angle depends on the interaction forces at the interface and can be used to calculate the work required to separate two phases, i.e. the work of adhesion. With complete wetting, the contact angle is zero, the work of adhesion is high and therefore phases are more difficult to separate. The corresponding calculation of the work of adhesion W_{sl} (obtained with the Young-Dupré equation [38]) for the studied interfaces is reported in table 2. It is important to note that the surface roughness of the solid can increase the work of adhesion. However, for simplicity of the calculations in table 2, the surface roughness is not considered here. It is found that the PTFE has low wettability, PET and PVDF have high wettability and all the other solid samples have perfect wettability. By comparing the obtained wettability of the solids and the shadowgraphs reported in figures 4 and 5, it is observed that the streamers always propagate exactly at the interface liquid/solid for the cases with PTFE and PVDF, which are the solids with the lowest work of adhesion. For the other cases, the streamers propagate at the interface with few branches into the liquid phase and/or mainly in the liquid phase. A summary of the observations is presented in table 2.

Note that the results in table 2 may suggest that the solid wettability parameter could influence the propagation path of streamers along the liquid/solid interfaces. However, it is unclear the relationship between the wettability of the solid and the streamer propagation mechanism. Thus, further experimentation (including interfaces with different degrees of wettability) is required for the better comprehension of the possible existing relationship between this parameter and the streamer propagation.

7. Conclusions

This paper has presented an experimental characterization of the inception and propagation of 2nd mode positive streamers along eight mineral-oil/solid interfaces. The characterization of the streamer inception has shown two main observations. The first observation refers to the existence of a time delay before for the injection of current of the streamer take place after the voltage is raised. It has been noted that this time delay persists for all the cases tested, even at voltages above the 100% inception probability. The second observation is that the inception voltage of 2nd positive streamers is influenced by the interface. The obtained results show that the presence of the interface can influence the streamer inception process by increasing the voltage is attributed to a variation of the critical radius due to the presence of the interface. Thus, it is observed that the inception voltage for interfaces of LDPE, PTFE, k107 kraft paper and kraft paper is statistically higher than in the cases with PET, PVDF, kraft fibril paper and lignin-free paper.

It has been observed that the threshold propagation voltage of 2nd mode positive streamers propagating along different mineral-oil/solid interfaces is independent on the liquid/solid interface. It has been shown that the threshold propagation voltage reminds unchanged for all the tested interfaces. Additionally, the corresponding estimations of the potential gradient and threshold propagation voltage of the 2nd mode positive streamers propagating along the studied mineral-oil/solid interfaces are presented in this paper.

The reported shadowgraphs of the streamers propagating along the mineral-oil/solid interfaces show that the interfaces can influence the streamer propagation. Streamers tend to propagate exactly at the interface, in contact with the solid surface for the cases with PTFE and PVDF which have the lowest work of adhesion. For the case with kraft fibril paper, PET and LDPE the streamer propagates in close contact with the solid surface and some branches into the liquid phase. For the cases with kraft paper, lignin free paper and k107 kraft paper the streamer propagate exactly at the interface (mainly in the liquid phase). The tendency of the streamer to propagate exactly at the interface (and not into the liquid phase) is suggested to be correlated with the wettability of the solid and the surface roughness.

It has been shown that streamers propagating along different interfaces with solids with the same dielectric permittivity have different injection of current, propagation time and velocity. Moreover, streamers propagating along permittivity matched interfaces of mineral-oil and LDPE and PTFE have very large differences in shape, stopping length, current charge and velocity. Thus, the capacitive coupling effect to the opposite electrode do not explain these physical differences of the streamers. Therefore, it is suggested that parameter of the interface such as wettability and adhesion energies could influence the streamer propagation by affecting the process of the formation of the gaseous phase of the streamer filaments. Additionally, it is also suggested that the chemical composition of the solid could also influence the streamer propagation by affecting the injection of charge of the

Material	Average surface roughness (nm)	Contact angle θ°	Work of adhesion W_{sl} (mJ m ⁻²)	Observation of the propagation
PTFE	130	55	77.1	Propagation at the interface
PVDF	360	20	95.0	Propagation at the interface
PET	3	15	96.3	Propagation at the interface/ few branches into the liquid
LDPE	30	0	98.0	Propagation at the interface/few branches into the liquid
Kraft fibril paper	350	0	98.0	Propagation at the interface/few branches into the liquid
Kraft paper	2000	0	98.0	Propagation mainly in the liquid
Lignin free paper	~2000	0	98.0	Propagation mainly in the liquid
κ 107 Kraft paper	~2000	0	98.0	Propagation mainly in the liquid

Table 2. Parameters of the wettability of the solid samples and observations of the streamer propagation.

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streamer. This is supported by the experiments reported with lignin-free paper and k107 kraft paper (high lignin content). The streamers propagating along interfaces with lignin-free paper have larger average injection of charge than those propagating with k107 kraft paper even when the permittivity of the lignin-free paper is lower.

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