Dung Van Nguyen

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Thesis for the degree of
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Faculty of Information Technology,
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Department of Electric Power Engineering

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Abstract

In this study, the characteristics of non-breakdown and breakdown streamers have been investigated through the effects of dissolved gases/air, carbon particles, additives, reduced pressure, liquid chemistry and voltage polarities on streamers. Two types of white oil (Marcol 52 and Exxsol D140) considered base liquids are examined. A point-plane electrode system is employed to form a high divergent field with the electrode gap of 8 cm. A "step" voltage (0.5/1700 μs) is applied to the electrode system. The voltage magnitude is varied in steps up to 540 kV maximum. Streamer characteristics are observed with stopping length, velocity, shape, breakdown and acceleration voltages. Current and light emission pulses are recorded. Both still and streak images are captured. The properties of positive streamer channel are investigated more closely. The electric field at the channel tip is determined by using the finite element method with COMSOL Multiphysics program, and mechanisms for streamer propagation are also discussed.

Dissolved gases/air has an insignificant effect on streamer propagation while carbon particles largely facilitate it. Carbon particles were seen to accelerate and markedly reduce inception, breakdown and acceleration voltages of streamers of both polarities. However, carbon particles have a stronger influence on negative streamers than positive ones. It seems that a small amount of carbon particles in the stagnant oil in the electrode gap can switch the slow 2nd mode[1] to fast 3rd mode streamers of negative polarity. Such a phenomenon cannot be observed in positive streamers.

Two kinds of additives are employed. These are a low ionization potential, *N,N*-dimethylaniline (DMA), and an electron scavenger, trichloroethene (TCE). DMA accelerates positive non-breakdown streamers of Marcol oil but seems to decelerate those of Exxsol oil due to the fact that DMA makes streamers either more filamentary for Marcol oil or more branched for Exxsol oil. Thus, DMA reduces the breakdown voltage of Marcol oil and increases that of Exxsol oil. DMA always decelerates positive breakdown streamers since a reduction in macroscopic field resulting from increasing shielding effect formed by more branching. Therefore, acceleration voltage is significantly increased. On the other hand, DMA does not have any significant impacts on negative streamers in both types of oil. TCE increases the velocity of both polarities because it makes streamers either less branched (positive polarity) or more filamentary (negative polarity). This leads to a decrease of both breakdown and acceleration voltages. However, TCE affects negative streamers much more than positive streamers. It is proposed that streamer propagation involves electronic processes in front of streamer channel tips.

[1] The 1st and 2nd modes are defined as slow modes while the 3rd and 4th modes are fast ones.

Reduced pressure makes streamers more branched, but it still largely facilitates streamer propagation, i.e. a dramatic increase in the stopping length, thus significantly reducing the breakdown voltage. Reduced pressure seems not to influence the velocity of positive streamers while it significantly changes that of negative streamers. While slightly decreasing the acceleration voltage of positive streamers, reduced pressure decreases that of negative streamers by a factor of about two. Consequently, gaseous processes are involved in streamer propagation.

Although, the general characteristics of streamers are similar in Exxsol oil and Marcol oil, streamers of these oils still show some differences. The 2^{nd} mode of positive streamers has multi-filament shape for Exxsol oil whereas more bushy shape can be observed in Marcol oil. In Exxsol oil, the 1^{st} mode of negative streamers (bush-like shape) has to switch to the 2^{nd} mode streamers (tree-like shape) to cross the electrode gap and induce breakdown. On the other hand, the 1^{st} mode streamers (bush-like shape) can propagate across the gap in Marcol oil. The ratio of acceleration voltage to breakdown voltage is higher than for positive streamers in Exxsol oil since the content of aromatics in Marcol oil is lower.

Positive streamers are about ten times faster than negative streamers. This is due to the fact that positive streamers are more filamentary whereas negative streamers are bushier. In addition, the breakdown voltage of negative streamers is about twice of that of positive streamers, and the acceleration voltage behaves in the similar way.

It seems that a weakly ionized plasma state is present inside low conductive channels of the 2^{nd} mode streamers of positive polarity, and critical space charges accumulate at channel tips. Gas discharge is considered to be responsible for the appearance of reilluminations. Nevertheless, reilluminations do not have any significant effects on the propagation of streamers. For the 4^{th} mode, channels of positive streamers are highly conductive possibly resulting from highly ionized plasma state, and critical space charges are still present at the channel tips. The similar characteristics are suggested for corresponding modes of negative streamers. It is proposed that tip processes governed by electric field, formed by the space charges, will control streamer propagation. The electric field at the channel tip is calculated. The values of 2.4 MV/cm and 7-20 MV/cm are for the 2^{nd} and 4^{th} modes of positive streamers, respectively. The corresponding values are 1.3-2 MV/cm and 11-20 MV/cm for negative streamers. Therefore impact ionization is possibly one main mechanism producing new charges for maintaining streamer propagation.

Preface

This thesis is submitted to the Norwegian University of Science and Technology (NTNU) for partial fulfilment of the requirements for the degree of philosophiae doctor.

This doctoral work has been performed at the Department of Electric Power Engineering, NTNU, Trondheim, with Prof. Hans Kristian Høidalen as main supervisor and with co-supervisor Lars E Lundgaard.

I would like to express my sincere gratitude to all the people who have helped in carrying out this research work for the degree of philosophiae doctor. This dissertation could not have been written without their help.

I first thank my supervisor, Prof. Hans Kristian Høidalen at *NTNU*, for his instruction, support, understanding and abundant help during my graduate studies. Thank you for giving me a chance to study at *NTNU*.

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I am particularly grateful for the help and guidance of Dag Linhjell at *SINTEF Energy Research*. Without his assistance on experimental setup and equipment operation, I could not have carried out the laboratory work. I acknowledge that his contribution is invaluable.

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Trondheim, February 2013

Dung Van Nguyen

Contents

Chapter 1. Introduction

1.1 Motivation

The transformer is generally considered to be one of the most important power system components. If it fails, the consumer is deprived of electrical energy and can no longer function properly in today's society. Oil-immersed transformers have commonly and economically been used for a wide range of voltages and power ratings for many decades, i.e. from distribution to transmission levels or from medium high voltage to ultrahigh voltage applications [1]. In oil insulated power transformers, the insulating system consists of paper wrapped conductors in the transformer windings plus mineral oil and pressboard to insulate the windings from ground. In this oil-solid composite insulation system, two types of failures may occur. The first type involves a complete failure between two electrodes (which can be bulk-oil breakdown, creepage breakdown along oil-solid interface or combination of both). The second one is a local failure (partial discharge), which may not immediately lead to failure between two electrodes. Sustained partial discharges lead to deterioration of the solid insulation eventually leading to a failure. It was found that about 60-80% of failure of in-service transformers occurs at on-load-tap changer, windings and bushing [1, 2]. One of the main origins of failure is the ageing/weakness of the oil-solid insulation system. Thus, the reliability of a power transformer is largely determined by its insulation condition, and the insulation of a transformer is therefore an important issue.

It was known that the breakdown in insulating oil is preceded by the pre-breakdown phenomena, called streamers. It means that the breakdown will not occur without the presence of streamers. One has also realized that pre-breakdown processes influence voltage-time (*V-t*) curves of insulating liquids and these curves can be very different depending on liquid chemistry. Thus, many studies have been performed during the last few decades to reveal the mechanisms for streamer initiation and propagation. Nevertheless, there is still a lack of understanding of the physical mechanisms taking place in initiation and propagation of streamers in insulating liquids. The need to understand these phenomena comes from the three following reasons. First, most of the designing criteria for transformer insulation are empirically based and derived from long term experience and not through basic scientific understanding. Second, the present standards for insulation tests on liquids do not reflect the functional needs of an insulating liquid. Third, the needs to improve the existing insulating liquids and design new insulating liquids that are environmentally friendly are indispensable.

Streamer initiation and propagation have been investigated under various gaps with various liquids such as mineral transformer oil, white oil[2], hydrocarbon liquid and ester oil and many papers published. Various experimental conditions were

[2] From here, white oil means mineral oil free from aromatic/polyaromatic content.

examined such as voltage magnitude, voltage polarity, voltage waveform, electrode tip radius, gap distance, hydrostatic pressure, viscosity and additives. With the huge number of those published papers, our knowledge on streamer has greatly expanded. Streamer phenomenon was well reviewed in [3, 4]. The main findings can be briefly presented as follows. Streamer characteristics (structure, current (charge), velocity, light emission…) were well observed and depended on experimental conditions. Streamers were classified according to specific propagation modes. A special phenomenon was observed that beyond a threshold applied voltage, i.e. *acceleration voltage*, streamer velocity jumps from 2 km/s to 100 km/s [5-9]. Simultaneously, streamer shape was observed to change from spherical envelope consisting of multi-channels to one or two filaments [6], i.e. apparent area of streamer branches drastically reduces. Low ionization potential additives were proved to increase the acceleration voltage of cyclohexane under short and long gaps [7, 10]. Streamer initiation is controlled by the electric field of the needle tip while the macroscopic field of streamer envelope governs its propagation. Gaseous plasma is possibly present inside streamer channels. Both gaseous and electronic processes are involved in streamer propagation. The mechanism for initiation of negative streamers is quite well known, but this is not the case of positive streamers. Several hypotheses for streamer propagation have been suggested. Although many results were obtained, there are still numerous problems that have not yet been addressed. To improve the qualitative understanding of streamers, this study will address the following problems; the correlation between branching and velocity of streamers, the effect of experimental conditions on streamers (carbon particles, dissolved gases/air, low hydrostatic pressure), the influence of additives on streamer characteristics, properties of positive streamer channels and mechanisms behind the fast mode.

The excellent property to withstand very high voltage, i.e. high acceleration voltage [6, 8], is one of the major reasons why mineral oil is the unique choice for power transformers. It is known that mineral oil mainly contains paraffinic, naphthenic and aromatic/polyaromatic compounds. The aromatic/polyaromatic compounds have two important electronic properties: low ionization potentials and large electron-trapping cross sections. It was found that low ionization potential additives strongly increase the acceleration voltage of positive streamers [7, 10]. Large electron trapping cross section additives (electron scavengers) drastically increase the velocity and largely reduce the breakdown voltage of negative streamers [7, 11]. In addition, it was observed that streamer behaviour strongly depends on the chemical composition of liquids [12]. However, the complex chemical composition of mineral oil makes it difficult to identify the effect of each chemical compound on streamer behaviour and acceleration voltage. Therefore, the streamer characteristics should be investigated in model oil with controllable types of chemical compositions. To the model oil (white oil), a small amount of either *N,N*-dimethylaniline (DMA) or tricloroethylene (TCE) is added. This is due to the fact that DMA has the low ionization potential property of aromatic compounds while TCE represents their properties of electron trapping.

The breakdown of streamers depends on the distribution of electric field in the inter-electrode gap. For quasi-uniform field, e.g. semi-uniform gap, the breakdown largely depends on streamer initiation [13]. However, for non-uniform field, e.g. point-plane gap, the breakdown is dominated by streamer propagation [13]. In addition, breakdown in long gaps is more relevant to that of oil-solid insulation system for practical high voltage transformers. Thus, the investigation of streamer characteristics should be performed with long point-plane gaps.

Increased hydrostatic pressure suppressed streamer propagation in pentane and cyclohexane in short gaps, thus the propagation of streamer may relate to gaseous processes [14, 15]. However, the effect of increased or reduced pressures on streamers has not yet been investigated in long gaps.

1.2 Research objectives

The main purposes of this study are to better describe the characteristics of streamers and develop the understanding of streamer propagation in long gaps. To achieve these main purposes, the following specific objectives are set out.

- Investigate the effect of experimental conditions (carbon particles, dissolved gases/air, low hydrostatic pressure, and voltage polarity) on streamers.
- Investigate the effect of low ionization potential and electron scavenging additives on streamers.
- Investigate the impact of base liquid's chemistry on streamers.
- Investigate the properties of the positive streamer channels.
- Suggest the mechanism responsible for fast mode streamers.

1.3 Contributions

The main contributions of this thesis are given as follows:

- Streamer characteristics of white oil (Exxsol-D140 and Marcol-52) in non-uniform field in a long gap are described. Streamers generally behave in similar way in these types of oil. When the applied voltage is increased, velocity of streamers increases in "step" and they become more branched at both the 2nd and 4th modes. Positive streamers are about ten times faster than negative streamers, and the breakdown and acceleration voltages of positive streamers are about half of negative streamers. The process of shape shifting from multi-channels to few channels is associated with the transition from the 2nd to the 4th modes of streamers. Finally, it is found that more branching results in lower speed and vice versa.

- This thesis presents the effect of various experimental conditions on streamers. Dissolved gases/air has no effect on streamer propagation while carbon particles significantly influence it, especially for negative streamers. With the presence of a small amount of carbon particles, velocity of the 2nd mode negative streamers is increased by a factor of about ten. However, these particles do not seem to affect the 3rd or 4th mode streamers. Carbon particles significantly reduce both inception and breakdown voltages of both polarities. Reduced pressure significantly facilitates streamer propagation of both polarities leading to a large reduction in breakdown voltage. Although reduced pressure markedly increases the number of streamer branches, the streamer velocity of positive polarity is still not reduced. However, reduced pressure decreases the velocity of non-breakdown negative streamers but raises that of breakdown streamers.

- The effect of additives on streamer propagation in a long gap is recorded. The propagation of streamers in white oil (Exxsol-D140 and Marcol-52) is significantly affected with the presence of a small amount of a low ionization potential additive (DMA) or an electron scavenger (TCE). DMA can either increase or decrease the breakdown voltage of positive streamers depending upon whether more filamentary channels or more branching is the dominating effect in the actual liquid. With more filamentary channels[3], DMA will speed up streamers whereas with higher number of branches, it will slow down streamers. However, DMA always makes breakdown streamers of positive polarity more branched with reduced speed and dramatically increased acceleration voltage. TCE accelerates streamers, especially of negative polarity, and reduces both breakdown and acceleration voltages of both polarities. Positive streamers in white oil with DMA behave more like those in mineral oil while TCE has the same impact on negative streamers.

- The characteristics of channels of the 2nd mode positive streamers are investigated and described. Streamer channels are dark channels with low conductivity during almost the entire propagation time. Some of channels show short illuminations several times during propagation. During illuminations, the channels become highly conductive. Dark and illuminating channels (reilluminations) occur simultaneously and propagate equally fast. Reilluminations, possibly resulting from gas discharges, play a crucial role in breakdown, but have insignificant effects on propagation. Thus, it seems that processes occurring at the streamer tips are more important for the propagation than those inside streamer channels. The nature of the 2nd mode positive streamer channel is proposed: Gaseous plasma phase, i.e. “cold” plasma, exists inside channel, and high density of space charges accumulates

[3] Filamentary streamers are those containing smooth and thin channels.

at the streamer head. An electric field formed by the space charges may govern streamer propagation, i.e. streamers in liquids behave like those in gases.

- The mechanism behind the fast mode streamer is suggested. The propagation of streamers is possibly maintained with impact ionization occurring at streamer head. The fast mode streamer channel may contain “hot” plasma phase inside, i.e. high conductivity. Thus the streamer propagation acts as if it extends the point electrode. This results in a high electric field at the streamer tip as streamer approaches the plane electrode. This high tip field is sufficient for tip processes which may cause photo-ionization in the volume around the streamer tip. Based upon the photo-ionization, the required seed electrons for impact ionization are created in the stressed volume.

1.4 List of publications

1. N.V. Dung, F. Mauseth, H.K. Høidalen, D. Linhjell, S. Ingebrigtsen, L.E. Lundgaard and M. Unge, “Streamers in Large Paraffinic Oil Gap,” Proceeding of IEEE International Conference on Dielectric Liquids, Trondheim, Norway, paper no. 113, 2011.

2. N.V. Dung, H.K. Høidalen, D. Linhjell, L.E. Lundgaard and M. Unge, “Influence of Impurities and Additives on Positive Streamers in Paraffinic Model Oil,” IEEE Transactions on Dielectrics and Electrical Insulation, vol. 19, pp. 1593-1603, 2012.

3. N.V. Dung, H.K. Høidalen, D. Linhjell, L.E. Lundgaard and M. Unge, “Influence of Impurities and Additives on Negative Streamers in Paraffinic Model Oil,” Accepted for publication in IEEE Transactions on Dielectrics and Electrical Insulation, 2013.

4. N.V. Dung, H.K. Høidalen, D. Linhjell, L.E. Lundgaard and M. Unge, “A Study on Positive Streamer Channels in Marcol Oil,” Proceeding of Annual Report Conference on Electrical Insulation and Dielectric Phenomena, Montreal, Canada, paper no. 161, 2012.

5. N.V. Dung, H.K. Høidalen, D. Linhjell, L.E. Lundgaard and M. Unge, “Effects of reduced pressure and additives on streamers in white oil in long point-plane gap,” Submitted to Journal of Physics D: Applied Physics, 2013 (accept pending revisions).

1.5 Thesis Outline

The thesis contains the following chapters:

Chapter 1: Introduction

This chapter presents the motivations, the objectives, the contributions and the outline of this work.

Chapter 2: Background

This chapter summarizes the history of mineral transformer oil and its compositions. Besides, the streamer initiation and propagation are briefly reviewed with the important findings on hydrocarbon liquids, mineral transformer oils and ester fluids.

Chapter 3: Experimental Setup

This chapter details the test setup, oil samples and experimental procedure. The methods to measure voltage waveform and current pulses are also included. In addition, the shadowgraphic imaging method is illustrated.

Chapter 4: Results

This chapter briefly summarizes the main findings published in paper 1-paper 5.

Chapter 5: Discussion

This chapter compares the results obtained in this work to those in previous published papers through the effect of various experiment conditions, additives and chemical composition on streamers. Furthermore, the model for positive streamer channel and mechanism for fast mode streamer are presented.

Chapter 6: Conclusions

This chapter contains the main conclusions of this work and suggest the future works for further understanding the streamers.

Appendix A: presents the modelling of electrostatic field.

Appendix B: contains the reprints of the journal and the conference papers.

Chapter 2. Background

2.1 Development history of transformer oil

In power transformers, oil function as a dielectric insulating material as well as heat transfer medium. It is also used for diagnostic purposes. The power transformers used in the transmission and distribution of electrical energy are expected to have a service life of several decades under nominal service stresses. In addition to possessing suitable properties initially, the oil should maintain these throughout the long useful life of the transformers. The oil used in the transformers must have demonstrated compatibility with the other materials present in the transformer such as metals and solid insulating materials. The properties of the oil used must neither rapidly degrade these materials nor be rapidly degraded by them [16].

Mineral oils have been used as liquid dielectrics in transformers since 1887 [17]. These low viscosity paraffinic petroleum oils served the purpose of providing superior insulation when impregnated into paper or other solid dielectrics. They also provided an excellent heat transfer medium for removal of heat generated by electrical losses. However, paraffinic oils contain large quantities of paraffin wax (*n*-alkanes) and therefore have high pour points which make them unacceptable for use in electrical apparatus exposed to low temperatures. The oxidation of paraffin-based crudes produces an insoluble sludge, which increases the viscosity. It results in reduced heat transfer capabilities, overheating and reduced service life. As a result, paraffin oils were replaced with naphthenic oils. Although naphthenic oils are more readily oxidized than paraffinic, the oxidation products are soluble in oil reducing the sludge problem [18]. With free linear paraffins, the pour point of the naphthenic oils is as low as -40^{o}C [19]. The problem of the naphthenic crudes is that these oils have low flash points in the range of 125-135^{o}C.

Askarels containing a group of synthetic fire resistant (chlorinated aromatic hydrocarbons) was used as electrical insulating liquids for applications where flammable mineral oils were not acceptable. The first transformer askarel was made in 1932 and it contained polychlorinated biphenyl (PCBs). The use of PCBs oil as non-flammable insulating liquids continued until the mid-1970s when it was banned due to environmental problems.

With the end of the PCBs, the industry developed silicone oils (polydimethyl siloxane) [17, 20]. Silicones have excellent electrical insulating properties, higher flash point than mineral oils, are less flammable, have excellent anti-oxidative properties and thermal stability due to their higher bonding energy of the Si-O siloxane bond. Nevertheless, because of high price, high viscosity and poor lubrication properties, the application of silicone oils is limited to distribution transformers.

A second commercial alternative to PCBs fluids was the high molecular weight hydrocarbon, called high temperature hydrocarbon (HTH). Several of these commercial HTH fluids were available. They were good electrical insulating fluids, however, like silicones, they also were flammable but with high flash points [17].

Mineral oils are not considered being environmentally friendly and are poorly biodegradable. In addition, petroleum resources are increasingly exhausted day by day, and this could result in serious shortages in the near future [21]. Thus, environmental and completely biodegradable fluids have been developed for replacing mineral oils. Such liquids are synthetic ester (e.g. Midel 7131) and natural ester fluids (e.g. Envirotemp FR3 and BIOTEMP). Compared to mineral oils, these ester fluids have higher flash points and similar dielectric properties at standard tests [22-24]. However, the ability of these esters to withstand overvoltage is lower than that of mineral oils [8, 9], and the breakdown voltage is more sensitive to gap distance [9]. Furthermore, ester based oils are quite expensive (especially the synthetic ester oils). Clearly, ester fluids are the candidates to replace mineral transformer oils, especially in situations with special fire and/or environmental concerns. Experience with distribution transformers seems to be good [25], but for higher voltages both costs and technical issues call for more careful considerations.

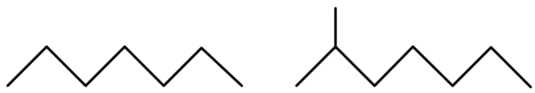
In summary, there are insulating materials that may be superior to mineral oils with respect to both dielectric and thermal properties; however, up to date, none has achieved the requisite combination of equal or better performance at an equal or lower price. Consequently, mineral oil continues to serve as the major type of liquid insulation used in power transformers [21].

2.2 Composition of mineral transformer oils

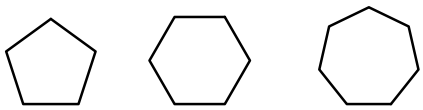
All types of mineral transformer oil are obtained from petroleum crude. The quality and composition of the crude oil reservoirs vary within quite small geographical areas. Like the crude oils themselves, insulating oils are mixtures of many hydrocarbon molecules having a variety of structures and a distribution of molecular sizes and weights. The three main groups of hydrocarbon molecules found in the oils are paraffinic, naphthenic and aromatic/polyaromatic compounds. In addition to these hydrocarbon compounds, a small proportion of sulphur and nitrogen are present. The blend of compounds that is present in a particular kind of mineral transformer oil is dependent on several factors, such as the source of the crude oil and the refining process.

The terms paraffinic and naphthenic refer to the arrangement of carbon atoms in the oil molecule. Carbon atoms that are arranged in straight or branched chains are referred to as being paraffinic. Carbon atoms that are bonded to one another to form saturated rings of generally five, six, or seven carbons are considered naphthenic. Carbon atoms that are bonded as rings of benzene are referred to as being aromatic.

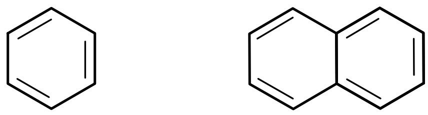
Carbon atoms that are contained in fused benzene rings are referred to as being polyaromatic. These structures of bonded carbon atoms are illustrated in Figure 1.



(a) Paraffinic and isoparaffinic structure



(b) Naphthenic structure



(c) Aromatic and polyaromatic structure

Figure 1. Structure of carbon atoms in mineral oil molecule.

Figure 2 shows the typical oil molecule. A particular type of oil will contain a mixture of many different molecular species and types of carbon atoms. If the oil contains more paraffinic carbon atoms than naphthenic carbons, it is considered paraffinic oil; otherwise it is considered naphthenic oil. The differences in the chemical composition will result in differences in physical and chemical properties. In general, paraffinic and naphthenic compounds will decide physical properties (viscosity, pour point, flash point, density…) while aromatic compounds strongly affect the chemical and electrical properties, e.g. oxidation resistance, gassing properties and electrical strength [16].

2.3 Definition of streamer

During the last few decades, the phenomenon leading to breakdown in oil have become the main research topic for understanding what really happens in the oil before breakdown, i.e. pre-breakdown processes called “streamers”.

A streamer is defined as a phenomenon of electrical discharge observed during the initiation of electrical breakdown of the dielectric medium [27]. In fact, the obvious and accurate definition of streamer in liquid does not exist. The term “streamer” in liquid has been borrowed from gas discharge physics. Here, a streamer has been defined by Raether [28] as follows: “A narrow, luminous channel formed within a gas in an electric field at pressures that are close to and above atmospheric in the stage preceding the electrical breakdown of the gas. Upon formation, a streamer lengthens at great velocity (~10^6 m/sec), a velocity several times higher than that of the charged particles between the electrodes. This speed is explained by the photo-ionization that occurs in the strong electric field created by the space charge near the advancing tip of the streamer. In their structure, streamers are similar in many respects to leaders in lightning discharges.” In liquids, the events leading to breakdown is usually denoted as a streamer [5]. These events have an optical refractive index that is different from the index of the surrounding liquid, and their shapes are quite similar to those observed in the breakdowns of gas and solid insulation [3]. Typical shapes of streamers in paraffinic oil (Exxsol oil) are shown in Figure 3.

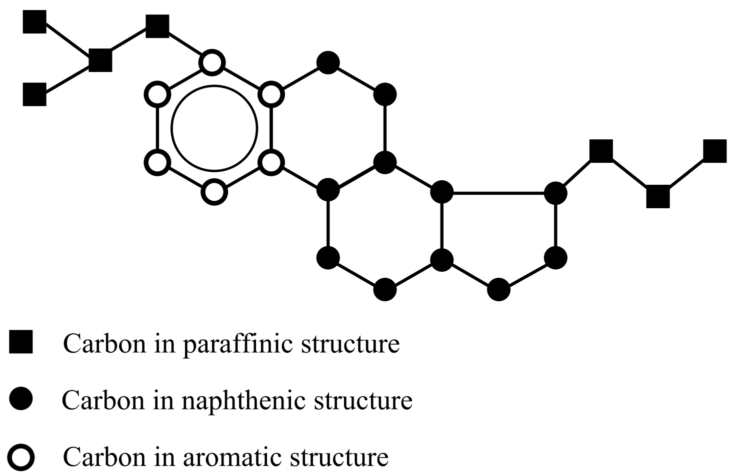


Figure 2. Typical molecule of mineral oil [26].

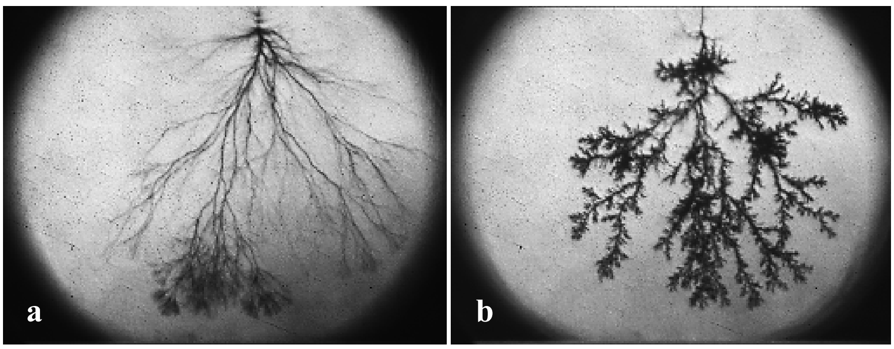


Figure 3. Typical examples of streamer shape in Exxsol oil [29]: a) Positive streamers at 210 kV; b) Negative streamers at 390 kV.

2.4 Overview of streamers

As mentioned in chapter 1, the breakdown in oil-solid insulation or oil alone is one of the main sources of failure in power transformers. A breakdown process in insulating oil is preceded by streamer initiation and propagation. Thus, the study of pre-breakdown and breakdown phenomena in liquid dielectrics has been reported in many publications over the past few decades. The understanding has been greatly developed by the use of fast digitizing oscilloscopes; optical system coupled with ultrahigh speed camera for shadowgraphic or schlieren photography; Kerr effect for measurement of electric field distribution; spectra analysis of emitted light from streamer [3].

Generally, voltage, current, total charge and light emission signals have been recorded during the initiation and propagation of streamers [6, 30-32]. Furthermore, framing images (still images) and streak images have been captured to illustrate the streamer shape. The streamer initiation has been detected by optical observation or charge (current) measurement or a combination method. The streamer propagation has been characterized by stopping length, propagation velocity, transient current, light emission and total charges.

It was found that streamer initiation depends upon various testing conditions such as voltage polarity, electrode geometry, hydrostatic pressure, liquid types and additives [14, 30, 32-35]. Streamer propagation was also controlled by various experimental conditions [6, 36, 37]. However, electrode tip radius does not affect the streamer propagation much while gap distance has a large impact [6, 8, 36].

To investigate streamers, the point-plane electrode system and “step” voltage have been widely used for following reasons; (i) creation of very high field at the point tip to start propagation; (ii) no space charges injected during the rise time of a steep step voltage; (iii) constant applied voltage during streamer propagation. Sometimes, streamers were investigated under AC, DC and special shape of voltage waveforms. Numerous liquid types have been investigated such as mineral transformer oil, hydrocarbon liquids, white oil, aromatics and ester fluids. For study of streamer mechanisms, investigations were usually performed with pure hydrocarbon liquids or white oil with and without additives.

Transformer insulation consists of minor and major insulation. The minor insulation, appearing between turn to turn and layer to layer (or disk to disk), suffers a part of applied voltage. The major insulation exists between coil to coil, coil to core, coil to tank, and intake lead to tank and is exerted full applied voltage. The distribution of electric field between coil to core or intake lead to tank is non-uniform while that of the others is uniform or quasi-uniform. The breakdown is dominated by streamer initiation for uniform (or quasi-uniform) field while streamer propagation governs the breakdown for non-uniform field [13]. It means that under uniform field every initiated streamer travels across the electrode gap with inducing breakdown. However, for mechanism studies, both non-breakdown and breakdown streamers need to be investigated. Therefore, studies on streamers should be performed with non-uniform field. The degree of non-uniformity of electric field geometry is characterized by a field enhancement factor, *f*, where

$$f = \frac{E_{\max}}{E_{avg}} \quad (1)$$

$E_{\max}$: maximum electric field at the surface of the irregular electrode

E_{avg}: average electric field calculated with the applied voltage and the electrode gap

A summary of important findings in the field of streamer study for non-uniform field is covered in the next sections.

2.4.1 Streamer initiation

2.4.1.1 Effect of electrode curvature

The streamer initiation strongly depends upon the radii of the electrode tip. The critical voltage where streamers first appear is defined as inception voltage. It was observed that the inception voltages of both polarity streamers strongly increased with the tip radius (1 µm-20 mm in mineral oil [33] or 0.5-15 µm in cyclohexane [38]). Furthermore, the inception voltage is affected by polarity regardless of types of liquids, i.e. inception voltage of positive streamers is higher than that of negative streamers [33, 38, 39]. This polarity effect can be explained with space charges accumulating in front of the electrode tip. Contrary to the inception voltage, the inception electric field, calculated by hyperbolic approximation method for radius smaller than 0.5 mm and charge simulation method for larger radii, largely reduces as the tip radius is raised [33, 38, 39]. The inception fields of positive streamers are about 10 MV/cm and 0.4 MV/cm for 1 µm and 10 mm of tip radius, respectively [33]. This reduction of the inception field is explained by the surface area effect. When the surface area of electrode is increased, i.e. larger tip radius, the probability of surface defects will also increase. These surface defects enhance local field, thus initiating streamers [33]. To verify this hypothesis, the streamer initiation in semi-uniform field was performed [34]. Although, all liquids show the similar tendency of decreasing the inception field as the tip radius is increased, the inception fields are different for different liquids [33]. Consequently, the inception field depends on tip radii, liquid types and polarity. No matter what kinds of polarities and liquids, local electric field is very important for the streamer initiation.

It was found that with large radii of the point tip, streamers did not occur immediately after the applied voltage reached its maximum value. This means that a streamer was always initiated after a delay time, called inception time or initiation time. This phenomenon was observed in mineral oil [5, 33], in ester oil [39] and in cyclohexane [30]. Large scatter data can be observed with an ester fluid [39]. During this inception time, no current or light signal was recorded, and no streamer could be observed by fast optical devices. The inception time was seen to increase with the tip radius and decrease with applied voltage [33, 39]. The statistical characteristics of the inception time were reported in [40, 41]. The inception time largely depends upon the electric field and other parameters such as electrode area, dissolved air and electrode conditioning [40, 41]. The mechanism responsible for the inception time is unclear.

In cyclohexane, the shape of the positive streamers at initiation depends on the needle tip radius. Below a critical tip radius, r_c, of about 3-6 µm, both bush-like and filamentary streamers were observed, otherwise only filamentary streamers appeared [31, 38]. The r_c is liquid dependent [42]. Similar to positive streamer, the structure of initiation streamers of negative polarity also change with radius of the tip. Up to a tip radius of 5 µm, negative streamers can appear with spherical or hemispherical or pagoda-like shape. When the tip curvature is increased above 5 µm, only bush-like streamers were observed [38].

2.4.1.2 Effect of hydrostatic pressure

For positive polarity, the inception voltage increased quasi-linearly with hydrostatic pressure from 1-15 atm regardless liquid types [43]. This result had been previously obtained with cyclohexane in [30].

For negative polarity, when using 40 µm radius tip and high resolution optical system (1 µm), the inception voltage of streamer in n-hexane was seen to increase with hydrostatic pressure and became saturated as the pressure exceeded 10 atm [44]. The similar result was achieved in [43]. On the other hand, using a high sensitive charge measurement method (sensitivity of 0.1 pC), Dumitrescu et al. [30] reported that the inception voltage seemed to be independent of hydrostatic pressure over the range from 1-101 atm. The contradiction of these results may come from the use of different techniques to detect the initiation of streamer.

2.4.1.3 Effect of additives

Generally, the role of electrochemical properties on prebreakdown processes in a pure and non-polar liquid has been investigated by adding selected additives that are either low ionization potential or high electron affinity compounds.

For positive streamer, the inception voltage of bush-like streamer was not changed when pyrene, an easily ionisable additive, was added into cyclohexane [31]. Nevertheless, with the same base liquid, the inception voltage of filamentary streamer reduces with increasing the concentration of pyrene [10]. In contrast, Ingebrigtsen et al. [32] observed that the low IP additive, *N,N*-dimethylaniline (DMA), increased the inception voltage of filamentary cyclohexane. The electron scavenger, perfluoro-n-hexane, did not change the inception voltage [32]. That result is different from what was observed in [43]. In [43], the inception voltage of tetraester increased by a factor of about 2 with 400 ppm in concentration of an electron scavenger (carbon tetrachloride or iodobenzene).

For negative streamers, both a low IP additive (DMA) and an electron scavenger (perfluoro-n-hexane) reduce the inception voltage of cyclohexane somewhat [32]. This result is opposite to what was seen in [43]. Like for positive polarity, carbon tetrachloride or iodobenzene largely increased the inception voltage of tetraester [43].

2.4.1.4 Mechanisms for initiation

a) Positive streamers

In positive polarity, the process leading to streamer initiation has not yet been fully understood. Nevertheless, two different theories for the initiation of streamers were proposed. These are theory of bubble formation by joule heating [30] and that of cavity formation by electromechanical forces [45].

- In [30], it was found that a very small current occurs below initiation voltage under impulse. This agrees well with what was already observed in similar condition under DC voltage [46]. The origin of this current is unknown. However, this current could be related to streamer initiation [30]. The hypothesis to explain streamer initiation was proposed in [30] as follows. The current emitted from a small discrete spot on the point tip (tip radii range from 1µm to 3 µm) would be large enough to boil the liquid within the inception time (10-100 ns). At a tip field of 10 MV/cm (typical magnitude of initiation field of streamers), the flow of a 100 nA current emitting from a spot of 0.1 μm^2 would give a temperature rise fast enough to boil the liquid at the tip within the typical inception time. The fact that increased hydrostatic pressure raised the inception voltage of cyclohexane [30, 43] because of possibly requiring higher energy to boil the liquid correlates well with the suggested mechanism.
- Lewis [45] suggested the theory based on the formation of cavities that are created by electromechanical forces resulted from a very high electric field (1-10 MV/cm). Since the time to develop the early stage of streamer is assumed to be in the nano- to micro-second range, he considered that the solid-like properties of a liquid would be manifest. If the tip field is high enough, the Griffith criterion for crack propagation under mechanical stress, proportional to εE^2, is satisfied, and the sub-micro cavities will develop into macro-voids (cracks) and initiation of streamer. The model also predicted that the streamer initiation of both polarities strongly affected by hydrostatic pressure and created by the same mechanism. However, initiation of negative streamer did not depend on pressure [30].

b) Negative streamers

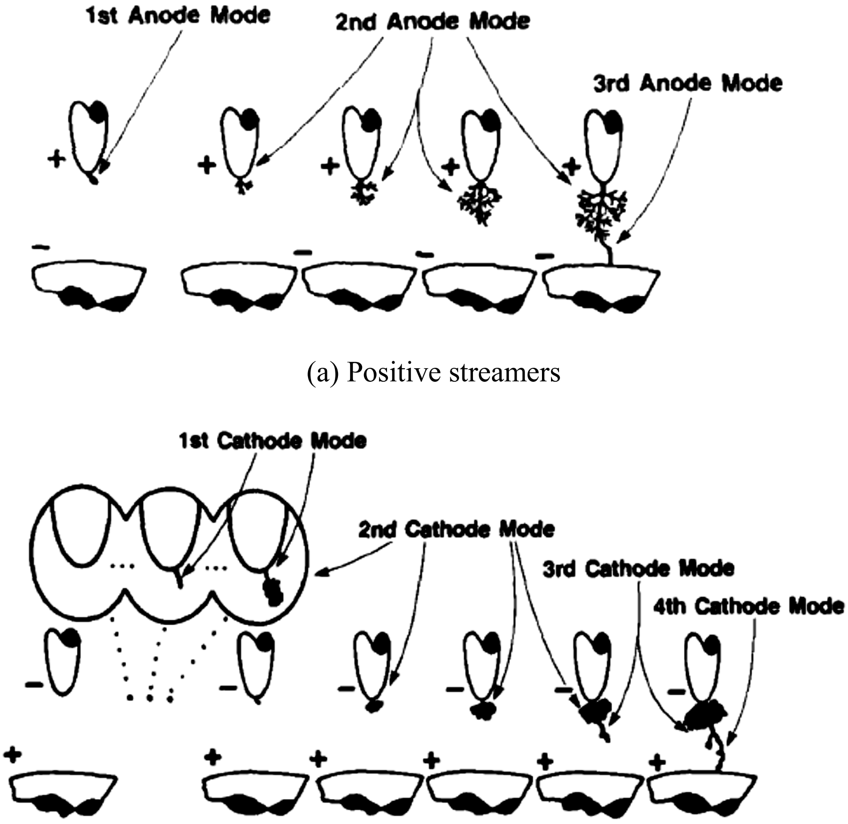
In negative polarity, the initiation mechanism is well known. When the electric field in the high field region reaches a critical value, the following observations can be made. Micrometre sized bubbles are induced by a pressure-independent electrical phenomenon: a fast electronic avalanche in the liquid phase [46, 47]. Following the avalanche by a few nanoseconds, a shock wave is radiated and a cavity develops [48]. Discharges occur inside the gas phase, generating fast current pulses and the growth of a slow negative bush-like streamer [48].

2.4.2 Streamer propagation

2.4.2.1 Modes and shapes

In an attempt to distinguish between different streamers appearing during the propagation process at the same applied voltage, modes of streamers in insulating liquids in short gaps under pulse voltages were first classified by Hebner [49]. He categorized streamers based on their instantaneous velocities as follows. Positive streamers can occur with three modes. The first is a bushy, subsonic structure. The second is a more filamentary, i.e. thinner, structure which propagates near the sonic velocity. The third mode is an order of magnitude faster than the second. Negative streamers were seen in four modes. The first mode is a thin pencil-like structure which can be as little as a few micrometres in diameter. This mode grows at a subsonic rate. The second mode, a bushier structure, also grows at a subsonic rate. The third mode is again a thin structure but this structure propagates at nearly sonic velocity. The fourth mode has nearly the same shape as the third, but propagates an order of magnitude faster. The sketch of modes appearing during streamer propagation is exhibited in Figure 4.

Lesaint [50] modified the mode classification for positive streamers in small gaps [49] with his experiment in mineral oil in long point-plane gaps under impulse voltages. The 1st mode expands a short distance with velocity of ~100 m/s. This mode is only observed with low applied voltage in short gaps with very sharp points (tip radii of ~1 µm) [31, 38]. The 2nd mode filamentary streamer travels at a supersonic speed of some km/s. It is observed with an applied voltage close to the breakdown voltage. Light emission from streamer channels and some reilluminations are observed. The shape of the envelope of streamer structure changes from being cylindrical with some main trunks to a spherical form with increasing applied voltage. In mineral oil, when the applied voltage is high above the breakdown voltage, i.e. around the acceleration voltage, the 3rd mode streamer occurs with velocity of 10-20 km/s. This mode streamer comprises of a main trunk enclosed by a numerous thin filaments. The 4th mode appears at voltages above the acceleration voltage, with a continuously illuminated channel propagating around some 100 km/s. The shape of this mode is constituted of a very luminous channel surrounded by some side branches. The correlation between mode, velocity and shape of streamer is shown in Figure 5. The typical velocities of streamer modes introduced by Hebner [49] and Lesaint [50] are illustrated in Table 1.



(b) Negative streamers

Figure 4. Streamer modes versus propagation in insulating liquids [49].

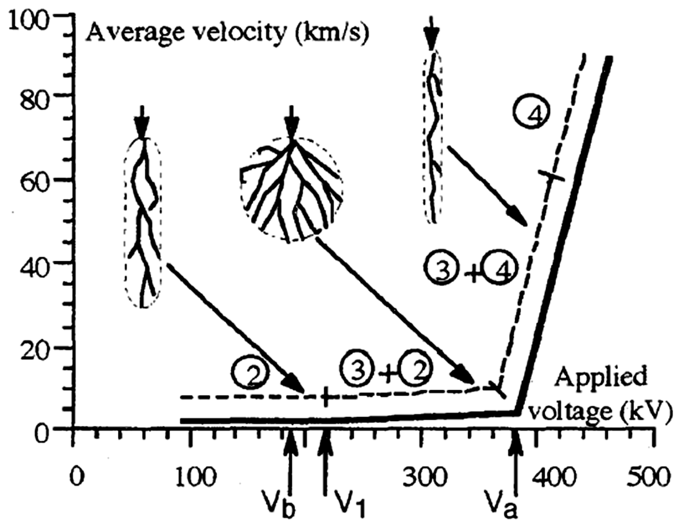


Figure 5. Correlation between mode, shape, velocity and applied voltage of positive streamers in mineral oil [50]; Numbers in circles denote streamer modes.

Table 1. Velocites of streamer modes (km/s)

Modes	**Hebner** [49]		**Lesaint** [50]
	Positive streamers	Negative streamers	Positive streamers
1st mode	0.2	0.2	0.1
2nd mode	4	0.2	1-2
3rd mode	40	2	10
4th mode		40	100

There are some hypotheses proposed to explain the transition from slow to fast mode streamers seen in mineral oil as follows, i.e. from the 2nd to 3rd (or 4th) mode streamers. Biller [51] suggested that the propagation of the 2nd mode streamers resulted from ionization of low number density molecules with lower IP compared to the main molecules, i.e. naphthenic/paraffinic molecules. As the applied voltage is highly increased, not only the easily ionisable molecules but also the high number density main molecules get ionized. Such ionization is expected at fields of around 30 MV/cm. Consequently, high density of space charges is created in front of streamer tips leading to a high electric field at there. As a result, the streamer velocity abruptly increases, i.e. the 3rd (or 4th) mode streamers appear. However, he could not define what kind of ionization and assumed that the same mechanism for both polarities. Based on this hypothesis and the model of field ionization suggested by Devins et al. [11], the 2nd and 3rd mode streamers were modelled by Hwang et al. [52]. Lundgaard et al. [53] proposed that electron avalanches created in front of the channel tips will extend streamer channel. The starting electrons for the avalanches have to be originated from the liquid by some feedback mechanisms. To switch from slow to fast mode streamers, photo-ionization in front of streamer tips within stressed volume was proposed [5]. With photo-ionization, numerous seed electrons are easily created in the liquid. Thus, impact ionization becomes more efficient and the streamer velocity is abruptly increased. Massala et al. [54] pointed out that the streamer shape is a very important factor to determine the macroscopic field, and thus the propagation mode. When the voltage is increased, streamers react by branching more, and this tends to regulate the macroscopic field. This process lasts until the overall shape of streamers turn out spherically with a maximum density of branches. Beyond this situation, streamer velocity abruptly increases with increasing applied voltage, i.e. the slow mode streamer switches to fast mode. The mechanism for the branching however remains undefined.

2.4.2.2 General properties of streamer propagation in insulating liquids under non-uniform geometries

Below the breakdown voltage V_b, streamer growth stops at a length L (named stopping length) shorter than the electrode gap and breakdown does not occur. From here on, the breakdown voltage V_b is defined as the value of 50% breakdown probability. Generally, L increases with applied voltage V, and scatters over a large range as seen in Figure 6. A similar shape of $L(V)$ was obtained with various gap distances [6]. Up to about 1/3 of the gap distance, the average stopping length increases quite linearly with voltage. Then the streamer length expands more rapidly with voltage until breakdown. This phenomenon has been explained from the fact that the voltage drop along the streamer channel, E_L, decreases with streamer current [55]. As the streamer approaches the plane, the capacitance of the streamer-plane enhances, leading to an increase in streamer current. Then E_L will reduce, i.e. the streamer tip field will enhance. This in turn favours the increased stopping length. A quick increase of streamer current (or charge) close to the plane electrode was found by measurement [54]. The scatter of L increases with V and gets maximum extent as the streamer comes close to the plane electrode. E_L can be roughly estimated from the inverse of the $L(V)$ plot slope and it is about 10-20 kV/cm for positive streamers in mineral transformer oil [36, 56]. For negative streamers, E_L is slightly higher (~ 24 kV/cm in [56] and 30 kV/cm in [36]). E_L is not constant along the streamer channel; it increases from the point tip to the streamer tip [55, 57]. Furthermore, Massala et al. [54] found that E_L reduces with increasing applied voltage. It even decreases to approximately 1 kV/cm when the applied voltage reaches the acceleration voltage [54]. It means that streamer becomes more conductive with increasing applied voltage. The stopping length L is polarity dependent [5, 36, 58]. At the same voltage, L is shorter for negative streamers. This may be because of either the voltage drop E_L or voltage required for forming filamentary streamers: Firstly, due to a higher voltage drop E_L, i.e. a smaller slope of the $L(V)$ curve, negative streamers require higher applied voltage to get the same length. Secondly, the transition from bush-like to filamentary streamers occurs easily in positive polarity as applied voltage exceeds the inception voltage [31, 38]. However, in negative polarity, the transition could not be observed although the applied voltage was about five times higher than the inception voltage [38]. It means that the transition from bush-like to filamentary streamer is much harder for negative polarity. Furthermore, the filamentary streamer propagates more easily than the bush-like one. Consequently, L of positive streamers is longer than that of negative ones at the same applied voltage.

Time to breakdown has been investigated over a large range of applied voltage above the breakdown voltage. With non-uniform field, the dependence of the time to breakdown on the applied voltage was observed in [37, 59]. Figure 7 illustrates the typical relationship between time to breakdown and applied voltage for a gap of 6.7 cm in mineral oil. The time to breakdown continuously reduced with increasing applied voltage and scattered over a large range. A sudden drop can be observed as voltage is raised beyond the threshold value called acceleration voltage. This acceleration can be explained from a macroscopic viewpoint as a strong reduction in the number of streamer branches, thus greatly increasing the macroscopic electric field at streamer tips. This phenomenon is accompanied by a sudden increase in the streamer velocity, i.e. appearance of very fast streamer (fast event). Hence the time can be divided in two groups based on the acceleration voltage. The short-time group represents very fast streamers, and the long-time group refers to slow ones. It is seen that in mineral oil the value of the short-time group ranges from one to five microsecond and 15 - 30 μs for the long-time group [37]. The value of these time groups varies with liquids, gap distances and polarities [8, 37, 59]. Most likely, there are different propagation mechanisms in the two groups. Further increasing the applied voltage leads to a slight reduction in time to breakdown.

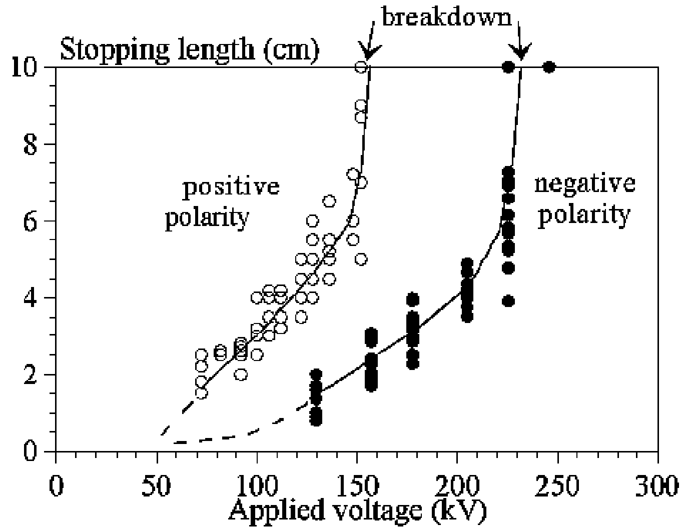


Figure 6. Stopping length against applied voltage of streamer in 10 cm gap in mineral oil [36].

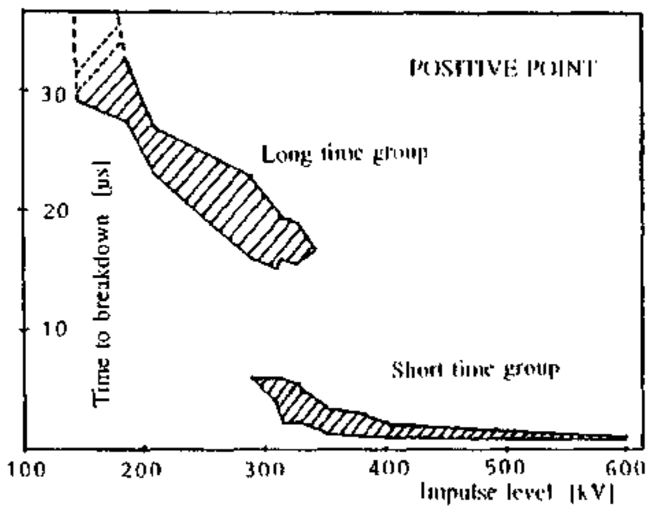


Figure 7. Time to breakdown versus applied voltage in mineral oil [37].

The propagation velocity of streamers has been quantified both as average and instantaneous values in insulating liquids. Below the breakdown voltage, the average velocity is determined by the stopping length and stopping time, i.e. propagation time of non-breakdown streamer. Above the breakdown voltage, the velocity is calculated with the electrode gap and time to breakdown. The average velocity increases in “step” with applied voltage [6, 8]. Figure 8 shows the typical plot of average velocity versus applied voltage for positive streamers. Up to breakdown voltage, streamers cross the gap with velocities of approximately 1-2 km/s. From the breakdown to the acceleration voltages, the velocity slightly increases because the branching of streamer will regulate the macroscopic field of streamer with voltage. Above the acceleration voltage, streamer velocity suddenly increases and the number of streamer branches dramatically reduces. The acceleration voltage indicates the ability of a liquid to successfully resist very fast streamers. The mechanism responsible for this phenomenon is still unknown. When applied voltage is further increased, the velocity increases slowly. Like the stopping length, the average velocity is strongly affected by polarity [36, 37, 58]. Positive streamers are always faster than negative ones. At breakdown voltage, the typical velocities of streamers in mineral oil are about 2 km/s and 1 km/s for positive and negative polarities, respectively [36]. The instantaneous velocity was calculated from framing image sequences, i.e. from difference in streamer length and that in time between framing images.

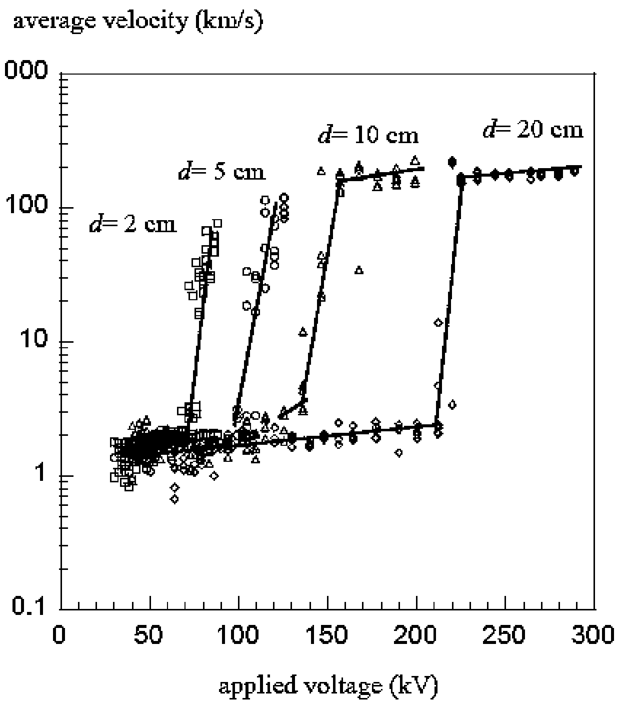


Figure 8. Average velocity versus applied voltage for positive streamers in natural ester with various gap distances [8].

Figure 9 presents the variation of instantaneous velocity during streamer growth. Below the acceleration voltage, the plot of the instantaneous velocity versus streamer growth has a resembling parabolic shape [5, 60, 61]. It means that streamers begin at the point electrode and terminate at the plane electrode with high velocity. A minimum value appears around 40-60% gap distance without regard to what liquid and polarity [60, 62]. This lowest velocity is possibly induced by the existence of minimum value of streamer tip field, calculated by either conducting growing sphere or cylinder models, during propagation [5, 54, 60, 61]. Around the acceleration voltage, the instantaneous velocity continuously increases (Figure 9b).

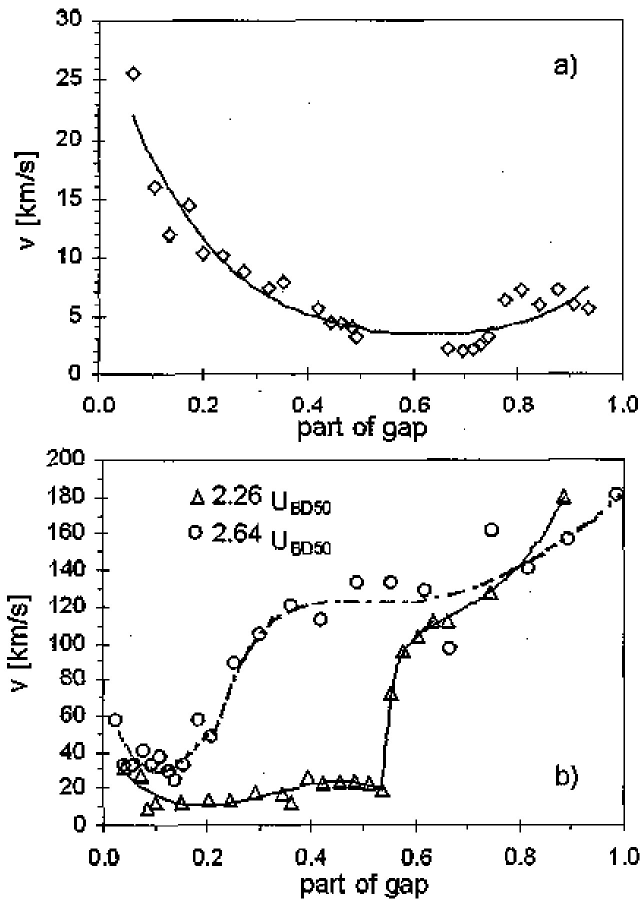


Figure 9. Instantaneous velocity versus positive streamer growth in 6.7 cm gap distance in mineral oil [5]: (a) at $2U_{BD50}$ = 290 kV (below the acceleration voltage); (b) Around the acceleration voltage.

To describe streamer propagation, the whole development process of streamers has usually been recorded with streak image accompanied with measured transient current, total charges, and light emission. Furthermore, framing images at certain times during propagation were also captured to illustrate the shape of streamer. The current signal has been measured either at the low voltage side of the test cell through a grounded needle [5], or a non-inductive resistor in series with the plane electrode [9] or at high voltage side of the test cell by using optoelectronic technique [63]. The method of measuring current at the high voltage side showed a better result [63]. The light emission from streamer is usually recorded by a photomultiplier. Typical streak photographs of positive and negative streamers in a long gap in mineral oil are presented in Figure 10, together with the recordings of transient currents and light emission. Both streamers propagate up to the plane electrode and induce breakdown. In both cases, streamers are composed of two characteristic components: a continuous light propagating at the streamer head, and periodical illuminating stems named reilluminations. A major difference is the relative intensities of these two components: in positive polarity, the continuous light is much weaker than the reilluminations, whereas these components get comparable intensities in negative polarity.

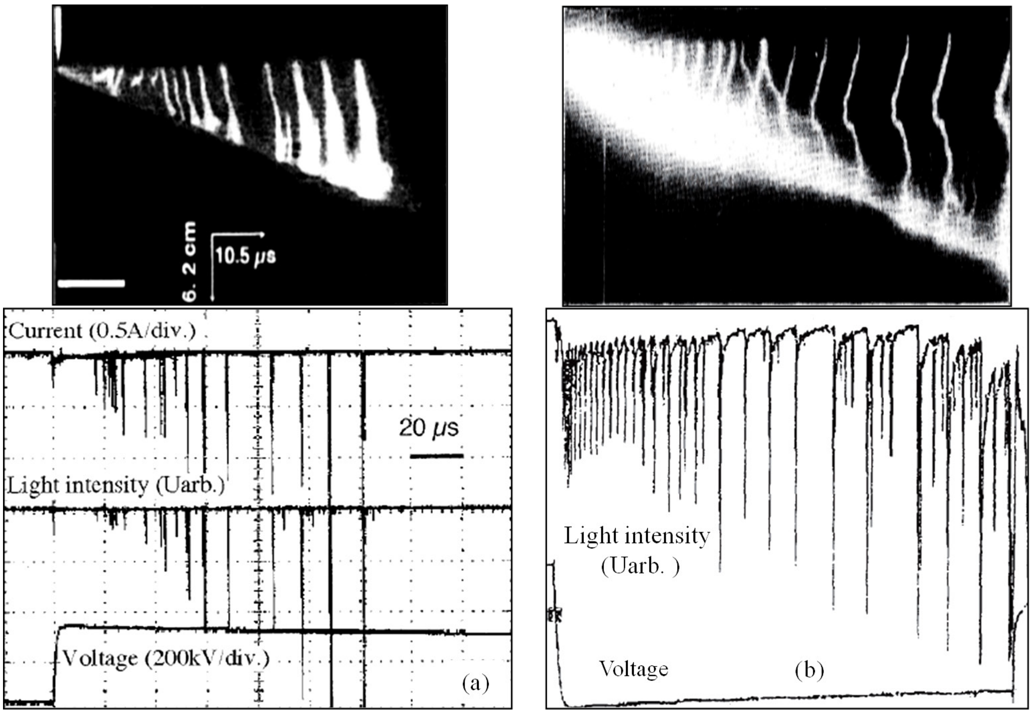


Figure 10. Streak image correlated to current and light recordings of streamer in 20 cm gap in mineral oil: (a) Positive streamer [6]; (b) Negative streamer [56].

For positive polarity, around the breakdown voltage, at the beginning of the streamer propagation, during 10 to 20 μs, only the initial continuous glow is visible, characterized by weak continuous light and current (~10 mA) signals [63, 64]. Such continuous signals are not visible on traces presented on Figure 10a, obtained with low sensitivity to enable recording of the entire streamer development. Then, reilluminations appear, correlated to fast light and current (up to >10 A at large distances [6]) pulses (10-15 ns in width [6, 37]). During this phase, the weak light emission continues between the pulses and the continuous light at the streamer tips still exists. Thus light pulses of smaller amplitude are recorded between reilluminations. However, no current pulses are observed. In the case of a stopping streamer (i.e. recorded below the breakdown voltage), the continuous light still appears at the streamer tips for some tens of µs after the last main reillumination [6]. When the applied voltage is increased above the breakdown voltage, the two following phenomena will occur: Reilluminations appear at the beginning of propagation, and thus the initial continuous glow is hardly observed. The number of reillumination increases, thus also increasing the frequency of light and current pulses. Above the acceleration voltage and in mineral oil, the very fast streamer (fast event) occurs when it approaches the plane electrode [6, 37]. The rapid growth in current and light correlated with the fast event was seen. Since there are no light and current pulses detected between reilluminations as summarized above, some authors suggested that streamer may propagate in step throughout the reillumination phase [8, 14, 65, 66]. Nevertheless, the background luminosity and small light pulses between reilluminations were easily observed in mineral oil [6, 38]. Whether streamer propagation is a gradual or continuous process is still under discussion.

Most of the above descriptions made for positive streamers can be applied to negative streamers except the following features. At the beginning of propagation, the continuous light emission from the streamer tips is much more intense as seen in Figure 10b. This creates background luminosity on the light recording and saturates the streak image [36]. As the streamer propagates, the intensity of reilluminations becomes comparable to that of the continuous light, observed throughout the propagation process [56].

The total charge (current) was observed to accompany with streamer propagation [6, 8, 53, 56]. Saker et al. [56] observed that the total charge Q transferred during the propagation only increases with the stopping length. Therefore, they believed that there exists a fixed charge quantity needed to create a streamer unit length, which is independent of the experiment parameters (electrode gap, applied voltage). From charge versus stopping plots, they roughly determined values of 10 µC/m and 8 µC/m for positive and negative streamers, respectively. In fact, the charge increases with applied voltage V, gap distance and the number of branches [6, 54]. Another parameter, Q/V, standing for the "capacitance" of streamer facing the plane electrode is proportional to stopping length. This parameter is independent of gap distance but depends on liquid types. The values of capacitance per unit stopping length are 0.3 pF/cm and 0.2 pF/cm for positive and negative streamers in mineral oil, respectively [36]. In an ester fluid, these values are higher and the same for both polarities (0.6 pF/cm) [8]. The difference between the two liquids can partly be explained by the higher dielectric constant of the ester fluid (2.8 compared to 2.2).

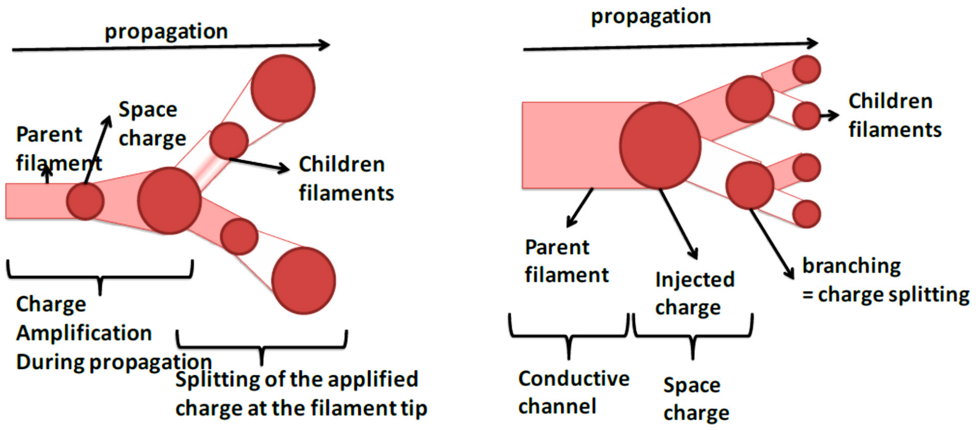
The breakdown voltage, V_b, has been used to evaluate the dielectric strength of insulating oil through standardized regulations of tests for a long time [67].

However, above V_b, the acceleration voltage (V_a) appears and streamers switch from slow to fast modes. For short impulses, a propagating slow streamer may be quenched and the gap will be self-heal, while a fast one may cross and result in breakdown of electric power equipment. Therefore, from both scientific and engineering viewpoints, the ratio between V_a and V_b is very important. Generally, V_b and V_a increase with the gap distance under both polarities [5, 36]. Around a gap distance of 10 cm in mineral oil, the ratio V_a/V_b is approximately 2.1 and 1.8 for positive and negative streamers, respectively. This ratio is polarity dependent and proportional to the gap distance [36]. It also found that, the ratio V_a/V_b was approximately 1 in positive streamers in pure liquids, e.g. cyclohexane [7, 10], polyaromatics [12], and ester fluids [8, 9]. It means that in these pure liquids, streamers accelerate immediately beyond the breakdown voltage. The reason for the difference of behaviour observed in mineral oil and pure liquids may be that mineral oil contains an amount of aromatics, which have lower ionization potential than paraffinic or naphthenic compositions. Aromatics will make positive streamers more branched, thus increasing shielding effect and reducing macroscopic field. Therefore, the acceleration voltage will be higher. This assumption was clarified by adding pyrene, a low ionization potential additive, into cyclohexane [10].

For both positive and negative polarities, the streamer propagation always associates with branching, and the degree of branching increases with applied voltage [6]. The branching is considered as the regulator of streamer velocity when the applied voltage is elevated [54]. Some hypotheses were introduced to explain the mechanism for branching of streamers in water or generally in liquids [68]. For positive streamers, the branching may be because of charge amplification and splitting (Figure 11a) or only charge splitting (Figure 11b) during propagation. If only charge splitting occurs, streamer filament will stop after some branching due to insufficient space charges to ensure plasma propagation. For negative streamers, branching can result from plasma splitting and/or interface instability having a thermal origin or electrostatic origin as shown in Figure 12. This electrostatic interface instability is electrohydrodynamic (EHD).

2.4.2.3 Effect of electrode curvature

It seems that there are only some studies on the influence of electrode tip radii on streamer propagation [8, 69] for both point and rod - plane gaps. In small gaps in white oil, the propagation rate (velocity) was independent of field geometry, i.e. radii of electrode tip [69]. This result was reproduced in 2 cm of electrode gap in an ester fluid with a much higher applied voltage and various radii [8]. Over a wide range of applied voltage (100 kV - 500 kV), the average velocity of positive streamers does not depend on radii of electrode curvatures (from 100 µm to 8 mm) as seen in Figure 13. A similar result was also obtained with negative streamers [8]. It means that the electric field at the electrode tip does not affect streamer propagation once it has started.



(a) (b)

Figure 11. Suggested branching mechanisms for positive streamers [68]; a) Streamer branching by charge amplification and splitting processes; b) Streamer branching by only charge splitting.

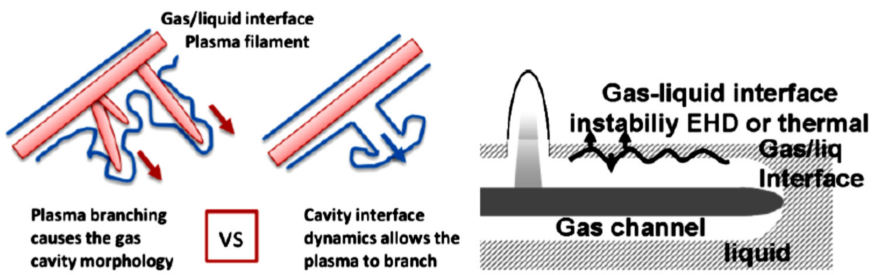


Figure 12. Branching mechanisms of negative streamers [68].

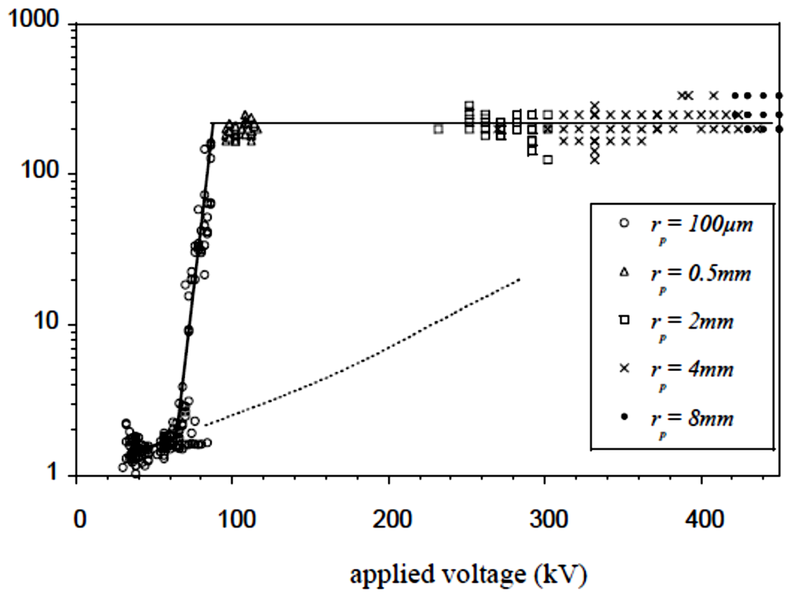


Figure 13. Average velocity of positive streamers versus applied voltage in ester oil with various tip radii [8].

2.4.2.4 Effect of hydrostatic pressure in short gaps

The influence of hydrostatic pressure on streamer propagation is one method to investigate the gaseous nature of streamers. Streamer propagation strongly depends upon hydrostatic pressure. At low applied voltages, from pressure of 0-1 atm, increased pressure suppressed streamer propagation in 25.4 mm gap in white oil (Marcol 70) [11]. A similar result was obtained in a smaller gap (3 mm) in transformer oil as the pressure was raised to 36 atm [70]. This result was reproduced with pressure up to 64.2 atm in 2.2 mm gap in pentane, a hydrocarbon liquid, in [15]. Therefore, increasing hydrostatic pressure increased the breakdown voltage of hydrocarbon liquids and mineral transformer oil as reported in [71, 72]. It was observed that when the pressure was raised up to 4 atm, the amplitude and duration of current and light emission pulses of negative streamers in cyclohexane were significantly reduced and disappeared [14]. With increasing pressure as high as 69 atm, the similar results were recorded [15]. It was also found that although propagation of positive streamers was quenched by high pressure, its velocity was not significantly varied [15]. At high enough applied voltage, the velocity of streamer did not seem to depend on the hydrostatic pressure [11, 70]; therefore, the time to breakdown at very high applied voltages was not controlled by the hydrostatic pressure [70].

2.4.2.5 Effect of liquid chemistry

The involvement of the electronic processes in streamer propagation has been evidenced by investigating the effect of additives, which have either low ionization potential or electron scavenging properties or both.

In a pioneering work, Devins et al. [11] found that small concentrations of polyaromatic compounds greatly reduced the dielectric strength of naphthenic white oil, e.g. Marcol 70, either due to an increase in streamer velocity or a decrease in the inception voltage. A typical polyaromatic compound, 2-methylnaphthalene, presented in transformer oil, markedly accelerates both positive and negative streamers, even at very low concentrations. This result was reproducible with 1-methylnaphthalene in n-hexane [73] and in cyclohexane [74]. Polyaromatic compounds have two electronic properties which are low ionization potentials and large electrons-trapping cross sections. These properties were believed to considerately impact streamer shape and propagation. The influence of each property is summarized as presented below.

The effect of electron scavengers on streamers was reported in [11] as follows. The addition of a non-ionic electron scavenger such as sulphur hexafluoride (SF_6) or ethyl chloride (C_2H_5Cl) to Marcol 70 or 2,2,4-trimethylpentane made the negative streamers more filamentary and faster. With the concentration of 0.02 mol/l, the effect of these scavengers becomes saturated. However, there is no measurable effect of these scavengers on positive streamers. Similarly, velocities of negative streamers in cyclohexane increased by a factor of 10 with 0.04 mol/l of carbon tetrachloride (CCL_4) [14, 73]. In small gaps, it was also observed that perfluoro-*n*-hexane largely accelerated the negative streamers in cyclohexane [74]. This result was reproduced with trichloroethylene (TCE) in a long gap [7]. On the other hand, a small quantity of CCL_4 suddenly increased the velocity of positive streamers in n-hexane [75].

The addition of a non-ionic low ionization potential (IP) compound such as DMA had no effect on velocity of negative streamers but did increase that of positive streamers in Marcol 70 and in 2,2,4-trimethylpentane up to the concentration of about 0.05 mol/l in short gaps [11]. The similar result was reported in cyclohexane (in a short gap [74] and in a long gap [7]) or in n-hexane in short gaps [61, 73]. Another low IP additive, e.g. pyrene, makes positive streamers in cyclohexane in both short and long gaps more filamentary and branched as seen in Figure 14 [10]. However, the effect of DMA or pyrene on the velocity of positive streamers depends on applied voltage and their concentrations. These additives accelerate non-breakdown streamers at low applied voltage [7, 10, 73], but decelerate breakdown streamers at higher applied voltage, because of branching effect [7, 10]. Thus adding DMA or pyrene into cyclohexane reduces the breakdown voltage but increases the acceleration voltage of positive streamers in long gaps as seen in Figure 15 [7, 10]. The change in appearance for positive streamers in a short gap caused by DMA was reported in detail in [74]. With concentration of 50 mg/g, the number of side branches decreased and the main channels propagated further. At the same time, main channels became thinner (diameter of 5-10 µm). Furthermore, the streamer channels got a smoother shape with fewer side branches. This is contrary to what was reported in a shorter gap [10]. On the contrary, DMA reduced the velocity of positive streamers and increased the breakdown voltage [76].

Ionic additives such as triisomylammonium picrate (TIAP) and Aerosol OT typically increase the velocity of streamers of both polarities by a factor of about ten [3, 77].

In summary, in short gaps low IP additives significantly affect the positive streamers whereas electron scavengers markedly influence the negative streamers. It is suggested that in long gaps, the similar results will be obtained in white oil. Logically, polyaromatic compounds having these two properties affect streamers of both polarities in mineral transformer oil. In addition, the effect of additives will get saturation as concentration of additive reaches a critical value.

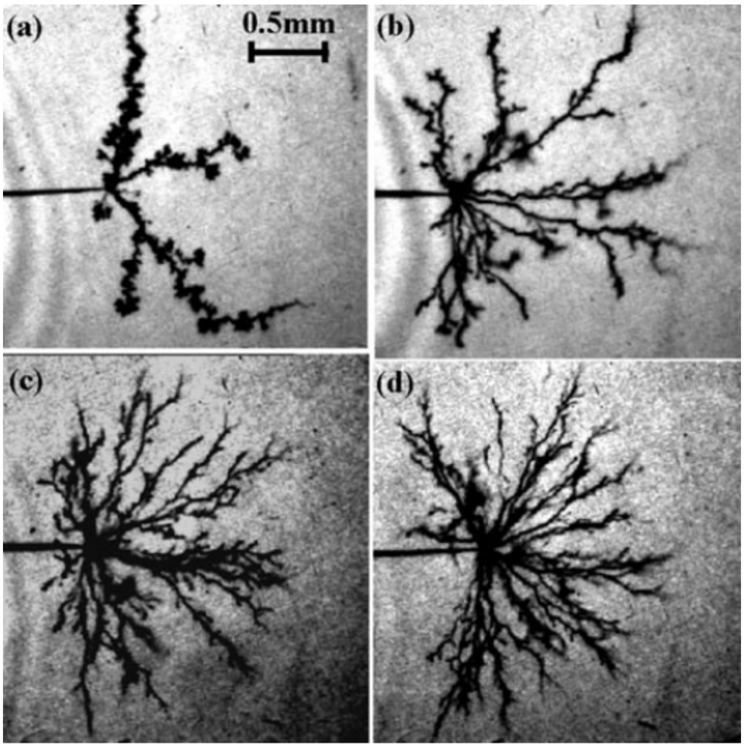


Figure 14. Effect of concentration of pyrene on branching of positive streamers in cyclohexane in 0.6 cm gap at 30 kV: (a) 0M; (b) 0.1M; (c) 0.7M; (d) 1M [10].

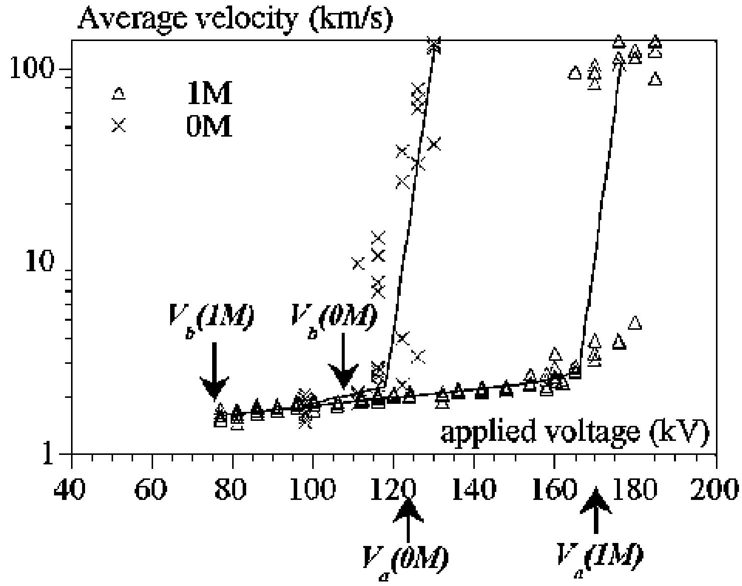


Figure 15. Effect of concentration of pyrene on velocity of positive streamers in cyclohexane in 5 cm gap [10].

2.4.2.6 Effect of streamer propagation in restricted volume in mineral oil in long gaps

It is known that streamer velocity and transition between modes depend not only on microscopic phenomena involved in the propagation of each streamer channel, but also on macroscopic effects involving all channels. A hypothesis arises that streamer velocity is controlled by the macroscopic field[4] resulted from the electrostatic interactions between channels. The numerous channels close to each other produce a shielding effect that reduces the macroscopic field and hence the streamer velocity. This effect increases with the density of channels. To test this hypothesis, the effect of constraint of branch extension on streamers was performed in [5, 54]. The extension of streamer branches was suppressed by pressboard surface parallel to the point-plane axis [5]. It was seen that at a significantly lower applied voltage, which is just above minimum breakdown voltage, fast mode streamers occurred. This is consistent with what was obtained in [54]. In [54], it was further found that in limited volume, i.e in a tube, streamers could propagate faster with lower breakdown and acceleration voltages. The mechanism behind this phenomenon was suggested to be an increase in the macroscopic electric field. This is because the extension of streamer branches and the geometric field regulation is hindered. Thus, streamers can propagate further, faster and accelerate at a lower voltage. The field dependence of streamer propagation was also proved by studying its growth in semi-uniform geometry [13], and supported in [11, 53, 61]. The minimum values of calculated velocity and calculated electric field simultaneously appear during streamer growth may be a manifestation of field controlled propagation [5].

2.4.2.7 The nature of positive streamer channel

Plasma state was considered to exist inside streamer channels, and this plasma state was speculated to be well-conducting [11, 37, 61]. With well-conducting channels, streamers should create a breakdown every time when touching the plane electrode. This is not the case as shown in [5, 6, 8, 36]. On the other hand, streamer channels were shown to be composed of vapour of liquid by investigating the effect of pressure on the dynamic of bubbles [35, 48]. This finding was supported by the fact that streamer propagation was suppressed by increasing hydrostatic pressure [15]. However, the precise nature of these gaseous channels, e.g. chemical compositions, pressure, and temperature, is still unknown [78]. The idea of streamer channels filled with vapour of liquid can be used to explain why sometimes streamers could touch the plane electrode without inducing breakdown, and almost no current recorded between reilluminations.

The voltage drop along a streamer channel in mineral oil is estimated to about 10-20 kV/cm and 25-30 kV/cm for positive and negative streamers respectively [36,

[4] The macroscopic field is the maximum electric field on the smooth surface of streamer envelope.

56]. Moreover, with Kerr effect measurements of the electric field in front of the point electrode in nitrobenzene, Kelley et al. [79] found that streamers were highly conducting, with a voltage drop across the streamer was smaller than 10% of the total voltage applying to an electrode system.

In [80], with spectroscopic study of light emitted during propagation of positive streamers in a 10 mm needle-plane gap in transformer oil under DC, the following findings were observed. Electron density depends on propagation time, spatial position on a streamer channel and applied voltage. The electron density is less than 10^{16} cm^{-3} for propagation time up to 1 μs before breakdown and it increases to above 10^{18} cm^{-3} at times 1 μs before and up to breakdown. In addition, the electron density varies along the streamer channel. It increases closer to the streamer tip and with increasing applied voltage. Thus, a tentative picture of the streamer structure was suggested as follows. Dense plasma is set up around the rim of streamer, i.e. streamer-liquid boundary, while the bulk of the streamer contains low electron density. It was also found that the temperature of the dense plasma region is higher than 10000 K, and a lower temperature of 3500-6000 K for low electron density region [80]. Gas temperatures of 2000-6000 K were reported for chlorinated liquids, and about 10% gas density and 0.1% degree of ionization present in the immediate trail of fast propagating positive and negative streamers in [81].

At low probability of breakdown voltage, streamer can touch the plane electrode without inducing breakdown but with a bright luminous section at the channel tip and a small current pulse is recorded [5, 8, 36]. This may indicate the presence of space charge at the streamer tip.

The dynamic of streamer filaments or vapour bubbles correlates well with the Rayleigh model for both polarities [35, 48]. This confirms the fact that growth and collapse dynamics of the filaments are controlled by liquid's inertia. During streamer growth, the filament has a cone-like shape with filament radius decreasing from its root to its tip because of high internal pressure [35]. For positive polarity, by using a laser beam and a photodiode the filament diameter of the 2nd mode streamers in a short gap (2.5 mm) in pentane was measured [35]. It is about 10 μm around the middle of filament length and reduces with increasing hydrostatic pressure. With longer gap (27.5 mm), the average diameter of channels of positive streamers was equal to 44 μm or 74 μm by directly measuring it on schlieren or shadowgraphic images [64]. In long gaps in mineral oil (2.5-10 cm), the filaments of positive streamers that can cross the gap were estimated to be about 100 μm in diameter [6]. For negative polarity, the diameter of vapour bubbles appearing in the very early stage of streamer is 2-10 μm [48]. A streamer channel was characterized by its conductivity, and the values of conductivity were 0.013 Ω^{-1}cm^{-1} and 0.01 Ω^{-1}cm^{-1} for the channel of 2nd mode and fast mode streamers, respectively [64]. This seems unreasonable because the conductivity is similar in the two cases. However, the higher values of conductivity for the above channels (10-50 Ω^{-1}cm^{-1} and 200-

1000 $\Omega^{-1}cm^{-1}$) were published in [82]. As compared to the conductivity of good conductors, e.g. copper (5.96×10^{5} $\Omega^{-1}cm^{-1}$ [83]), the conductivity of the fast mode streamer channel in [82] is about 600 times lower.

In summary, it seems that the gaseous channels are filled with the low density of charges and electrons, and the higher density of space charges accumulates at the gas/liquid interface.

2.4.2.8 Mechanisms for propagation

a) Positive streamers

To explain the propagation of positive streamers, some hypotheses have been proposed.

- The theory of field ionization was introduced in [11]. According to this theory, the maximum field at the channel tip of positive streamers can reach a value of approximately 10 MV/cm. Due to this high field, the liquid will be directly ionized even in the normal density. The high field forming at the streamer tips is the sum of the local coulomb field of positive space charges and the Laplacian field of the electrode system [61].
- Another theory based on a model quite similar to that of the streamer theory in gas discharge physics was suggested in [53]. To keep streamer propagating, electron avalanches have to be created in front of the channel tips by collisional ionization. This means that the local tip field must be higher than a critical field for ionization. The required seed electrons for collisional ionization possibly come from photo-ionization generated by light emitted from streamer itself.
- A mechanical model of propagating filaments was developed in [50]. According to this model, due to charge injection in the very high field at the filament tip, a fast and intense injection of thermal energy occurs. This brings the liquid into a supercritical state and a shockwave is radiated. In addition, a vapour phase instantaneously develops, that afterwards expands while its pressure and temperature decrease. Thus, the filament tip acts as a moving point source of heat of ~10 W in power, and the streamer filament is formed by the expanding vapour track left behind. They concluded that the basic mechanism of the filament propagation is the continuous creation of a new liquid/gas interface and not the displacement of such an interface.
- A model for streamer propagation in water was proposed in [68]. Streamer propagation results from numerous physical processes being able to occur simultaneously as seen in Figure 16.

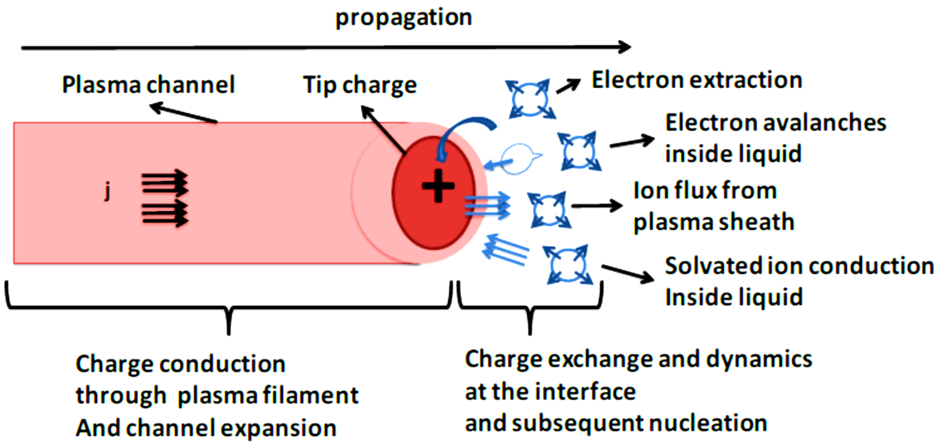


Figure 16. Proposed mechanisms for streamer propagation in water [68].

b) Negative streamers

- For negative streamers, the two-step model was proposed in [11]: the first consisting of electron injection and trapping, and the second consisting of ionization. When the voltage is sufficiently high, electrons will be field emitted from a negative point. These electrons will be trapped at a distance from the point dependent upon the electron scavenger concentration. The space-charge accumulation will reduce the field at the point and increase it at the boundary towards the anode. This will continue until this latter field reaches a critical value where ionization in the liquid occurs. Plasma similar to that produced in the positive streamers will result. Electrons will then be injected into the liquid from the plasma, become trapped, and again lead to a build-up of the field at the trapping boundary. Thus, the streamer will develop with this two-stage process across the gap. This model can explain why adding electron scavengers will significantly speed up the negative streamers due to a reduction in both trapping distance and time for the first step.
- Felici [84] suggested the following hypothesis to explain the propagation of the slow 1st mode streamers. Streamer channels are filled with a weak ionized gaseous phase that is formed by partial discharges in a vapour. Hot electrons created by a discharge will bombard the gas/liquid interface, thus heating and evaporating the liquid. This extends the streamer channel. For continued propagation, the electrons at the channel tip, soon becoming negative ions and swept aside by the liquid flow, must be replaced by new hot electrons supplied by successive discharges in the vapour. This theory was supported by authors in [85]. A two-step model was presented in [85]. The first is injection of carriers (electrons) by field emission and then followed by bubble generation. After that, the discharges take place in the liquid vapour. Electrons from the vapour, impinging the liquid and vaporizing it, produce the expansion of the

gaseous pocket. This process lasts until the voltage across the gas is insufficient to sustain discharges. However, the conclusion was given that no single mechanism was responsible for propagation of negative streamers [85].

- The model of streamer theory for gas discharge physics was still proposed to explain the propagation mechanism of negative streamers in liquids [53].
- The streamer propagation in water occurs because of electron emission from plasma channel tips and (or) negative charges absorbed on the interface [68] as illustrated in Figure 17. The presence of negative charges on the interface leads to not only an interface instability but also a high electric field region in the liquid in front of the channel tips.

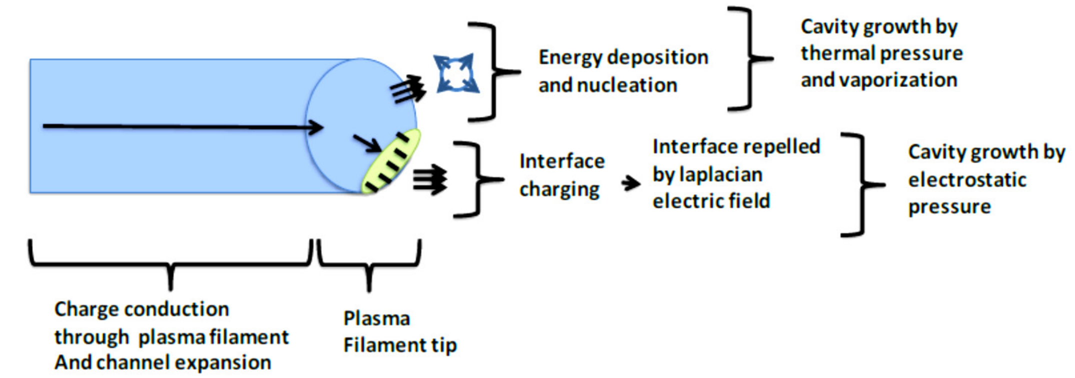


Figure 17. Mechanisms for propagation of negative streamers in water [68].

2.5 Summary

In this chapter, streamer initiation and propagation are briefly reviewed with the most important results obtained. Streamer initiation has been well studied and understood for negative polarity. The phenomena leading to streamer initiation for positive polarity seem more complex than for negative, and mechanisms for initiation of positive streamers are still unknown. Although many studies on streamer propagation have been performed as summarized above, the propagation is still not fully described and understood. Whether streamers propagate in steps or not is unknown. The precise nature of streamer channel is undefined. Streamer behaviours in mineral transformer oil were extensively investigated, but the studies on streamers in compositions of mineral oil in long gaps are few. In short gaps, the influence of additives on the propagation is well investigated, but this is not the case of long gaps. Some hypotheses to explain the slow and fast mode streamers were proposed. However, these do not agree with each other. Many studies have focused on positive streamers while there is a little work published on negative streamers in long gaps.

To address several of the above uncertainties, the following approach is chosen in this work: Streamer propagation in white oil, representing the naphthenic/paraffinic structures of mineral oil, with and without additives in a long gap (8 cm) is examined in detail. Each additive has one of the two electronic properties; low ionization potential or large electron trapping cross section. These electronic properties are associated to the so called aromatic/polyaromatic compound, which is one main component of mineral transformer oil. Thus, the mixture of white oil and additives can be considered as model oil with similar behaviour as mineral transformer oil. The various testing conditions such as voltage polarity, impurities, reduced pressure and liquid chemistry are included in the experiment. The results achieved in this study are compared to those of cyclohexane and mineral transformer oil under the similar experimental conditions.

Chapter 3. Experimental description

3.1 Experimental setup

The schematic of experimental setup is shown in Figure 18. A point-plane electrode system was located inside a test cell made of glass. The point electrode was connected to high voltage while the plane electrode is grounded. An electrode gap of 8 cm was used throughout this study. A Marx generator was used to supply step voltages (0.5/1700 μs). A resistor of 76 Ω was utilized to dampen oscillations and limit the breakdown current. The applied voltage was measured at the high voltage side of the test cell via a capacitor combined with an integrator giving good step response and slow decay [86]. Streamer current was measured at the low voltage side of the test cell in an arrangement with a gas gap overvoltage protector and attenuators were used in the connection to the oscilloscope. Light emission pulses from streamers were recorded by a photomultiplier located close to a window of the test cell. Framing and streak images were captured by an image converter camera - Imacon 468. A Xenon flash was utilized to produce shadow-graphic images. The Marx generator, the flash, and the camera were synchronized by a trigger system. A picture of experimental setup in the laboratory is illustrated in Figure 19.

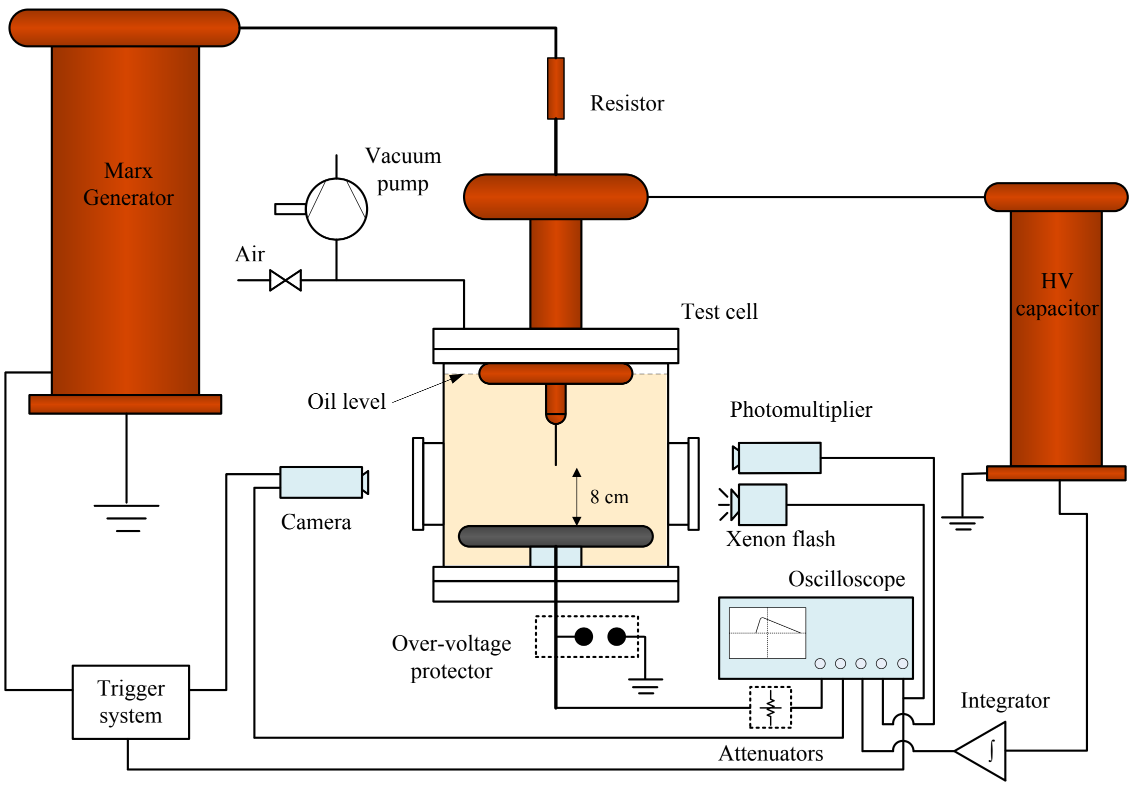


Figure 18. The schematic of experimental setup.

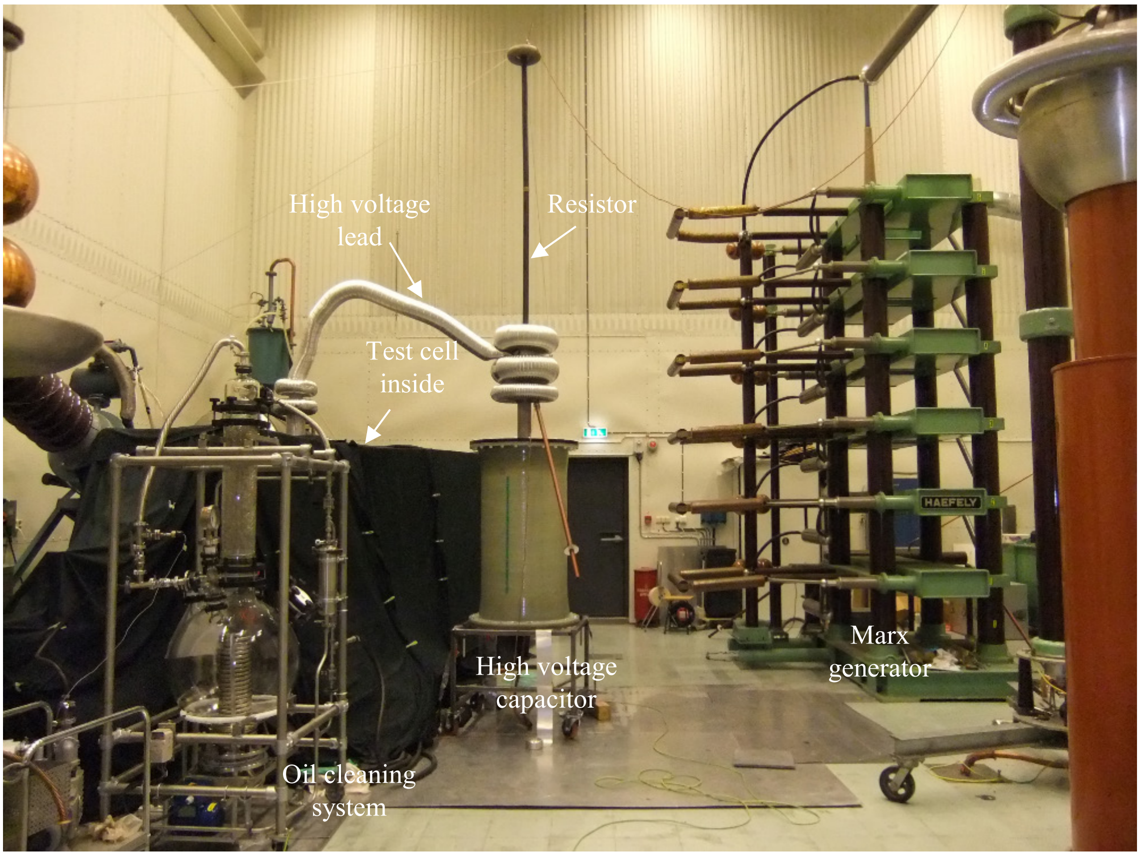


Figure 19. The picture of experimental setup.

3.2 The test cell

The cylindrical test cell has inner diameter of 45 cm and height of 60 cm. It is made from borosilicate glass and has two ports for streamer observation. At the ports, quartz glass windows are installed with an aperture of 14 cm. The whole development process of streamer is monitored through these windows. The test cell in completed setup is presented in Figure 20.

3.3 The electrode system

The point-plane electrode system with 8 cm gap is used for experiment. The point electrode is made of tungsten wire having diameter of 0.15 mm. This point electrode has a rounded tip instead of a sharp tip for two reasons: the tip radius does not affect streamer propagation as mentioned above, and after only one breakdown, the sharp tip will be worn. To remove edge effect, after being cut, the point electrode was conditioned with ten breakdowns. After this treatment, the point tip resembles a hemisphere when observed under a microscope. Then this treated point electrode was used to run experiments. When changing either voltage polarity or oil type, the same procedure for treating the new point electrode was repeated. Therefore the tip of the point electrode is of similar shape in experiments with different polarities or oil types.

The plane electrode, having a disk shape of 340 mm in diameter, is made of stainless steel, and its edge was rounded.

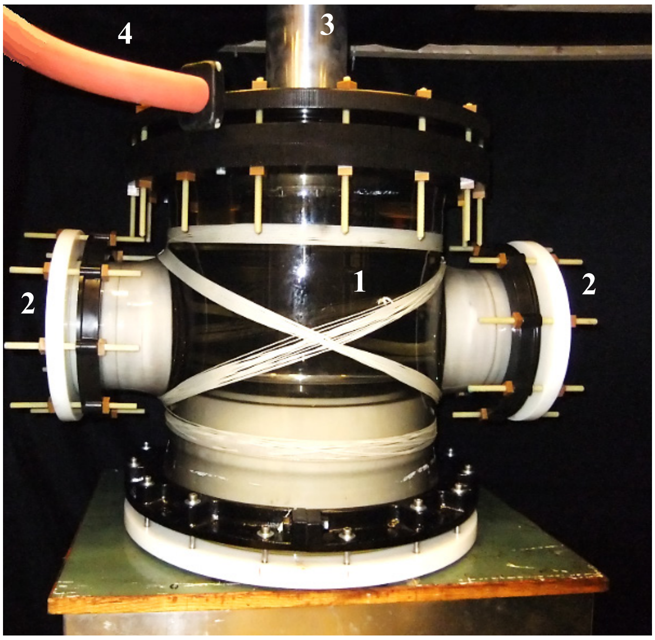


Figure 20. An entire setup of the test cell: (1) The test cell; (2) Quartz glass windows; (3) High voltage field grading tube; (4) Oil pipe.

3.4 The high-voltage impulse generator

A 6-stage Haefely impulse generator with a maximum voltage of 1200 kV and stage energy of 15 kJ was used to produce the "step" voltage (0.5/1700 μs). The maximum voltage drop during one streamer sequence is about 2% and 10% for positive and negative polarities, respectively. Figure 21 shows a circuit diagram of the impulse generator. The principle of operation of the generator is that all capacitors are charged in parallel to a given voltage, and then they are discharged in series through spark gaps. Ideally, the output voltage is equal to six times of the charging voltage of stage. The most important thing is that the spark gap G_1 must first discharge. However, this gap cannot be self-discharged. Therefore, to trigger a discharge in this gap, a special circuit, known as 'trigatron', is used. As soon as the first gap G_1 discharges, the voltage across the second gap G_2 doubles, so the discharge easily occurs in the second gap. The process of increasing voltage across the gap and discharge is repeated through each gap until the last gap G_6. Thus, ideally the output voltage will be six times of the charging voltage.

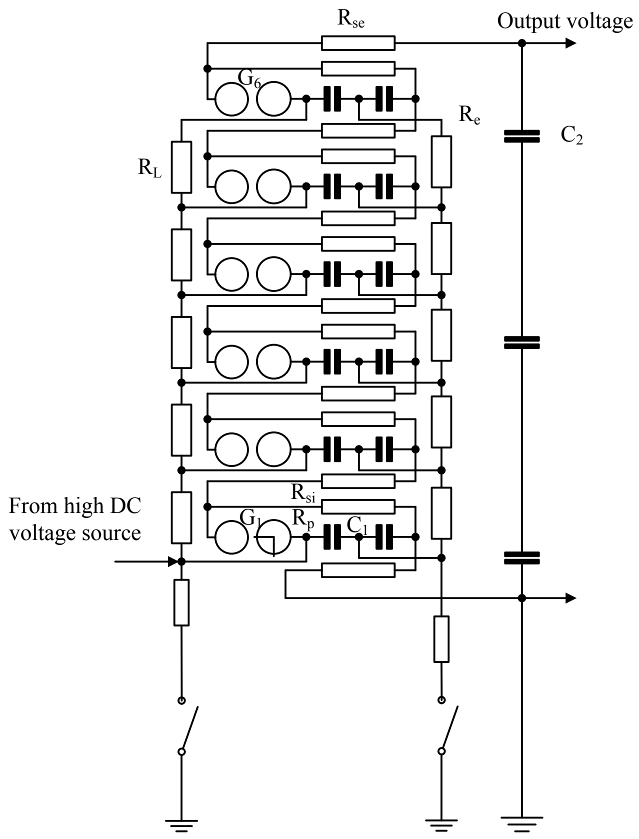


Figure 21. Circuit of Haefely impulse generator. G: spark gap, R_L: charging resistor, R_{si}: wave front resistor, R_p: wave tail resistor, R_e: discharging resistor, R_{se}: damping resistor, C_1: generator capacitor, C_2: load capacitor.

3.5 Oil cleaning system

During experiment, the liquids were filtered after every ten shots of breakdown for positive streamers and after each shot resulting in breakdown for negative streamers to remove carbon particles. The reason is that carbon particles strongly affect breakdown voltage as well as streamer propagation. In addition, carbon particles also cause the oil to become darker, thus reducing quality of streamer images taken by a camera. The diagram of oil cleaning system is shown in Figure 22. The oil can be filtered either in air or vacuum. The filter, made of polyester, has a pore size of 0.2 μm.

3.6 The current measurement system

Streamer current was measured at the low voltage side of the system. The setup of the measuring system is shown in Figure 23. Streamer current flows through a 50 Ω coaxial cable to a 50 Ω input channel of an oscilloscope Tektronix DPO4104. A gas-gap type of protector is used to short-circuit the measuring system at the input terminal when an over-voltage is taken place, i.e. the measuring system is prevented to be infected by high voltage. To further prevent over-voltage at the input channel of the oscilloscope, some attenuators are connected in series. The entire ratio of attenuations is 500:1. The amplitude of streamer current is calculated by

$$I_{streamer} = I_{input} = \frac{V_{out}}{50} \times 500 \tag{2}$$

This measurement system is simple. However, it only responds well with current resulting from reilluminations and has some drawbacks as mentioned in [87]: (i) large charging capacitive current, (ii) low sensitivity, (iii) not all current from the point electrode coming to the plane electrode, and (iv) interference by electromagnetic sources.

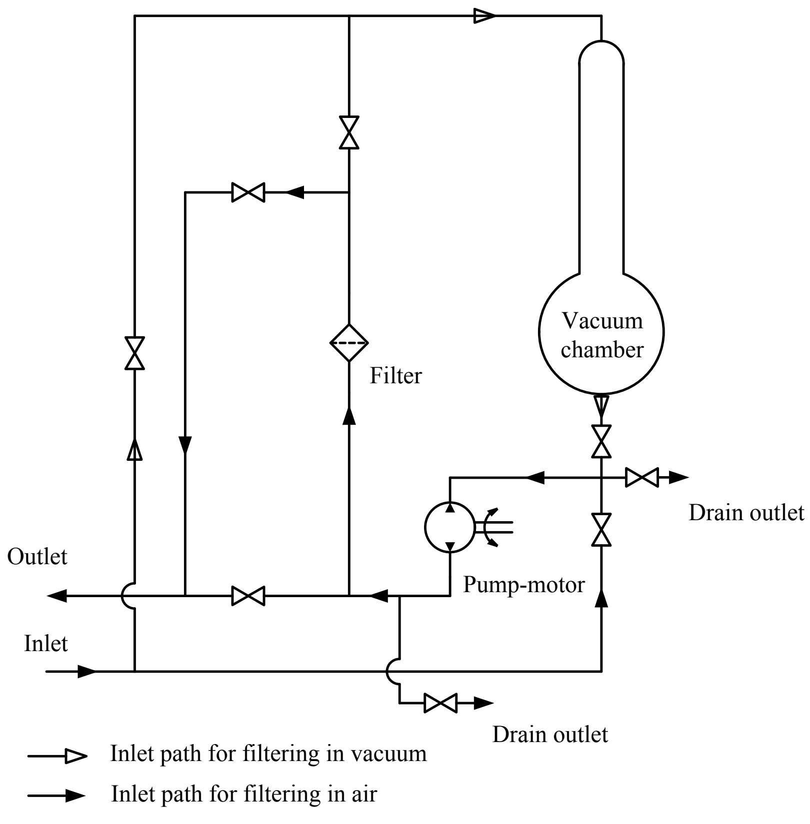


Figure 22. Schematic of oil cleaning system.

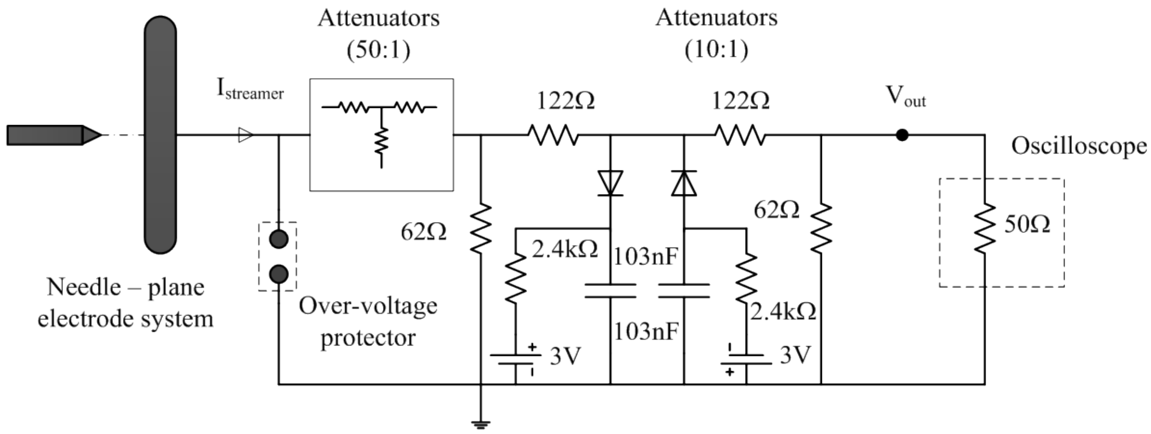


Figure 23. Schematic of current measurement system located at low voltage side of the test cell.

3.7 The high-voltage measurement system

A measuring system of high magnitude of step voltage is shown in Figure 24. The principal operation of this system is that a current signal through a high voltage capacitor will be integrated into voltage pulse observed by an oscilloscope. This means that we can measure the applied voltage by integrating the capacitive current as seen in equation 2. This system is employed due to the fact that large oscillations are recorded during the rise time of step voltage when a conventional high voltage capacitive divider is employed to measure high voltage applied to the point-plane electrode.

$$i_c(t) = C\frac{dV(t)}{dt} \Rightarrow V(t) = \frac{1}{C}\int i_c(t)dt \tag{3}$$

In detail, C_0 is the capacitance of a high voltage capacitor. I_0 is the input current. The output voltage V_{out} is proportional to the integral of I_0. The magnitude of input high voltage is determined by equation 3 [86].

$$V_{in}(t) = \frac{R_3(C_2 + C_3)}{R_1 C_0} V_{out}(t) \tag{4}$$

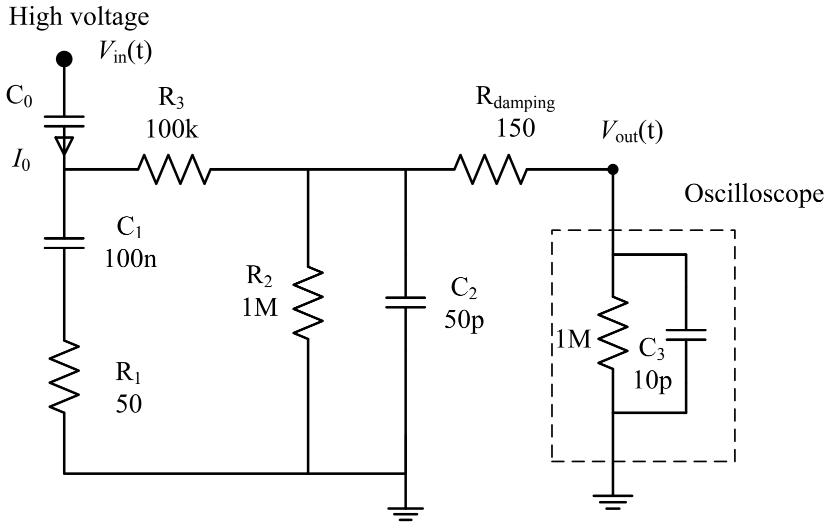


Figure 24. Sketch of setup for high voltage measurement system.

3.8 Shadowgraphic imaging method and high speed camera

The shadowgraphic technique has been used to take streamer images. This method requires a light source and a high speed camera to capture the events. If an event has a different refractive index compared to the surrounding media, e.g. a gaseous bubble in oil, the bubble will show up in darkness if illuminated with collimated light (Figure 25). In this study, a xenon flash with 50-μs duration, a fresnel collimated lens and an image converter type of camera (IMACON 468) constitute a completed system to produce shadow images. The camera has a resolution of 576 × 385 pixels per frame, the maximum framing rate of 10^8 frames per second, and the minimum exposure time of 10 ns. It can capture eight frame images (seven still and one streak images) with individual exposure time, delay time and image amplification settings. For the still images, the exposure time is about 200 ns for shadowgraphic method and 1-2 μs for self-emission light method, i.e. streamer structure is captured by its own light. In addition to the still images, the camera can simultaneously record the streak image with maximum duration of 100 μs.

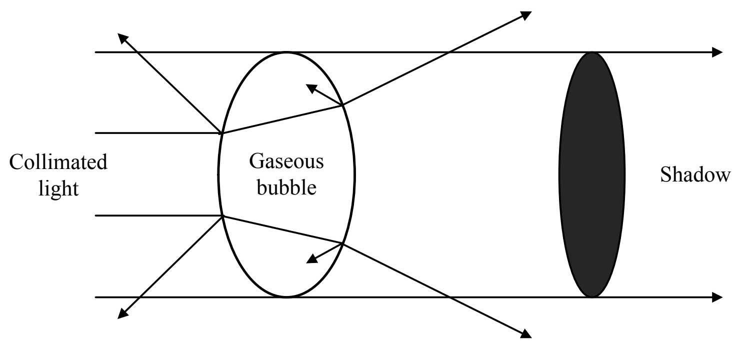


Figure 25. The principle of the shadowgraphic method [88].

3.9 Liquids under test

3.9.1 Base liquids

Two types of white oil, used as base liquids, were investigated in this study. These are Exxsol-D140 and Marcol-52. Exxol-D140 oil is an aliphatic hydrocarbon fluid, extracted from crude oil. It contains carbon atoms in straight chains, i.e. paraffinic structures, and a small amount of aromatic compounds of less than 0.6 wt% according to datasheet. Marcol-52 oil is a highly refined mineral oil. It contains 67% and 33% of carbon atoms in paraffinic and naphthenic structures respectively. From the datasheet, it is virtually free from aromatics/polyaromatics. The basic properties of the investigated oil, which consist of physical, chemical and electrical parameters, are extracted from the data sheets as exhibited in Table 2.

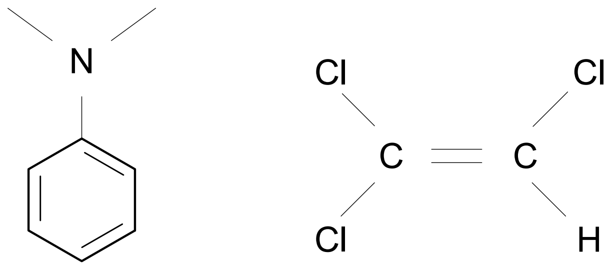
Table 2. Basic properties of investigated oil

Properties	**Units**	**Exxsol D140** [89]	**Marcol 52** [90]
Electrical			
Dielectric constant			2.1
Physical			
Density at 15^oC	g/ml	0.825	
Density at 20^oC	g/ml		0.825 - 0.834
Viscosity at 40^oC	mm^2/s	4.68	7 - 8
Flash point	^oC	137	150
Pour point	^oC		-6
Boiling point	^oC	275	316
Chemical			
Antioxidant additives	wt%		
Water content	Ppm		35
Acidity	mg KOH/g		
Carbon type (paraffinic/naphthenic/aromatics)	%		67/33/0
Content of composition (paraffinic/naphthenic/aromatics)	wt%	99.4/0/0.6	
Ionization potential	eV	~10[a]	~10[a]

3.9.2 Additives

Two kinds of additives were added into base liquids (Exxsol-D140 and Marcol-52). These are a low ionization potential additive, *N,N*-dimethylaniline (DMA), and an electron scavenger, trichloroethylene (TCE). Their molecular structures are illustrated in Figure 26, and their basic properties are listed in Table 3.

[a] Ref. [85]



(a) *N,N*-dimethylaniline (b) Trichloroethylene

Figure 26. Molecular structures of additives.

Table 3. Basic properties of additives

Properties	Units	DMA	TCE
Density	g/cm^3	0.96[b]	1.46[b]
Molar mass	g/mol	121[b]	131[b]
Boiling point	^{o}C	194[b]	87.2[b]
Dielectric constant		5.02[c]	3.39[c]
Ionization potential	eV	7.12[b]	9.46[b]
Electron attachment cross section	cm^2		[d]7.8×10^{-16}

3.10 Experimental procedure

There are two types of oil samples used in this study called the cleaned oil and the contaminated oil. The cleaned oil was formed by conditioning the new high purity oil taken from the drum by ten shots resulting in breakdown. Then the oil was filtered in air for 30 minutes through a cleaning system consisting of a filter with a pore size of 0.2 μm as shown in Figure 22 . This treatment is done for the following reasons: (i) the similar oil condition, i.e. carbon particles and dissolved gases/air, must be kept for non-breakdown and breakdown experiments, and (ii) the breakdown voltage is very sensitive to a small amount of carbon particles.

The contaminated oil was formed by applying 20 shots resulting in breakdown to the cleaned oil sample prior to the experiments. After these above described treatments, both oil samples contain carbon particles and dissolved gases/air. However, much higher concentration of carbon particles is present in the contaminated oil sample.

To investigate the effect of carbon particles on streamers, the contaminated oil sample was used. During this investigation, the oil was not filtered, so the density of carbon particles will increase during the experiment. The particle content in oil after the experiment was measured and compared with the cleaned condition and a sample of contaminated oil from before the experiment series. The particle content was

[b] Ref. [83]
[c] Ref. [91]
[d] Ref. [92]

measured by a particle counter (PAMAS SBSS-C) according to the ISO 4406 and NAS 1638 classes. Most of the particles are in the 1-4 µm size range. For positive streamers, the total numbers of particles per 100 ml were 1.03×10^5, 6.05×10^5 and 33×10^5 for cleaned, contaminated and after investigation oil samples, respectively. Similarly, the total numbers were 1.03×10^5, 6.05×10^5 and 12.8×10^5 for corresponding oil samples of negative streamers. The distribution of particle sizes is shown in Figure 27.

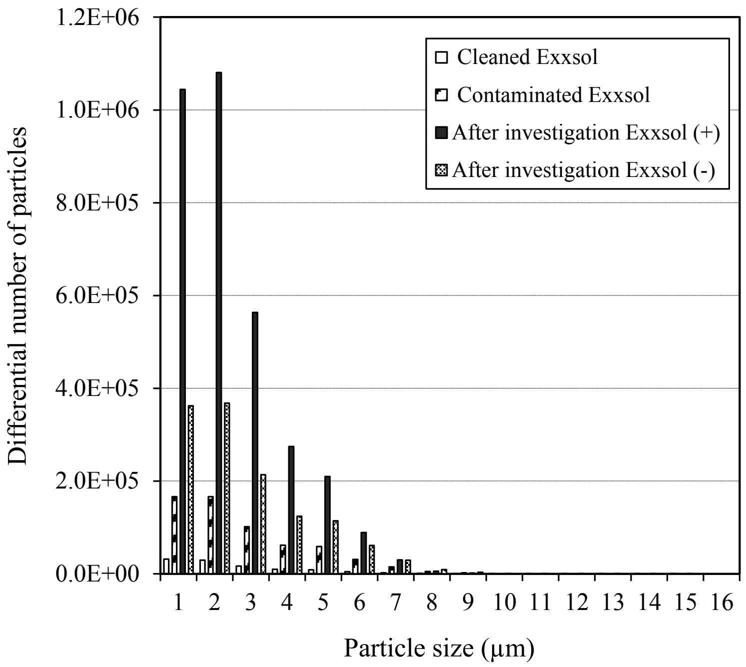


Figure 27. Particle size distribution.

The impact of dissolved gases/air on streamers was investigated for cleaned oil. The oil was passed through a column filled with glass rings to give a large surface and a particle filter either under vacuum or air. This was done for 30 minutes after ten shots for breakdown positive streamers and after each breakdown shot for negative streamers. Filtering under vacuum will degas the oil and remove carbon particles, while filtering in air only removes carbon particles and will mix in some air.

To investigate the influence of additives on streamers, DMA and TCE were separately mixed into the cleaned oil to a concentration of 0.064M, i.e. mol/l. The same cleaning condition as used in experiments for studying influence of dissolved gases/air on streamers was applied. The mixtures of base oils and additives were only filtered in air because degassing, i.e. cleaning in vacuum, will deplete these additives.

For examining the influence of reduced pressure on streamers, the tests were made either under ambient or reduced pressure. The reduced pressure was achieved by connecting a vacuum pump to the lid of the test cell to create a vacuum of 3 mbar above the oil surface during experiments. The oil was filtered after every ten shots at each voltage step under vacuum condition.

The experiment sequence was divided into four stages. The voltage was increased in different steps depending on the stage. The 1st stage, initiation stage, was performed with 5 kV steps. In the 2nd stage, from initiation to breakdown, voltage was increased with 10-30 kV steps. During the 3rd stage, breakdown stage, 5 kV steps were applied again, and finally 30 kV steps were used for the propagation stage, i.e. the 4th stage. Ten repetitive shots at each step were applied for all stages except the 4th stage of negative streamers. Only five shots were used at this stage because of time consumption for filtering the oil after each breakdown.

Table 4 summarizes types of experiments investigated in each type of oil. About 300 shots of step voltages are applied for each case.

Table 4. Oil and experimental types

Experimental types \ **Oil types**	**Exxsol-D140**	**Marcol-52**
Positive polarity	×	×
Negative polarity	×	×
Carbon particles	×	
Dissolved gases/air	×	
Reduced pressure (vacuum)		×
N,N-Dimethylaniline (DMA)	×	×
Trichloroethylene (TCE)	×	×
Channel characteristics		×

3.11 Multi-level test method and Weibull distribution

Multi-level method has been used to determine 50% breakdown probability of impulse voltage. In [93], the procedure of this method is: (i) apply a fixed number of shots at various voltage levels, (ii) count the number of breakdowns at each voltage level, (iii) plot the probability $P(V)$ versus applied voltage V, (iv) draw a line of best fit on a probability scale, and (v) determine V_{50} at $P(V)$ = 50%. Figure 28 shows the probability of breakdown distribution using the multi-level method. The advantage of this method is that it does not assume normality of distribution. The disadvantage is that it is time consuming, i.e. many shots are required. In this study, 4-6 voltage levels were chosen with 5 kV per step and ten shots per voltage level was used. The number of breakdowns at each voltage level was counted. Both V_{50} and shape parameter, i.e. data scattering, were used to compare between oil types, but only V_{50} can be determined from Figure 28. Thus two-parameter Weibull distribution was used to fit the results. Its cumulative distribution function is expressed in equation 1. Here V_0 and β are the scale and shape parameters, and V is the peak voltage.

$$F(V) = 1 - \exp\left[-\left(\frac{V}{V_0}\right)^{\beta}\right] \tag{5}$$

A comparison of V_{50} determined from Figure 28 (method A) with that calculated from Weibull distribution (method B) is exhibited in Table 5. It is seen that the methods of fitting data will influence V_{50}, and using Weibull distribution will increase the V_{50} by 1-9% depending upon the types of liquids. However, the relative change in V_{50} when DMA or TCE is added is similar in the two methods. Thus, with the confidence level of 90%, V_{50} determined from the Weibull distribution is similar to that of multi-level test method. In this work, the Weibull distribution is used to calculate V_{50}.

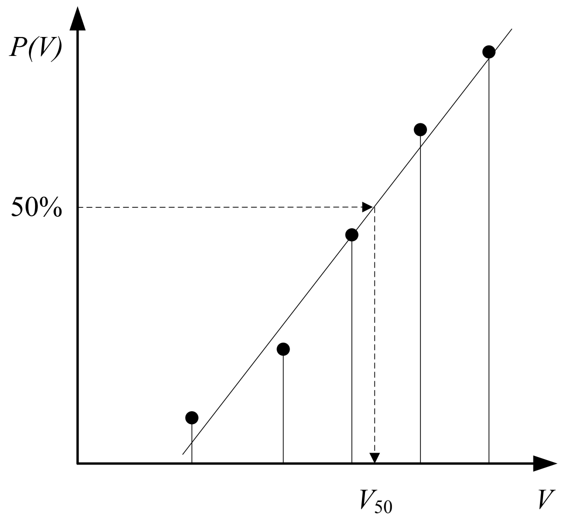


Figure 28. Probability of breakdown distribution.

Table 5. 50% probability breakdown voltages of liquid types determined from using different methods of fitting data (kV).

No	Liquid types	Polarity	Method A	Method B	Differences (%)
1	Marcol	+	152	162.1	6.6
2	Marcol/DMA	+	129	137.1	6.3
3	Marcol/TCE	+	141	151.2	7.2
4	Marcol	-	382	388.6	1.7
5	Marcol/DMA	-	403	408.2	1.3
6	Marcol/TCE	-	193	208.4	8
7	Exxsol	+	139	144.7	4.1
8	Exxsol/DMA	+	153	166.2	8.6
9	Exxsol/TCE	+	146	157.2	7.7
10	Exxsol	-	276	281.2	1.9
11	Exxsol/DMA	-	272	277.4	2.0
12	Exxsol/TCE	-	198	205	3.5

Chapter 4. Results

This thesis is a synthesis of five published papers, all of which this author is the first author. The main findings of these papers are presented as follows.

Paper 1 exhibits the investigation of both polarity streamers in Exxsol-D140 oil. Carbon particles are seen to have a strong effect on both polarity streamers, especially on negative streamers. These particles increase both streamer stopping length and velocity, and reduce inception, breakdown and acceleration voltages. On the other hand, dissolved gases/air has a small influence on both polarity streamers. Easily ionisable additive, e.g. DMA, significantly influences only positive streamers. It reduces streamer velocity and increases both breakdown and acceleration voltages due to more branching. In addition, DMA really raises the ratio V_a/V_b from 1.65 to 1.95. Around the breakdown voltage, positive streamers are about 2 times faster than negative ones (2 km/s compared to 1 km/s). However, beyond the acceleration voltage, the ratio between the velocity of positive and negative streamers is about 5 (100 km/s compared to 20 km/s). The breakdown voltage of positive streamers is approximately half of negative streamers. The correlation between the apparent area, mimicking streamer branches, and streamer velocity is well established. From this correlation, the sudden increase in streamer velocity when applied voltage slightly exceeds the acceleration voltage can be explained by increasing macroscopic electric field resulted from a dramatic reduction in the number of branches.

Paper 2 is an extended version of paper 1 under the same experimental conditions. In this paper, only results of positive streamers in Exxsol-D140 are presented. Average velocity increases in "step" with increasing applied voltage. Three modes of streamers are observed classified as mode 2 to 4. For the 2nd mode streamers, instantaneous velocity shows a minimum value of about 2 km/s in the 40-60% gap distance and increased to approximately 3-10 km/s at both ends of the gap. In contrast, the instantaneous velocity continuously increases during the growth of the 4th mode streamers. The streamer branching significantly influences streamer velocity. However, it has more effect on the 2nd mode than the 4th mode. The transition process from the 2nd to the 3rd to the 4th mode is well described with frame and streak images correlated to recordings of current and light emission pulses. Streamer first switches from spherical shape consisting of multi-filaments to more elongated shape with some main branches surrounded by short side branches, and then to a bright channel. During streamer propagation, both weak continuous luminosity, emitted from stems and tips of streamer channels, and reilluminations appear. Corresponding to reilluminations, high current and light emission pulses are recorded. In the 2nd mode, the number of reilluminations as well as its frequency of occurrence increases with applied voltage. Contrary to DMA, TCE increases the streamer velocity and decreases both the breakdown and the acceleration voltages. From a macroscopic viewpoint, it is observed that TCE makes positive streamers less branched. Especially, the ratio V_a/V_b decreases to approximately 1 as the concentration of TCE is raised to 0.128M. It was found that streamers with low speed have more branching. Conversely, more branching streamers correlate to low speed. It means that the mutual relationship exists between speed and branching.

Paper 3 is a further extended version of paper 1 under the same experimental conditions. This paper only reports the results of negative streamers in Exxsol-D140. To propagate across the electrode gap, negative streamers must change from bush-like (the 1st mode) to tree-like (the 2nd mode) shape at the threshold voltage V_{th}. Above V_{th}, a sudden increase in stopping length was recorded. Similar to positive streamers, the velocity of negative streamers increase in steps with applied voltage. However, in addition to the second step at the acceleration voltage, the first step at V_{th} can also be seen. Four modes of streamer propagation were recorded. A minimum value of instantaneous velocity appearing during streamer growth can be observed in both low and fast mode groups. Most of the properties from streak images and reilluminations reported for positive streamers in the paper 2 can be applied to negative streamers except the following features. Weakly continuous luminosity is more pronounced especially at the beginning of propagation. Light emitted from streamer tips is also much more intense and continuous. In comparison with positive streamer, the impact of carbon particles on negative streamer is much stronger. A small amount of carbon particles can bring negative streamers into the 3rd mode from the 2nd mode, i.e. streamer velocity is increased by a factor of about ten. However, these particles have no effect on the 3rd mode streamers. TCE markedly accelerates the negative streamers, and reduces both the breakdown and the acceleration voltages. Corresponding to this phenomenon, it was observed that TCE makes negative streamer more filamentary, i.e. thinner, and branched. With the presence of TCE, negative streamer velocity is increased about tenfold, i.e. negative streamers jump from the 1st to the 2nd mode.

In paper 4, the physics of positive streamer channel in Marcol-52 oil is studied. Three kinds of streamer channels were observed around breakdown voltage. These are dark, partly illuminating, and fully illuminating (reillumination) channels. No current could be detected for the dark channels. The partly illuminating channels correlate with small current pulses in some hundreds of milli-amperes. However, the reilluminations are associated with much higher current pulses of some amperes. All types of channels occur simultaneously and propagate almost equally fast. Streamers with reilluminations almost always terminate in breakdown. On the other hand, streamers with dark or partly illuminating channels have much lower probability for breakdown, and they even cross the gap without inducing breakdown. Reilluminations do not have significant effects on the propagation of streamers as well as the time to cross the gap and time to breakdown. In the 2nd mode streamers, 30 - 50% of their branches are able to become illuminated, and the number of reilluminations as well as illuminating branches is proportional to the applied voltage. Under reduced pressure, streamers travel with much lower voltage drop along the streamer channel. Thus, the stopping length greatly increases, and the breakdown voltage drastically drops. All crossing streamers result in breakdown, and the number of reilluminations is much lower than that under ambient pressure. The inception voltage is not influenced much by reduced pressure while the breakdown voltage is reduced to 50%. This indicates that processes of initiation of streamers take place in liquid phase. The physics model of the positive streamer channels is introduced.

Paper 5 shows the results of streamers in Marcol-52 oil under various experimental conditions varying voltage polarity, pressure and additives. The characteristics of streamers in this oil are similar to those of streamers in Exxsol-D140 oil reported in the papers 2 and 3. Nevertheless, the step increase of negative streamer velocity at the threshold voltage V_{th}, below the acceleration voltage, does not exist. The effects of DMA and TCE on Marcol oil are similar to those of these additives on Exxsol oil except that both DMA and TCE reduce the breakdown voltage of positive streamers. DMA increases the ratio V_a/V_b from 1.3 to 2.1. Reduced pressure strongly increases the stopping length and thus reducing the breakdown voltage of both polarities about 50%. However, it slightly increases the velocity of positive non-breakdown streamers or even decreases the velocity of negative non-breakdown streamers. Reduced pressure does not change the acceleration voltage of positive streamers while it significantly reduces the acceleration voltage of negative streamers. Furthermore, reduced pressure markedly increases the magnitude and number of current pulses of the 2nd mode positive streamers. DMA increases both magnitude and number of light emission pulses of positive streamers while TCE reduces these values. Above the acceleration voltage, the effect of reduced pressure on negative streamers is quite similar to that of TCE. The impact ionization is suggested to be one main mechanism responsible for streamer propagation.

Chapter 5. Discussion

In this chapter, the main results - separately presented in the published papers - are synthesized to show correlations between experimental findings and trends of these results. This leads to the discussion of a hypothetical model. This chapter starts with the effect of additives, carbon particles and reduced pressure on streamers and then comparison of liquids is presented. Lastly, mechanisms for streamer propagation are other topics of this chapter.

In this study, a compound is a chemical substance consisting of two or more different chemical elements. In addition, filamentary streamers contain smooth and thin channels. The streamer is bush-like if there are numerous branches of bubble-like shape originating from what look like a common root point on the electrode. Dark channels are branches having a low conductivity and emitting weak light. Luminous channels have high conductivity and release strong light. The macroscopic field (E_t) is a maximum electric field either on the surface of streamer envelope or at the channel tip under the assumption that the channel tip is hemisphere with smooth surface. The shielding effect is a phenomenon that the mutual influence between streamer channels will reduce the macroscopic field.

The ionization potential (IP) of a molecule A is the energy needed to remove an electron and create a positive A^+

$$A \rightarrow A^+ + e^- \; ; IP = U_{A+} - U_A \qquad (6)$$

The electron affinity (EA) of a molecule A is defined as the amount of energy released when an electron is added to the molecule A to form a negative ion A^-

$$A + e^- \rightarrow A^- ; \; EA = U_A - U_{A-} \qquad (7)$$

Where U_A is the energy of molecule A, U_{A+} is the energy of its anion and U_{A-} is the energy of its cation.

In the aspect of this work, low IP additives are substances sufficiently having lower IP than hydrocarbon liquids (IP ~ 10 eV). The low IP additives will release electrons with low energy received. Additives containing halogen elements have high value of EA and strongly capture free electrons, i.e. electron scavengers.

The 3rd mode streamers occur around the acceleration voltage. The streamers of this mode always start with fast streamers followed by slower ones. It means that the 3rd mode streamers are ambiguous and appear to have combination characteristics of the 2nd and 4th mode streamers. Therefore, only the 2nd mode and 4th mode streamers are mainly discussed in this chapter.

5.1 Effect of additives, carbon particles and reduced pressure

As mentioned in the chapter 2, the following hypothesis is formulated. *A low IP additive will significantly affect positive streamers while an electron scavenger will markedly influence negative streamers in long gaps in white oil.*

5.1.1 Low ionization potential additives

For positive polarity, a low IP additive, e.g. DMA, may either accelerate or decelerate non-breakdown streamers depending on whether streamers become more filamentary or more branched (*paper 5*). With more filamentary channels, DMA will speed up streamers and reduce the breakdown voltage V_b (*paper* 5). This is in line with what were reported in cyclohexane in [7]. With higher number of branches, DMA will decelerate streamers and raise V_b (*paper 2*). However, DMA always reduces the velocity of breakdown streamers and increases the acceleration voltage V_a as well as the ratio V_a/V_b of investigated liquids in Table 6. A similar result was seen when another low IP additive (pyrene) was added into cyclohexane [10]. An explanation is that molecules of DMA are easier to be ionized (IP_{DMA} = 7.12 eV, $IP_{white\ oil}$ ~ 10 eV, $IP_{cyclohexane}$ = 9.86 eV), leading to an increase in the number of electron avalanches, i.e. higher number of streamer branches. Thus the shielding effect increases and the velocity of breakdown streamers is reduced leading to an increase in V_a.

Table 6. Breakdown and acceleration voltages of streamers in various liquids; needle tip radius (r_p), electrode gap distance (d).

Ref.	Base oil	Additive	r_p (mm)	d (mm)	Positive streamers			Negative streamers		
					V_b (kV)	V_a (kV)	V_a/V_b	V_b (kV)	V_a (kV)	V_a/V_b
	Marcol-52		0.075	80	162	210	1.3	389	390	1.0
	Marcol-52	0.064M DMA	0.075	80	137	290	2.1	408	400	1.0
	Marcol-52	0.064M TCE	0.075	80	151	160	1.1	208	270	1.3
	Exxsol-D140		0.075	80	145	240	1.7	281	390	1.4
	Exxsol-D140	0.064M DMA	0.075	80	166	300	1.8	278	360	1.3
	Exxsol-D140	0.064M TCE	0.075	80	157	180	1.2	205	246	1.2
[7]	Cyclohexane		0.6	77	118	125	1.0	179		
″	Cyclohexane	0.064M DMA	0.6	77	102	255	2.5	182		
″	Cyclohexane	0.064M TCE	0.6	77	122	117	1.0	150	238	1.6
[6]	Voltesso 35		0.1	75	140	300	2.1			
[36]	Voltesso 35		0.1	80	150	320	2.1	190	310	1.6
[6]	Voltesso 35		0.1	100	180	350	1.9	230	350	1.5
[12]	Iso-propylbiphenyl		0.04	80	140					
″	Iso-propylbiphenyl		0.04	200	220	200	0.9			

For negative polarity, DMA does not seem to have any significant effects on streamer propagation (*papers 3* and *5*). The similar result was obtained with cyclohexane [7].

With the presence of DMA, V_a of Marcol oil is significantly raised to a value that is similar to Voltesso oil, a type of mineral transformer oil. DMA also raises the ratio V_a/V_b of Marcol oil to 2.1, which is in line with Voltesso oil (1.9-2.1) as seen in Table 6. Moreover, as seen in Figure 29, the plot of velocity versus applied voltage of the case of Marcol-0.064M DMA has a tendency of approaching Voltesso oil. The similar result is obtained with Exxsol oil.

As shown in Figure 29, the lower value of V_a correlates to the higher value of the velocity of the 4th mode streamers, which are observed when applied voltage is well above V_a. With the presence of DMA, V_a is increased and the velocity of the 4th mode streamers is largely reduced and independent of base liquids. It can be explained by the fact that all channels are luminous and filamentary for neat white oil whereas with the presence of DMA, streamers show numerous dark side branches surrounded by many short ramifications (*paper 5*). Due to numerous ramifications, the shielding effect is increased. This gives a reduction in the macroscopic field as well as the velocity.

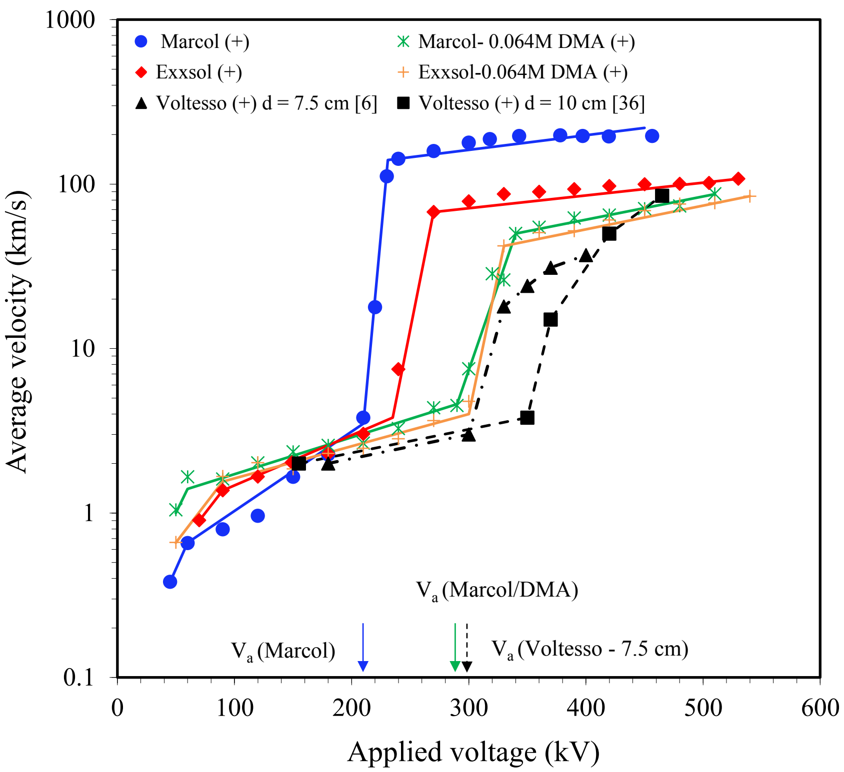


Figure 29. Effect of DMA on average velocity of positive streamers.

In summary, a low IP additive, e.g. DMA, significantly influences positive streamers in a long gap in white oil. This confirms the hypothesis. For positive streamers, one can state that the mixture of a low IP additive and white oil acts as mineral transformer oil. Finally, it is suggested that high values of V_a and ratio V_a/V_b of mineral transformer oil possibly results from the low IP property of aromatic/polyaromatic compounds.

5.1.2 Electron trapping additives

Contrary to low IP additives, electron scavengers, e.g. TCE, affects both polarities of streamers especially the negative ones. TCE significantly accelerates the velocity of negative streamers. This is in agreement to what was reported in [7]. Furthermore, TCE reduces both V_b and V_a of observed liquids in Table 6. The significant influence of electron scavengers, e.g. TCE, on negative streamers is explained by their ability to capture free, energetic electrons formed at the channel tip. This attachment will build up negative space charges in front of the channel tips, thus forming a higher electric field at the boundary toward the plane electrode. With this high field, the ionization of liquid molecules becomes stronger leading to a dramatic increase in streamer velocity.

When TCE is added into Marcol oil or Exxsol oil in this work, the three following effects are observed. First, as shown in Figure 30, TCE increases the velocity of negative streamers to a value of mineral transformer oil (~1 km/s) probably related to streamers becoming more filamentary. Second, both V_b and V_a has a tendency to be reduced to a value comparable to mineral oil (Table 6). Finally, the velocity of fast mode streamers is increased to that of mineral oil (Figure 30).

In addition, TCE still accelerates positive streamers and reduces both V_b and V_a in this study (*papers 2* and *5*). This may be explained because TCE has the strong ability of trapping free and hot electrons. Thus, the number of electron avalanches will be reduced, and hence streamer branches. It means that the shielding effect formed by streamer branching is also decreased. This increases the macroscopic electric field and accelerates streamers.

Similarly to positive streamers, negative streamers with a lower value of V_a show a higher velocity for the 4th mode (Figure 30). With TCE added, V_a is reduced and the velocity of the 4th mode streamers is significantly increased and independent of base liquids. An increase in the velocity of the 4th mode streamers can be explained by either the electron trapping of TCE as proposed above or the conductivity of streamer channel. It is observed that all branches are luminous for the 4th mode streamers in the oil containing TCE while almost all branches are dark for streamers in neat oil (*paper 3*). Dark channels may have a lower value of conductivity than luminous ones (*papers 4* and *5*). Thus, luminous channels get the higher tip field and hence the higher velocity.

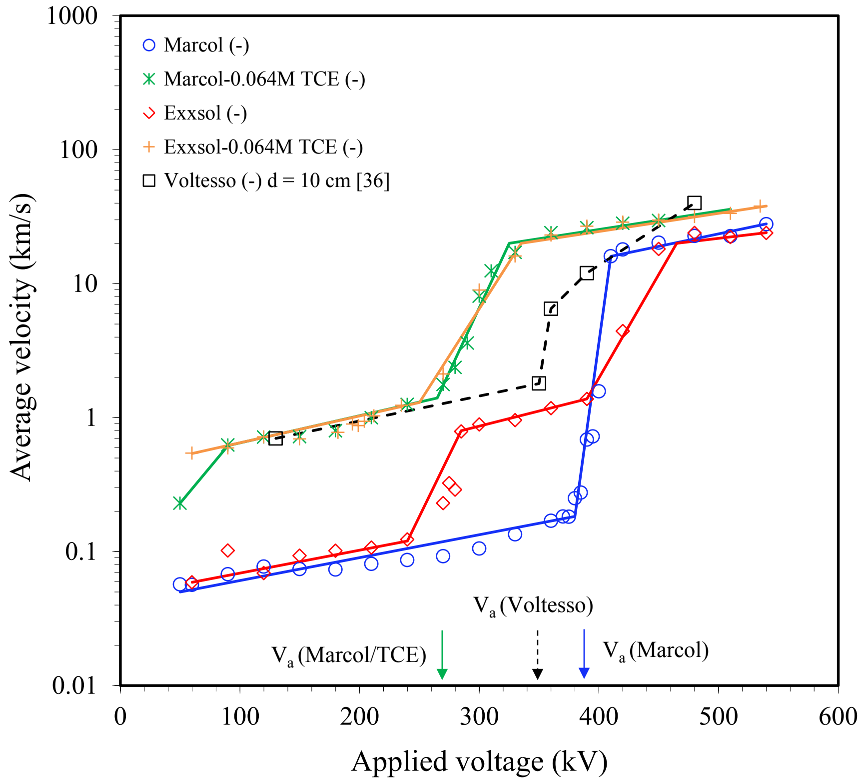


Figure 30. Effect of TCE on average velocity of negative streamers.

In conclusion, an electron scavenger, e.g. TCE, markedly impact negative streamers in a long gap in white oil, leading to a confirmation of the hypothesis. The mixture of an electron scavenger and white oil behave more like mineral transformer oil. The low value of both V_b and V_a and the high streamer velocity of mineral transformer oil may be attributed to the presence of aromatic/polyaromatic compounds having an electron trapping property.

5.1.3 Carbon particles

In this study, carbon particles were seen to significantly affect streamers of both polarities. However, negative streamers are more sensitive to carbon particles than positive ones. These particles reduce both V_b and V_a, and increase stopping length as well as streamer velocity (*papers 2* and *3*). In contrast, the stopping length in ac-field is not influenced by carbon particles [94].

The most evident impact of carbon particles on negative streamers in Exxsol oil is that with a small amount of these particles, streamers switch from the 2nd mode to the 3rd mode with about tenfold increase in velocity (*paper 3*). The similar result is observed for both the 1st and 2nd mode streamers in Marcol oil. The reason may be that carbon particles in the oil would greatly enhance the local electric field around them as illustrated in Figure 31. This will dramatically increase the velocity of streamers. Such a phenomenon cannot be observed either for the 2nd (or 3rd or 4th) mode positive streamers or for the 3rd (or 4th) mode negative ones. It is suggested that since the macroscopic fields at the channel tips of the 2nd mode positive streamers and the 3rd mode negative ones anyway are sufficient, the effect of field enhancement by carbon particles is insignificant. In addition, it seems that there is a threshold tip field for transforming the 2nd mode into the 3rd mode of negative streamers. It means that dominant processes at the channel tip are different in the 2nd and the 3rd modes, and depend upon the tip field.

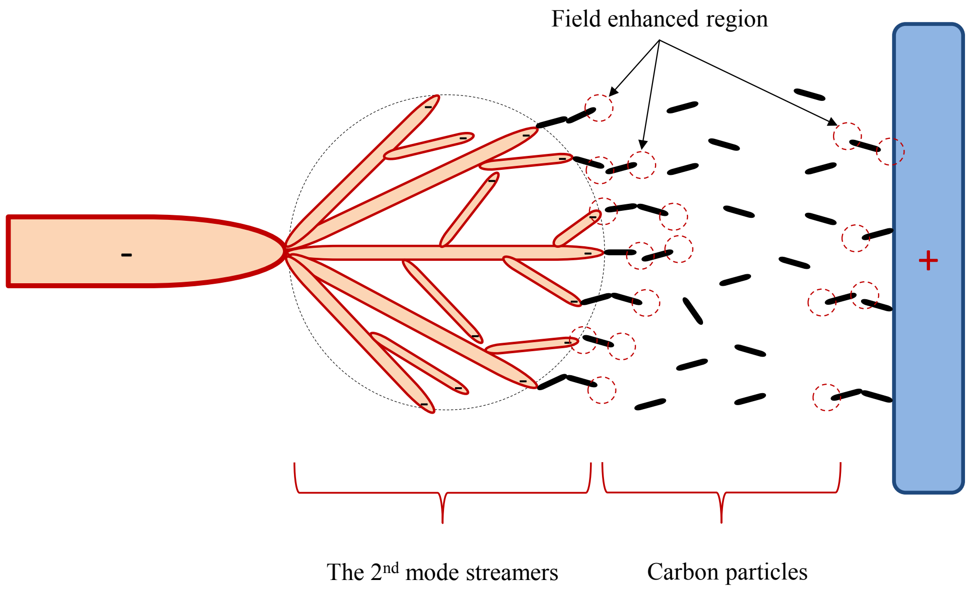


Figure 31. The sketch of local field enhancement by carbon particles.

5.1.4 Reduced pressure

Reduced pressure enhances the propagation of streamers of both polarities (*paper 5*). This leads to a significant increase in stopping length and a large reduction in breakdown voltage (Figure 32). The possible explanation is that a reduction in pressure will either reduce the boiling point of oil or facilitate bubble formation [35, 48]. This eases the formation of gaseous channels and by this streamer propagation.

For positive streamers, although reduced pressure makes streamers more branched, it does not reduce streamer velocity (Figure 33). This is because an increase in the shielding effect due to more branching is possibly counterbalanced by the enhancement of either oil evaporation or bubble formation processes induced by reduced pressure. In addition, V_a of positive streamers is almost unchanged by reduced pressure. It is deduced that the appearance of fast streamers possibly depends on only electronic processes at channel tips and there is a threshold value of the electric field at the channel tip for switching from slow to fast streamers. It is seen that inception voltage for 2nd mode streamers and acceleration voltage seem unaffected by reduced pressure (Figure 33). This could indicate that the processes, i.e. avalanches, occur within the liquid phase.

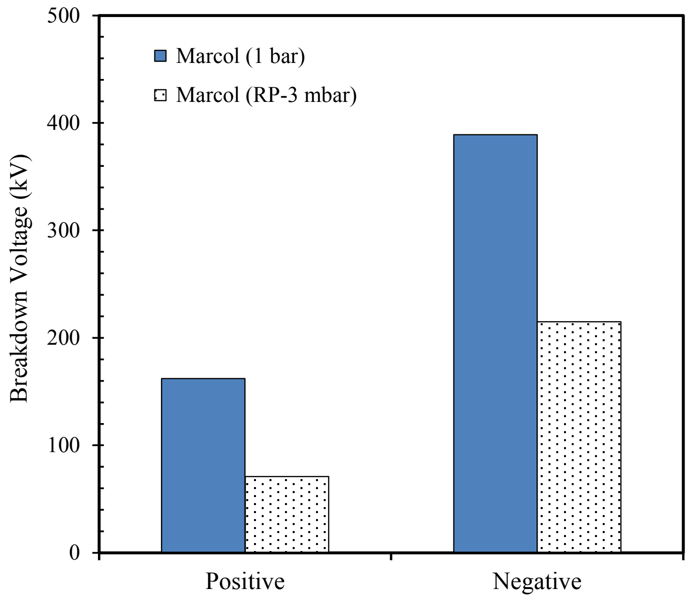


Figure 32. Effect of reduced pressure on the breakdown voltage. RP: reduced pressure (data extracted from *paper 5*).

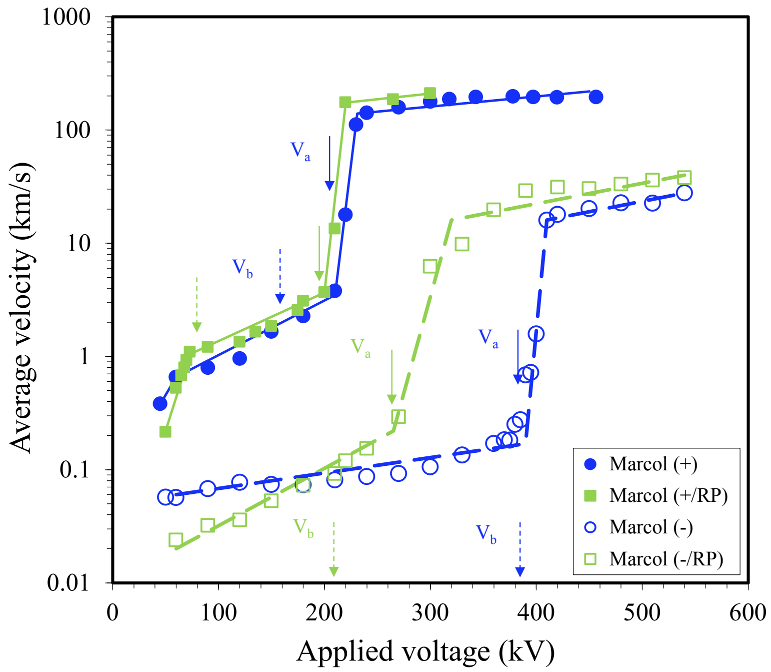


Figure 33. Influence of reduced pressure on streamer velocity. RP: reduced pressure (*paper 5*).

For negative streamers, reduced pressure markedly changes streamer velocity (Figure 33). It decelerates non-breakdown streamers but accelerates breakdown ones. This indicates that gaseous processes play an important role in all modes of streamers. In addition, in spite of lower velocity and higher number of branches, the 1st mode streamers can propagate much further under reduced pressure. Thus, the propagation of the 1st mode streamers largely depends on the gaseous processes. Reduced pressure significantly reduces V_a of negative streamers. It means that both electronic and gaseous processes control the occurrence of fast mode negative streamers.

5.2 Comparison of liquids

5.2.1 Positive streamers

A comparison between Voltesso oil (mineral transformer oil) [6, 36], cyclohexane liquid (naphthenic compound) [7], Exxsol oil (paraffinic compounds), Marcol oil (a blend of naphthenic and paraffinic compounds) and isopropylbiphenyl (aromatic compound) [12] is performed. The general characteristics of positive streamers are quite similar for these liquids as explained below. Streamer shape and speed are changed with increasing applied voltage resulting in different propagation modes, and velocity of streamers increases in “step” with increasing applied voltage as seen in Figure 34.

Despite similarities, streamers in these liquids are still different. It is observed that the structures of the 2nd mode streamers are liquid dependent leading to a change in streamer velocity, and in breakdown and acceleration voltages. First, V_b is lowest for cyclohexane while the other liquids exhibit similar values. Second, Voltesso oil has the highest value of V_a whereas cyclohexane and isopropylbiphenyl liquids show the lowest values. Finally, the ratio V_a/V_b is 1.3 and 1.7 for Marcol oil and Exxsol oil and increases to about 2.0 for Voltesso oil. However, this ratio is reduced to approximately 1.0 for cyclohexane and isopropylbiphenyl liquids.

In summary, V_b, V_a and the ratio V_a/V_b of positive streamers depend on the chemistry of liquid, and mineral transformer oil shows the best ability to successfully withstand fast streamers.

5.2.2 Negative streamers

Negative streamers in different liquids behave in a similar way with increasing applied voltage as seen in Figure 34. However, there are still differences between white oil and mineral transformer oil in terms of velocity, V_b and V_a.

The most noticeable difference at negative polarity is that below V_b, streamer velocity is about ten times higher for Voltesso oil (Figure 34). In addition, V_b is lowest for Voltesso oil and highest for Marcol oil (Table 6). This is possibly due to the presence of aromatic/polyaromatic compounds, having the property of electron trapping, in Voltesso oil. Lastly, Voltesso oil shows the lowest ability to withstand fast negative streamers, i.e. smallest value of V_a (Table 6).

In conclusion, as for positive streamers both V_b and V_a of negative streamers are governed by the chemistry of liquid. For negative polarity, mineral transformer oil now exhibits the lowest capability to withstand breakdown and fast streamers.

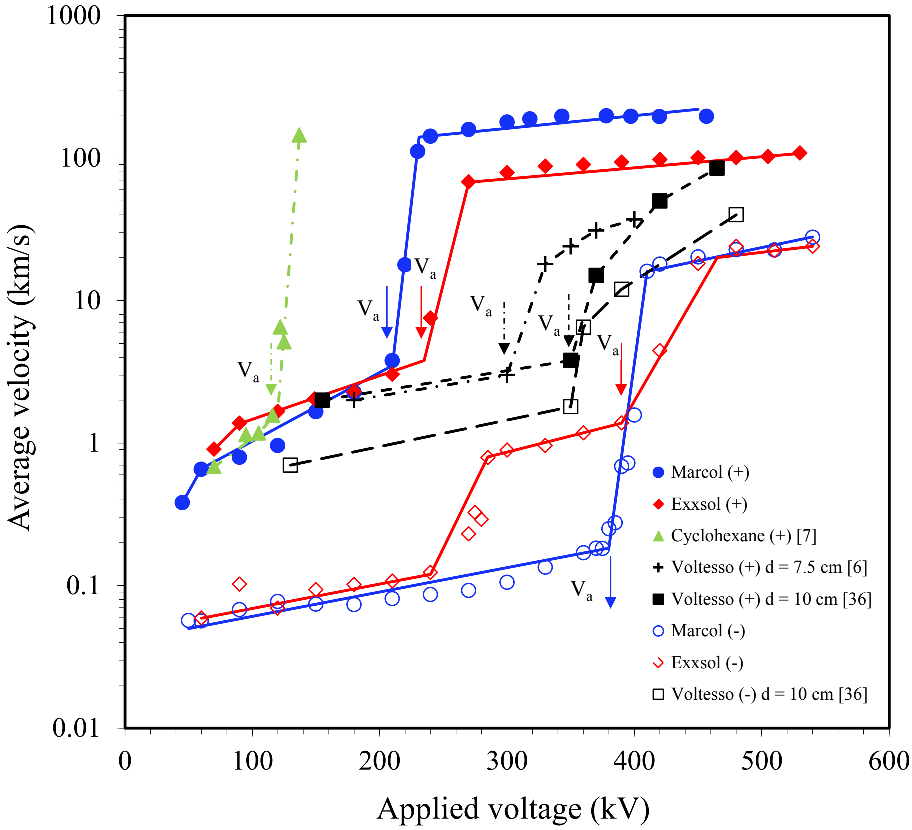


Figure 34. Average velocity versus applied voltage with different liquids.

5.2.3 Polarity comparison

The polarity of the applied voltage significantly influences the propagation of streamers in Marcol oil as well as Exxsol oil. Similar results were previously reported for cyclohexane [7] and for mineral transformer oil [36]. Generally, streamer structures are polarity dependent, thus leading to existence of differences in velocity, breakdown and acceleration voltages between positive and negative streamers.

In Marcol oil, positive streamers are about ten times faster than negative streamers (Figure 35), which is in agreement with what was reported in cyclohexane [7]. This can be explained by higher channel tip field as a consequence of more filamentary branches below V_a for positive streamers. Well above V_a, channels are more luminous for positive streamers (*papers 2, 3* and *5*). This could indicate that the channels of the 4th mode of positive streamers have higher conductivity than negative streamers, leading to a higher electric field at the channel tip and hence the velocity. On the other hand, in mineral transformer oil positive streamers are only about 2-3 times faster than negative ones explained by the presence of aromatic/polyaromatic compounds [36]. With the ability of capturing free electrons, these compounds will drastically accelerate the negative streamers. This hypothesis was supported by adding electron scavengers into either cyclohexane [7] or white oil in this study.

The ratio $V_{b(-)}/V_{b(+)}$ is about 2.4 for Marcol oil calculated from Table 6. This ratio was seen to decrease to 1.3 for Voltesso oil. This is explained by the electron trapping property of aromatic/polyaromatic compounds, which was seen to decrease the breakdown voltage of negative streamers by 20% and 40% for cyclohexane [7] and for white oil, respectively.

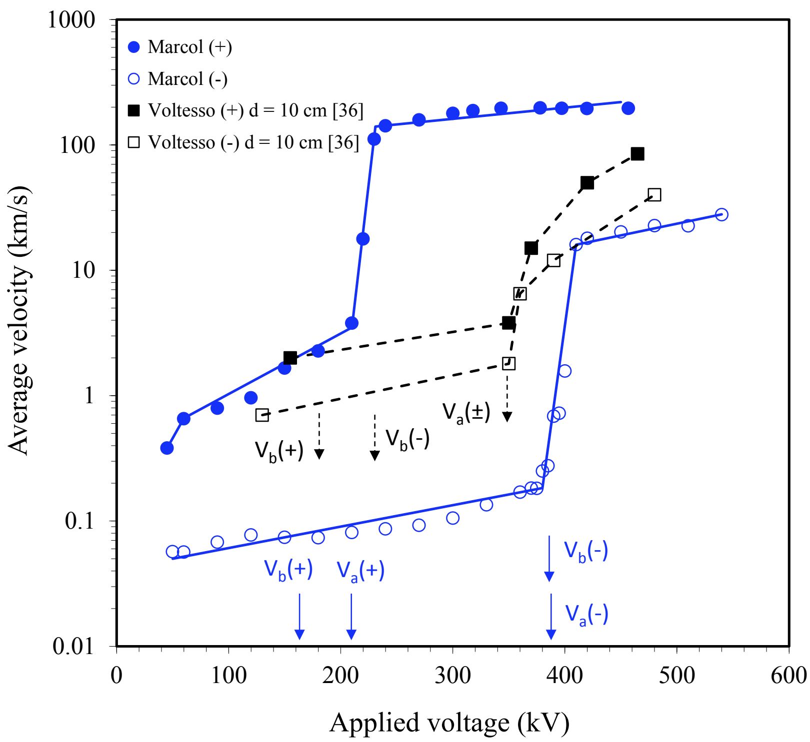


Figure 35. Effect of voltage polarity on average velocity of streamers (*paper 5*).

The ratio $V_{a(-)}/V_{a(+)}$ is about 1.9 for Marcol oil determined from data in Table 6. However, this ratio is approximately 1.0 for Voltesso oil. This can be explained since while the low IP property of aromatic/polyaromatic compounds was seen to increase V_a of positive streamers in cyclohexane [7, 10] and white oil in this work, the electron trapping ability of these compounds was found to reduce V_a of negative streamers in [7] and in this study.

In summary, streamers in white oil are more sensitive to polarity of applied voltage than in mineral transformer oil.

5.3 The correlation between branching, velocity and electric field

The correlation between velocity and branching of positive streamers is introduced in *paper 2* as follows. Streamers with low velocity allow branches to grow, i.e. more branching. With higher number of branches, the macroscopic field of streamers will be lower and the velocity is further reduced. On the other hand, when the velocity is high, streamer branches get less chance to develop. Thus, the macroscopic field increases in front of the dominating branch and the velocity is further increased. The block diagram for depicting the correlation is shown in Figure 36. The macroscopic electric field of streamers has been found to govern streamer propagation [13]. Streamer branching forms a so called shielding effect that decreases the field and hence the streamer velocity [54]. To establish the quantitative correlation between the velocity v and the macroscopic field E_t during streamer propagation, v and E_t associated with each framing image of the 3rd mode streamers in Exxsol oil at 210 kV are calculated. The method for determining E_t is presented in detail in appendix A. The velocity is calculated from framing image sequences. The relationship between the velocity and the electric field is illustrated in Figure 37. It is seen that high velocity is associated with high electric field, and vice versa.

A case study of the shielding effect between branches is performed by electric field calculations detailed in appendix A. It is found that the channel tip field is significantly reduced with density of branches, i.e. smaller angle α between channels, as seen in Figure 38. In addition, when streamers approach the plane electrode (trace with circle symbol), the shielding effect is reduced. Clearly, more branching reduces the macroscopic field of streamers.

As seen in Figure 37, it is possible to keep streamers propagating at high speed (~50 km/s) if the electric field at the channel tip E_t reaches about 10 MV/cm. Thus, the calculation of E_t at the initiation voltage (270 kV) of the 4th mode streamers in Exxsol is performed to test this assumption (seen in appendix A). As expected, the tip field of 8-25 MV/cm is estimated during most of the crossing of the 4th mode streamers. Therefore, a threshold value of about 10 MV/cm can be suggested as a condition to switch from low to fast mode streamers. However, this threshold value is estimated with channel of hemisphere tip and disregarding the value of space charges at the tip so the real value of the threshold tip field may be higher.

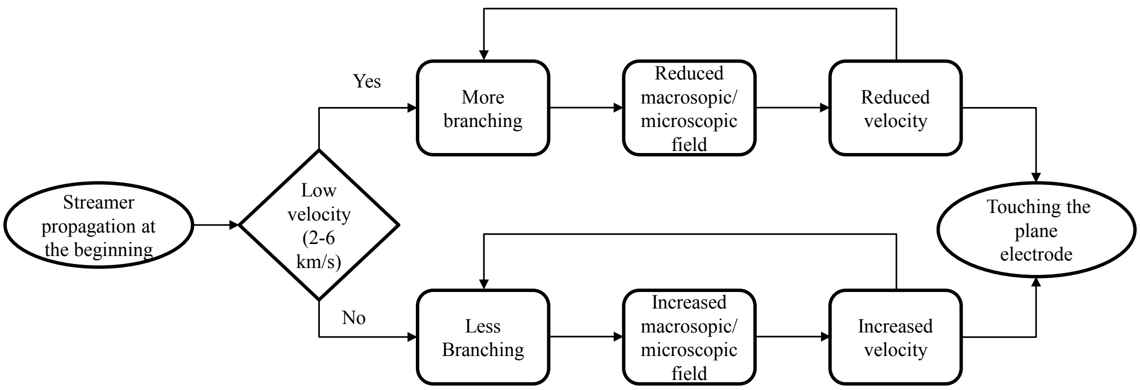


Figure 36. Block diagram of mutual relationship between branching and velocity of streamers.

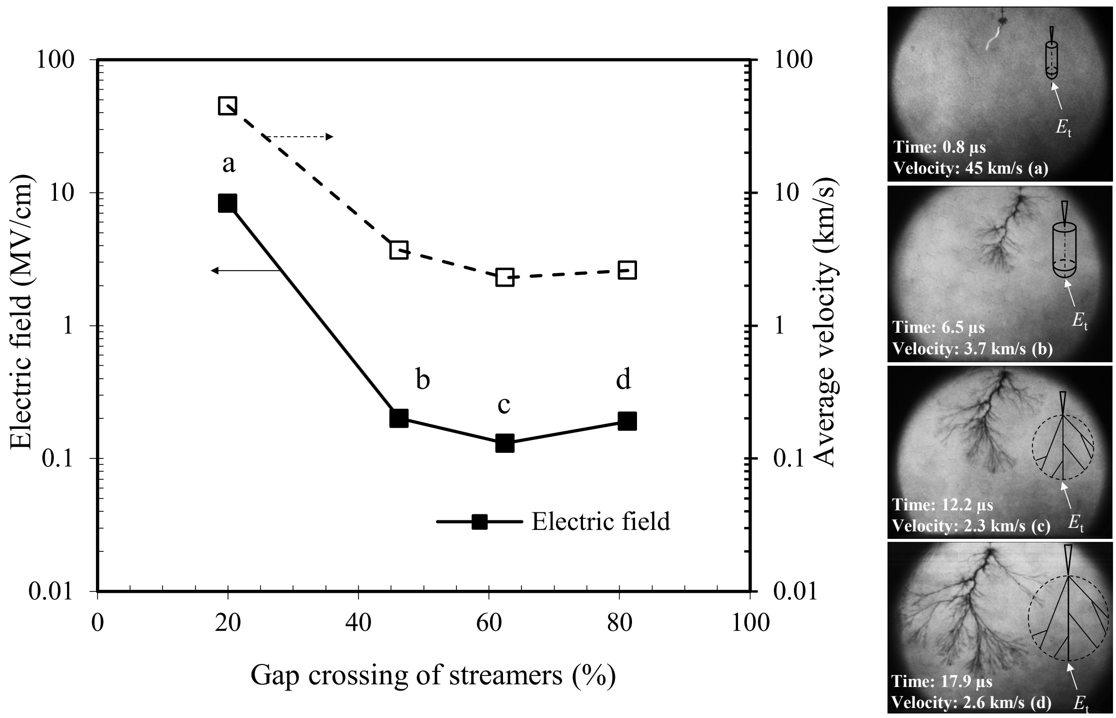


Figure 37. The correlation between velocity and electric field of streamers (Exxsol oil at 210 kV referred to figure 27 in *paper 2*).

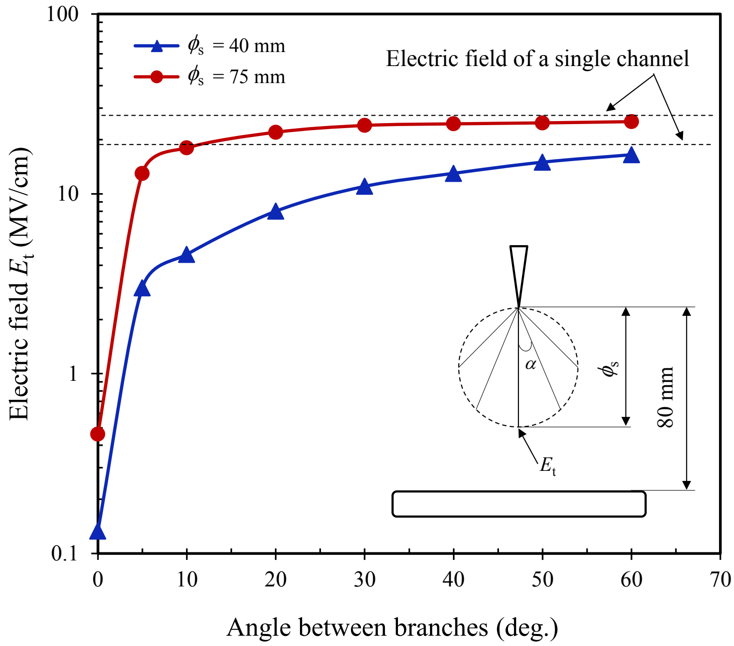


Figure 38. Electric field versus angle between branches of positive streamers at 210 kV.

5.4 Streamer propagation mechanisms

5.4.1 Characteristics of channels of positive streamers

Table 7 summarizes the types of streamer channels (*papers 4* and *5*). The resistance of the channel is calculated from the applied voltage and measured current at the instant of touching the plane electrode. The conductivity of streamer channel σ is determined according to the equation

$$\sigma = \frac{l}{R \times A} \tag{7}$$

where l: channel length

R: channel resistance

A: cross section area of channel

It is seen that the conductivity of dark channels, being responsible for the propagation of the 2nd mode streamers, is only about 3.3‰ of that of bright channels of the 4th mode streamers. Thus the nature of streamer channels would be different in these two modes.

Table 7. Types of streamer channels.

Manifestations/Properties	Types of channels			
	Dark	Partly illuminating	Fully illuminating (reillumination)	Bright
Streamer mode	2^{nd}	2^{nd}	2^{nd}	4^{th}
Applied voltage (kV)	150	150	150	220
Current (mA)	~ 5 [64]	~ 200	2×10^3-3×10^3	~ 6×10^3
Diameter of channel (µm)	~ 150	~ 150	172	254
Length of channel (mm)	82.9	83.9		88.1
Light emission	Weak, permanent	Strong, temporary	Strong, repeated	Strong, permanent
Velocity (km/s)	~2	~2	~2	~100
Breakdown (Yes/No)	Yes/No	Yes/No	Yes/No	Yes
Resistance (MΩ)	30	0.75		0.037
Conductivity ($\Omega^{-1}cm^{-1}$)	1.56×10^{-3}	63.34×10^{-3}		474×10^{-3}

5.4.2 A hypothetical model for streamer propagation

It was observed that increased hydrostatic pressure suppressed propagation of streamers in a small gap of both polarities [14, 15]. The thermal energy of about 10 W at the channel tip of a positive streamer was estimated [35]. The dynamic of expansion and collapse of channels of positive streamers are in line with Rayleigh model [35]. Low IP additives strongly affect the propagation of positive streamers while electron scavengers significantly influence that of negative streamers [7, 10, 11]. Positive streamers can hit the plane electrode without inducing breakdown [5, 6]. Instead, a bright luminous section occurs at the channel tip. High voltage drop is observed along the channel (10-20 kV/cm for positive streamers [54]; ~24 kV/cm for negative streamers [56]). Kerr effect measurement shows that streamer channels of both polarities are conductive [79]. The electron density of the channel of the positive streamer is estimated to be approximately 10^{16} cm^{-3} [80]. The macroscopic electric field of streamers was shown to govern the propagation of both polarities [58]. The branching of positive streamers forms the shielding effect that decreases the field and hence streamer velocity [54].

From above arguments, a hypothetical model for streamer propagation is suggested as follows. Gaseous plasma is present inside streamer channel while space charges accumulate at the channel tip. Electric field formed by the space charges will govern processes at the channel tip. Due to tip processes, streamer channel will grow as long as the tip field is high enough. When the electric field reaches a critical value, streamers will switch from the 2^{nd} to 4^{th} modes. The model is depicted in Figure 39. The possible processes occurring at the channel tip are illustrated in Table 8.

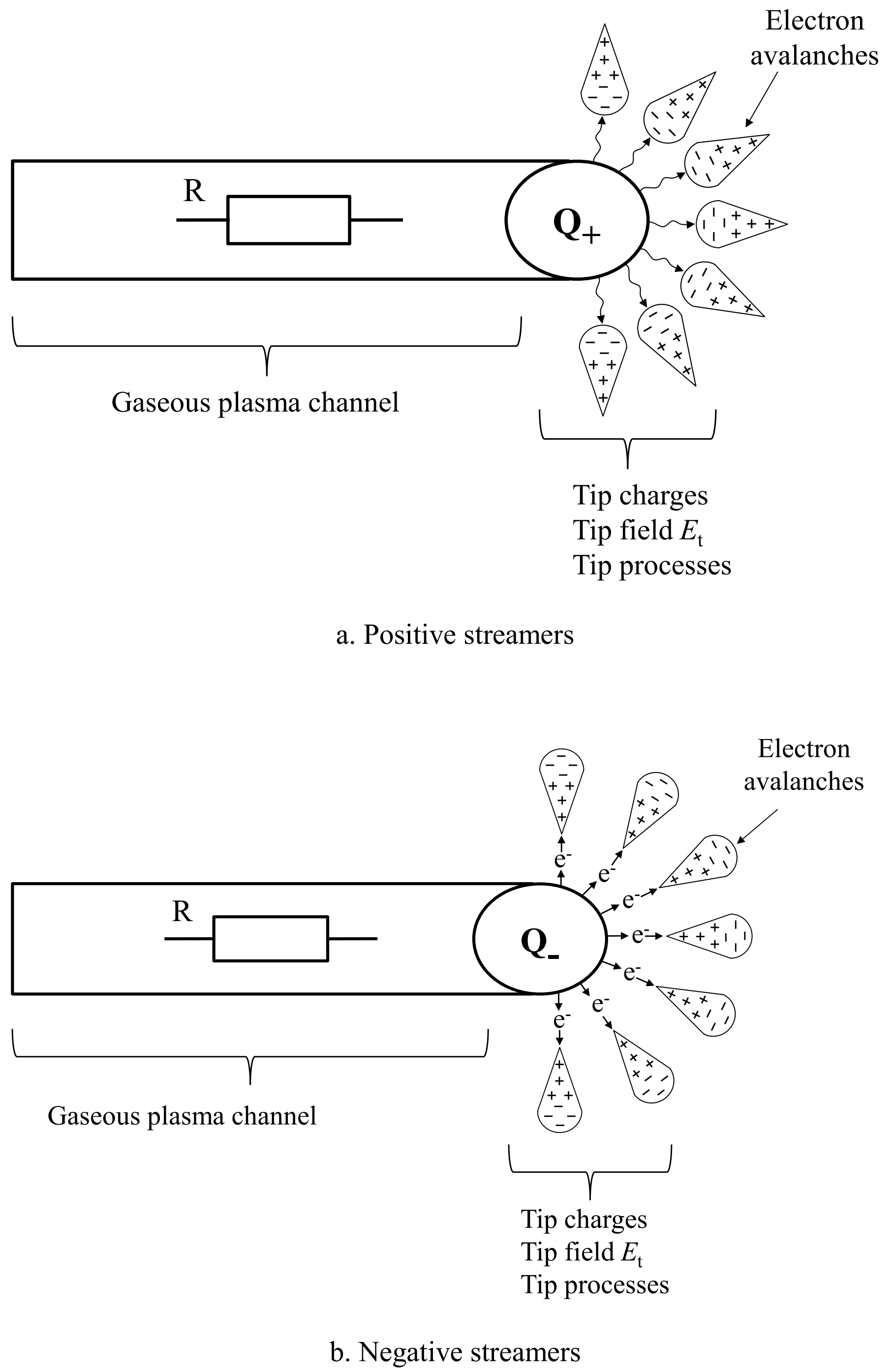


Figure 39. The model of streamer propagation.

Table 8. Possible processes occurring at the channel tip.

Tip processes	Positive streamers		Negative streamers	
	2nd mode	4th mode	2nd mode	4th mode
Micro-bubble formation	×	×	×	×
Molecular excitation and de-excitation	×	×	×	×
Photon emission	×	×	×	×
Electron injection			×	×
Impact ionization	×	×	×	×
Field ionization		×		×
Joule heating	×	×	×	×
Evaporation of liquid and bubble formation	×	×	×	×

5.4.3 Supporting evidence for the model of positive streamers

5.4.3.1 The 2nd mode streamers

It is observed that dark channel can induce no breakdown and no current detected when touching the plane electrode (*paper 4*). Reduced pressure largely enhances streamer propagation (*paper 5*), i.e. gaseous processes are involved in streamer propagation. However, the voltage drop of about 10-20 kV/cm is observed along the channel of positive streamer channel (*papers 2* and *5*). From these experimental results, dark channels are low conductive possibly with a state of weakly ionized plasma inside. The fact that a bright luminous section occurs at the channel tip when non-breakdown streamers touch the plane electrode (*paper 4*) may be an indication of high electric field at the tip. The high tip field cannot be explained by low conductivity of channel. Therefore, only space charges can create the high field, i.e. space charges probably exist at the channel tip. It is seen that streamer channels can switch between dark channels and reilluminations (*paper 4*). Gas discharges are suggested to be responsible for occurrence of reilluminations (*paper 4*) and the discharges only occur when the ratio E_L/p (where E_L: voltage drop along streamer channel; p: pressure of vapour inside) is satisfied. Although showing a crucial effect for triggering breakdown, reilluminations do not play any significant roles on streamer propagation in this mode, i.e. processes occurring at the streamer tips are more important than those inside its channels (*paper 4*). Low IP additives, e.g. DMA, significantly affect streamer propagation (*papers 2* and *5*). Thus, electronic processes are related to streamer propagation. During streamer propagation, successive fast pulses of emitted light and current are seen in *paper 5*. This could indicate that the light is originated from relaxation of excited states possibly formed during avalanches. The electric field at the channel tip E_t is estimated to be at least 2.4 MV/cm which is probably high enough for impact excitation and ionization of liquid in the stressed volume in front of the channel tip (*paper 5*). Seed electrons for impact ionization must come from liquid phase and possibly generated by photo-ionization. Joule heating and gaseous processes, formed by movement of electrons and negative ions, extend streamer channel by evaporating new oil volume.

When a low IP additive, e.g. DMA, is added into pure oil, the stressed volume where ionization may take place in front of the point tip is extended. As the field required for impact ionization is lower for DMA than for base oil, the volume where ionization may occur is larger. With a higher ionized volume, there is a higher probability to form more electron avalanches, i.e. the number of branches will increase. Thus DMA facilitate initiation and propagation of streamers at lower voltage with a higher number of branches from the point tip (*paper 2*). With increasing voltage, the velocity becomes lower than in pure liquids due to the shielding effect from branching at the point tip reducing tip field. In turn, lower-speed streamers will become more branched at the channel tip with longer and denser ramifications forming a spherical shape. As expected, lack of low IP molecules gives higher inception voltage and therefore fewer ramifications and higher speeds afterward. This observation supports the hypothesis on correlation between branching and velocity. The sketch of the relation between initiation, propagation and branching is summarized in Figure 40.

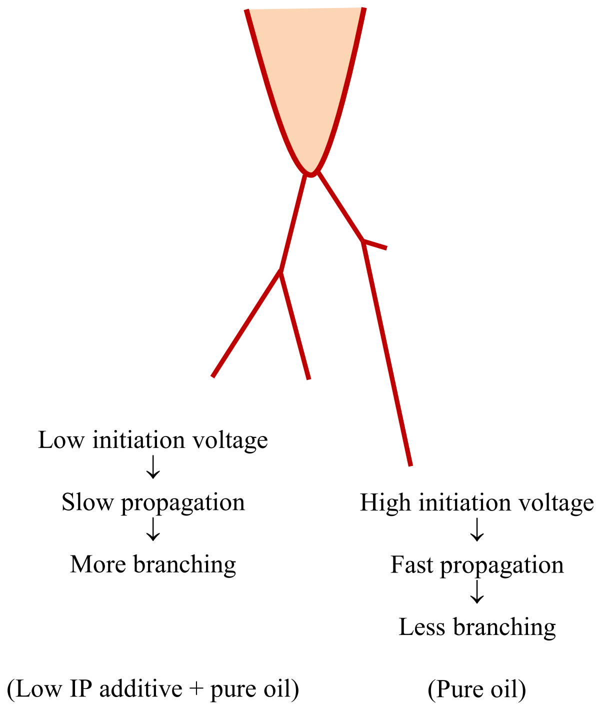


Figure 40. A sketch of relation between initiation, propagation and branching.

5.4.3.2 The 4th mode streamers

The 4th mode streamers propagate with very luminous channels and very high velocity of 100-200 km/s (*papers 2* and *5*). Streamers current continuously increases to some amperes [8]. Continuously luminous light is obtained with streak images (*papers 2* and *5*). Low voltage drop is observed along streamer channel (~1 kV/cm) [54]. In addition, the calculated conductivity of the bright channel is about three hundred times higher than the dark channel as seen in Table 7. Therefore, the 4th mode streamer channel is suggested to be highly conductive and highly ionized plasma state is proposed to be present inside the channel. DMA markedly reduces the velocity of the 4th mode streamers (Figure 29). Reduced pressure still slightly increases streamer velocity (Figure 33) and make streamers more branched. It means that both electronic and gaseous processes are still involved in the propagation of the 4th mode streamers. The calculated tip field is about 7-20 MV/cm during most of the crossing (*paper 5*). Thus, the electric field at a distance of tip radius from the tip, E_r, is 2-6 MV/cm, which is sufficient for impact ionization of liquid [47]. In addition, the IP of molecules is field dependent and significantly reduced with increasing applied electric field [95]. Thus, with very high field at irregular sites on the surface of the channel tip and a reduction of the IP, photo-ionization and impact ionization even field ionization of liquid molecules in front of the channel tip is plausible.

With high conductivity channels, the propagation of the 4th mode streamers is considered as an extension of the point electrode. Thus, the channel tip field will increase continuously and become several times higher than that of the 2nd mode streamers as obtained by simulation (7-20 MV/cm compared to 2.4 MV/cm). Due to higher tip field, the impact ionization and photo-ionization, if possible, in front of channel tips are stronger leading to higher charge concentration and electric field. This ultimately leads to a drastically increase in the velocity of the 4th mode streamers.

5.4.4 Supporting evidence for the model of negative streamers

5.4.4.1 The 2nd mode streamers

Reduced pressure significantly facilitates the propagation and largely reduces the inception voltage for the 2nd mode negative streamers (*paper 5*). An electron scavenger, e.g. TCE, increases streamer velocity by a factor of about ten (*paper 5*). It means that both electronic and gaseous processes play important roles in streamer propagation of this mode. In addition, numerous reilluminations are observed in streak images (*papers 3* and *5*). This could indicate that dark channels are still present and responsible for propagation of the 2nd mode streamers of negative polarity, and reilluminations result from gas discharges inside the dark channels. The electric field at the channel tip of the 2nd mode streamers is estimated to be 1.3-2 MV/cm during most of the crossing (*paper 5*). Thus, the electric field at a distance of tip radius from the tip, E_r, is 1.2-1.7 MV/cm. This field value satisfies the minimum requirement for impact ionization in n-hexane (1.3 MV/cm [96]) but does not meet the condition of 2.5 MV/cm for cyclohexane and propane in [47]. However, if the value of space charges at the channel tip and irregular points on the surface of channel tip are considered, E_r may reach the value of 2.5 MV/cm. Seed electrons for impact ionization are perhaps emitted from a plasma channel tip. Similar to positive streamers, Joule heating and gaseous processes will extend streamer channel by evaporating new oil volume.

5.4.4.2 The 4th mode streamers

The 4th mode streamers propagate across the electrode gap with a channel tip field of 11-20 MV/cm calculated in *paper 5*. The electric field at a distance of tip radius from the tip, E_r, is 3-5 MV/cm. This high tip field meets the condition of 2.5 MV/cm for impact ionization [47]. It is therefore possible that impact ionization of liquid could occur at the channel tip. The reduced pressure still has a quite strong effect on streamers of this mode (Figure 33), i.e. the role of Joule heating and gaseous processes cannot be excluded. TCE significantly increases the velocity of the 4th mode streamers (Figure 30). It means that the propagation of the 4th mode streamers still depends on electronic processes. In addition, with very high applied voltage, the streak image of this mode streamer only shows continuous luminosity (*paper 5*). It means that streamer channel may be highly conductive because of highly ionized plasma inside the channel, and field ionization is possibly another mechanism besides impact ionization.

As compared to the 2nd mode streamers, the channel tip field is about ten times higher for the 4th mode streamers due to higher conductivity and higher applied voltage. Thus, the electrons emitted from the channel tip will have higher kinetic energy leading to stronger impact ionization. This further increases the charge density at the channel tip and hence the tip field. Therefore, a drastic increase in velocity of the 4th mode streamers is observed.

Chapter 6. Conclusions

6.1 Concluding remarks

An extensive study on the characteristics of streamers under various experimental conditions including polarities, impurities, liquid chemistry and additives has been carried out. About 600 test series with a total of 6000 shots of step voltages were applied to nineteen cases of studies. From a scientific viewpoint, a mixture of additives, having low IP property or high ability of electron trapping, and white oil was used as a model liquid for streamer mechanism studies. The main findings are presented as follows:

For positive streamers, both dark channels and channels responsible for reilluminations occur simultaneously and propagate almost equally. Dark channels are low conductive while reilluminations are high conductive. Although, reilluminations show a crucial effect for triggering breakdown, they do not play any significant roles in streamer propagation. It means that reilluminations and channel conductivity are not essential for the propagation of streamers. Thus, processes occurring at the channel tips are more important than those inside channels. The experimental results support the model that gaseous plasma may exist inside the channels and critical space charges for maintaining streamer propagation are present at the channel tips. It seems that high electric field formed by the space charges governs the tip processes and hence streamer propagation.

Reduced pressure significantly facilitates streamer propagation and markedly reduces breakdown voltage. This indicates that gaseous processes are involved in the propagation of streamers. In addition, it was found that the initiation voltage was not significantly different for normal and reduced pressure, indicating that streamer initiation is dependent on processes in the liquid phase. For positive polarity and under ambient pressure, there is a clear correlation between streamer velocity, branching and the electric field for the 2^{nd} and the 3^{rd} modes. Streamers with low velocity correlate to low electric field at streamer heads and more branching, and vice versa. In contrast, high velocity streamers associate with high electric field at streamer heads and less branching. This indicates that a mutual interaction between the velocity and branching exists. However, under reduced pressure, streamer branching has a lesser effect on the velocity. It means that streamer propagation depends on both the channel tip field and tip processes influenced by reduced pressure.

Dissolved gases/air has an insignificant influence on streamer propagation of both polarities. On the other hand, carbon particles have a strong effect on streamers. These particles reduce the inception, breakdown and accelerating voltages, and increase both stopping length and velocity, especially for negative polarity. It means that carbon particles can be considered as an important factor to reduce the dielectric performance of insulating oil in high voltage equipment.

DMA has a high capability of releasing electrons while TCE shows a high ability of trapping electrons. Therefore, DMA has a large effect on the positive streamers only, while TCE impacts both polarities, especially negative streamers. This could indicate that electronic processes are involved in streamer propagation. Adding DMA caused positive streamers to behave like those in mineral transformer oil while adding TCE had the same influence on negative streamers. If both DMA and TCE are added, it is suggested that TCE will decrease the impact of DMA on positive streamers because of electron trapping, which reduces the number of electron avalanches, i.e. the number of branches, while DMA does not affect the influence of TCE on negative streamers.

The impact ionization is considered to be a dominant mechanism to create new charges in front of streamer channels for both polarities. For the positive streamers, seed electrons for the impact ionization may be generated by the photo-ionization of liquid in the stressed volume in front of channel tips. For the negative streamers, the corresponding electrons are possibly emitted from the tips of plasma channels.

It is clear that in white oil, positive streamers are more dangerous than negative ones because of ten times higher velocity and two times lower breakdown and acceleration voltages. However, the hazard from positive streamers at lightning impulse is significantly reduced for mineral transformer oil. The reason is possibly that the low IP property of aromatic/polyaromatic compounds slightly changes the velocity and the breakdown voltage, and largely increases the acceleration voltage of positive streamers. For negative streamers, in contrast, the electron trapping property of such compounds increases the velocity by a factor of ten, and reduces the breakdown and acceleration voltages by 50% and 30% respectively. The sufficient difference in IP between aromatic/polyaromatic compounds and paraffinic/naphthenic compounds is considered as a main reason for the very high acceleration voltage of mineral transformer oil, i.e. favourable *V-t* characteristics. For practical application, it is suggested that the ability to withstand fast streamers of insulating oil can be improved by adding a certain amount of a sufficiently low IP additive.

6.2 Future work

A deeper understanding of the streamer propagation requires further work as follows.

As mentioned in *paper 5*, the photo-ionization is proposed to be the source of supplying seed electrons for impact ionization of liquid because of lots of light recorded during streamer propagation. The IP of white oil molecules, considered to be similar to those of hydrocarbon liquids, is approximately 10 eV, so the light having a wavelength of 124 nm is capable of causing photo-ionization of these molecules. Such light is in the range of ultraviolet. However, the energy of the emitted light is not yet determined. The next study should be the measurement of the wavelength of the light emitted from streamers to prove that it has enough energy to ionize oil molecules.

The low IP additives, e.g. DMA and pyrene, dramatically increase the number of streamer branches. This can be explained by using the hypothesis that molecules of DMA or pyrene are easier to be ionized by collision with energetic electrons than those of paraffinic/naphthenic molecules. It means that DMA or pyrene may create a lot of seed electrons in the stressed oil volume in front of streamer heads. This leads to an increase in the probability of forming electron avalanches. To verify this hypothesis, we suggest using the X-ray or ultraviolet light as a source to form seed electrons in the bulk of oil. If this process significantly increases the number of branches, the hypothesis of impact ionization is proved.

The effect of only a low IP additive or an electron scavenger on streamers in a long gap is well observed. It will be interesting if both additives are added into white oil. This would produce a type of liquid similar to mineral transformer oil for streamers of both polarities.

The shielding effect resulted from streamer branching tends to regulate the macroscopic field and hence the streamer velocity as increasing applied voltage. Especially, under the presence of DMA, more branching can be observed, i.e. higher degree of the shielding effect. This makes it difficult to distinguish the effect on streamers from DMA and branching. Thus, the future study of streamer characteristics should be performed in constrained volume, e.g. in a tube, with and without DMA.

As proposed above, both gaseous and electronic processes are related to streamer propagation. As soon as electron avalanches occur, liquid is quickly heated and evaporated, i.e. there is a phase change from liquid to gas at the streamer heads. The question arises that whether streamers appear or not if the phase change is largely limited. To answer this problem, the effect of increased pressure on streamers in long gaps should be studied.

Finally, future theoretical studies should consider developing model of streamer propagation with respect to channel tip field, branching effect, impact ionization, photo-ionization and electro-thermal hydrodynamic processes.

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Appendix A: Modelling of Electrostatic Field

1. Modelling method

The electric field E_t presented in this study is determined by using the finite element software package COMSOL Multiphysics. Figure A.1 shows a 2D axisymmetric geometry representing the whole setup of the test cell. The geometrical model of streamers is either cylindrical or spherical depending on the real shape of streamer envelope.

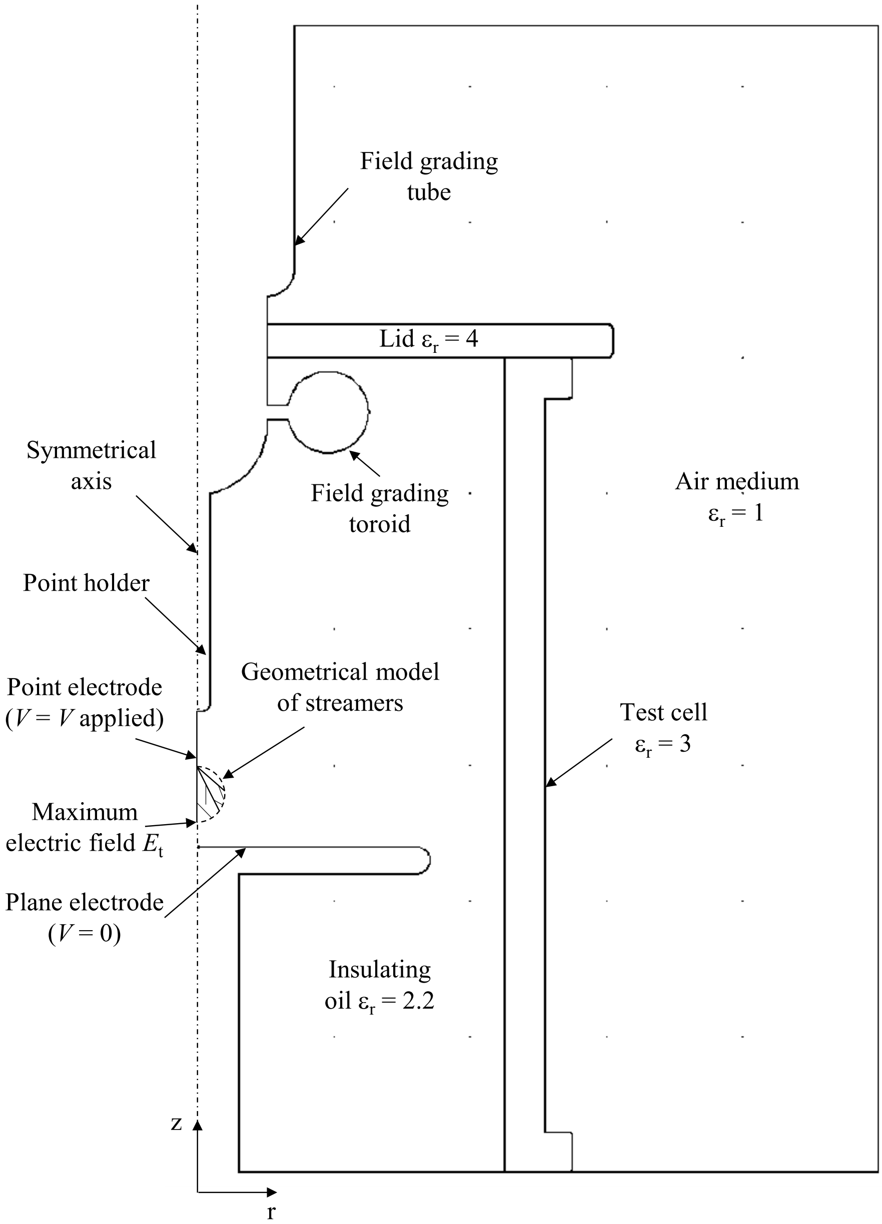

Figure A.1. Model for calculation of electric field E_t.

The electric field is calculated by negative gradient of the electric potential V (Eq. A1). Therefore, the potential V is initially determined.

$$E = -\nabla V \tag{A1}$$

From Maxwell's equation,

$$\nabla E = \frac{\rho}{\varepsilon_0 \varepsilon_r} \tag{A2}$$

where ρ is volume charge density, ε_0 is air or space permittivity (8.854×10^{-12}) and ε_r is relative permittivity of dielectric material. The Poisson's equation can be obtained by substituting Eq. A1 in Eq. A2

$$\nabla^2 V = -\frac{\rho}{\varepsilon_0 \varepsilon_r} \tag{A3}$$

Because of the charge $\rho = 0$, the Laplace's equation can be written as follows

$$\nabla^2 V = 0 \tag{A4}$$

In the case of 2D axial symmetry, the potential distribution does not depend on coordinate θ. Therefore, the Eq. A4 is rewritten

$$\nabla^2 V = \frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial V}{\partial r}\right) + \frac{\partial}{\partial z}\left(\frac{\partial V}{\partial z}\right) = 0 \tag{A5}$$

When all boundary conditions are known, FEM method presented in [1-3] is used to solve equation (A5). The point-plane gap is an open domain problem. It means that the electric field may extend to infinity. To simplify the calculation, the outermost boundaries can be considered at infinity. According to this, boundary conditions are set as follows.

$V = V_{applied}$ on the point (high voltage)

$V = 0$ on the plane (ground)

$nD = 0$ on outermost boundaries

2. Computation of maximum field of positive streamers in Exxsol oil at 210 kV

The images of the 3rd mode streamers during propagation are illustrated in Figure A.2. For simplified simulation, streamers are considered to be conductive. The streamer envelope has cylindrical or spherical shapes as seen in Figure A.2. Thus, conducting cylinder and sphere used to be models for simulating the distribution of electric field are illustrated in Figure A.3. The sizes of cylindrical and spherical models are determined from the images in Figure A.2. The electric field distribution formed by using COMSOL program is shown in Figure A.4. The electric field at model surfaces reaches maximum value (E_t) at the point facing the plane electrode.

The maximum field E_t is calculated and plotted with increasing streamer extension as seen in Figure A.5.

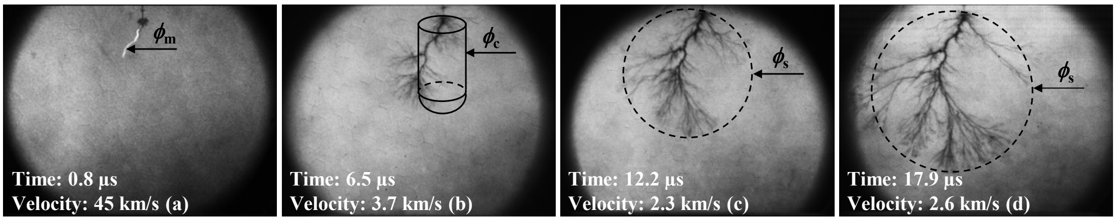

Figure A.2. Framing images of Exxsol oil at 210 kV and models for calculation of electric field (referred to Figure 27 in *paper 2*).

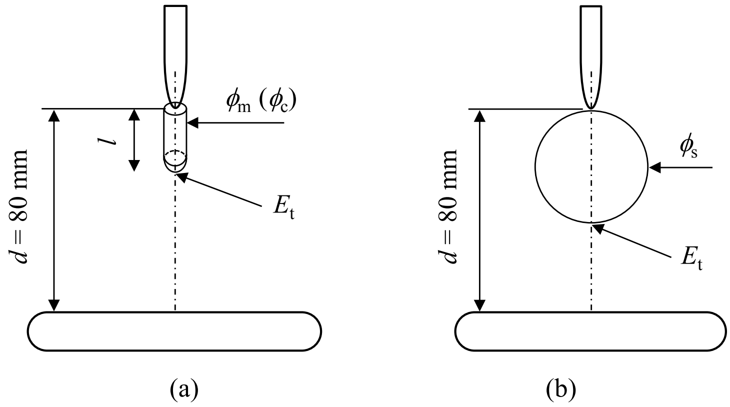

Figure A.3. Models for calculation of E_t; (a)-l = 16 mm and ϕ_m = 0.2 mm for streamers in Figure A.2a, l = 37 mm and ϕ_c = 23 mm for streamers in Figure A.2b; (b)-ϕ_s = 50 mm and 65 mm for streamers in Figure A.2c and d.

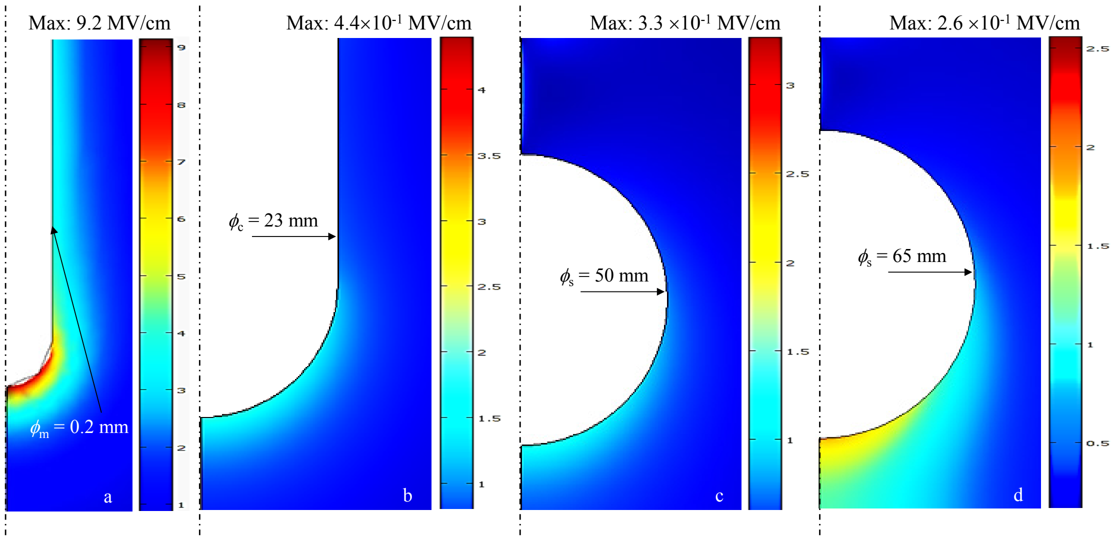

Figure A.4. Surface plots of electric field. Letter symbols referred to images in Figure A.2.

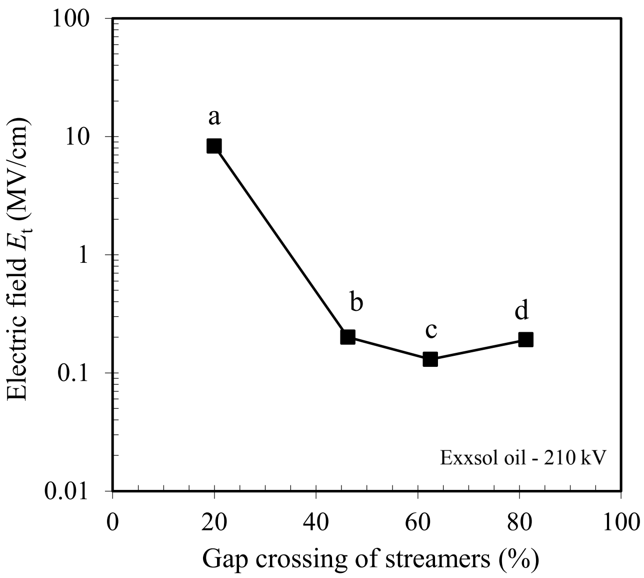

Figure A.5. Electric field E_t during streamer growth. Letter symbols referred to images in Figure A.2.

3. Computation of channel tip field of positive streamers in Exxsol oil at 270 kV

Figure A.6 shows the images during the propagation of the 4^{th} mode streamers in Exxsol oil at 270 kV. Streamers are in the 4^{th} mode and consist of one main channel surrounded by numerous short side branches. The main channel has a diameter of about 0.15 mm directly determined from the images in Figure A.6. Due to high conductivity of the bright channel of the 4^{th} mode streamers as presented in the discussion part of this work, the model of conducting growing cylinder is employed to simulate the electric field distribution (Figure A.7). The length l of growing cylinder is increased in steps of 10 mm. Again COMSOL program is used to be a simulation tool. The surface plots of the electric field are illustrated in Figure A.8. From these plots, the maximum field E_t was obtained, and the increase of E_t during streamer growth is shown in Figure A.9.

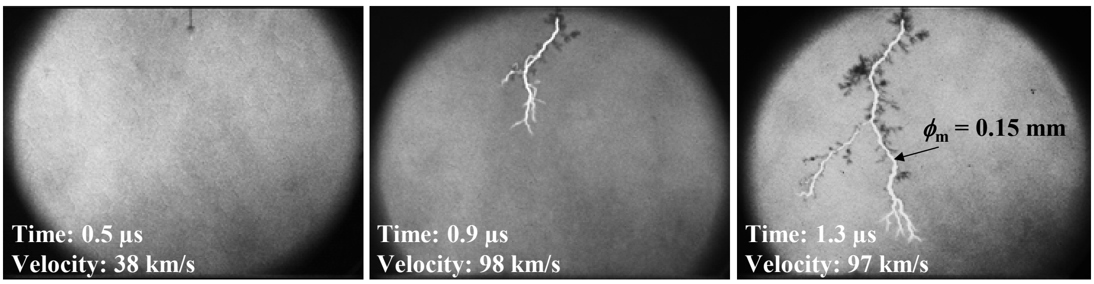

Figure A.6. Images of streamers during propagation.

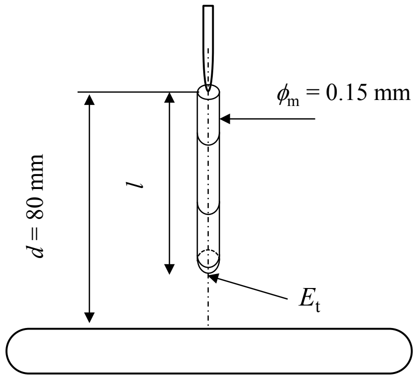

Figure A.7. Growing cylinder model for simulation.

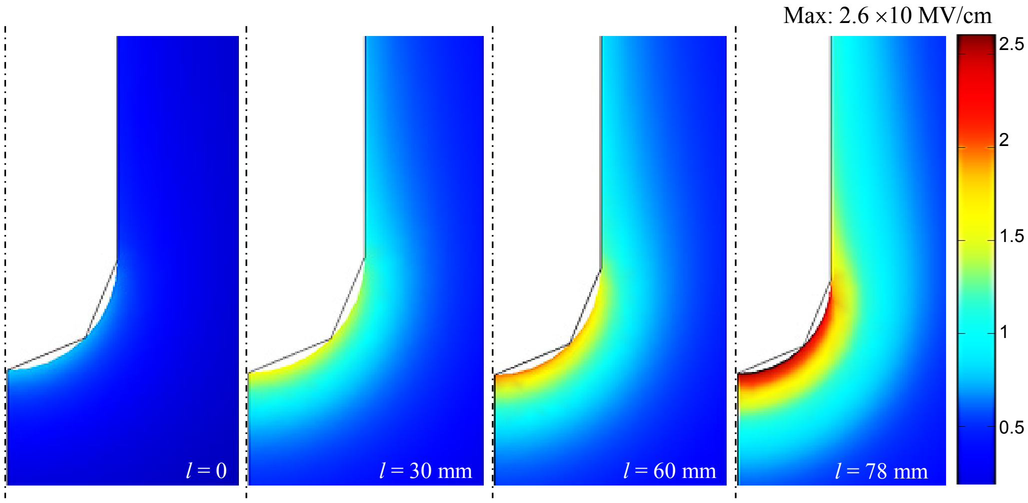

Figure A.8. Surface plots of the electric field.

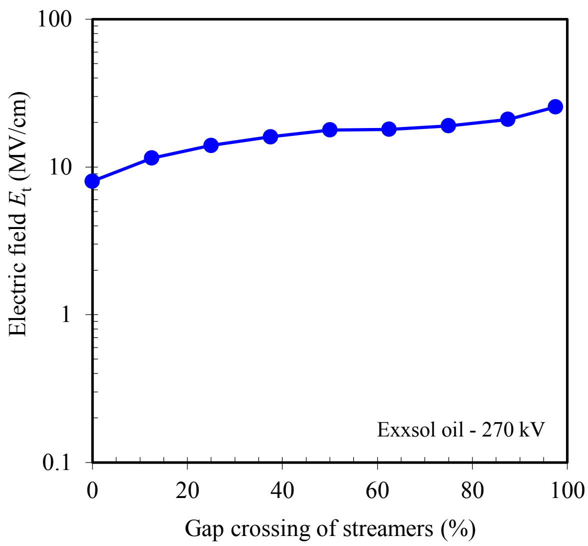

Figure A.9. Calculated channel tip field E_t during streamer growth based on growing cylinder model.

4. Simulation of shielding effect of positive streamers

Figure A.10a shows the image of the 2nd mode streamers in Marcol oil at 210 kV. It is seen that streamer envelope has spherical shape consisting of numerous filamentary branches. Streamer branches are considered to distribute in r-z plane and around the z axis as seen in Figure A.10b. It means that simulation of the shielding effect is really a 3D problem. For simplicity, the angle β between surrounding branches is considered to be 0^o, i.e. hollow cones encircle the main channel and the shielding effect around z axis is maximum. Therefore, a 2D axial symmetry model will be used to simulate the shielding effect (Figure A.11). The main channel (ϕ_m = 0.1 mm) coincides with the z axis. Thickness, *t*, of the hollow cones is 0.05 mm. Both the tip of the main channel and the edges of hollow cones lie in an imaginary sphere surface. Diameter of the sphere (ϕ_s) is 40 mm and 75 mm. For each diameter of the sphere, the angle α between branches will be increased in steps from 5^o to 60^o. For simplified simulation, both the main channel and hollow cones are considered to be conductive. The electric field distribution is simulated with COMSOL Multiphysics program. Some typical simulation results with sphere diameter of 75 mm are shown in Figure A.12. It is seen that the electric field reaches maximum value (E_t) at the tip of main channel. Outside the tip surface, the electric field significantly reduces. The channel tip E_t is higher with higher value of angle α and determined from surface plots of field distribution. The tip field E_t correlated to angle α between branches is illustrated in Figure A.13.

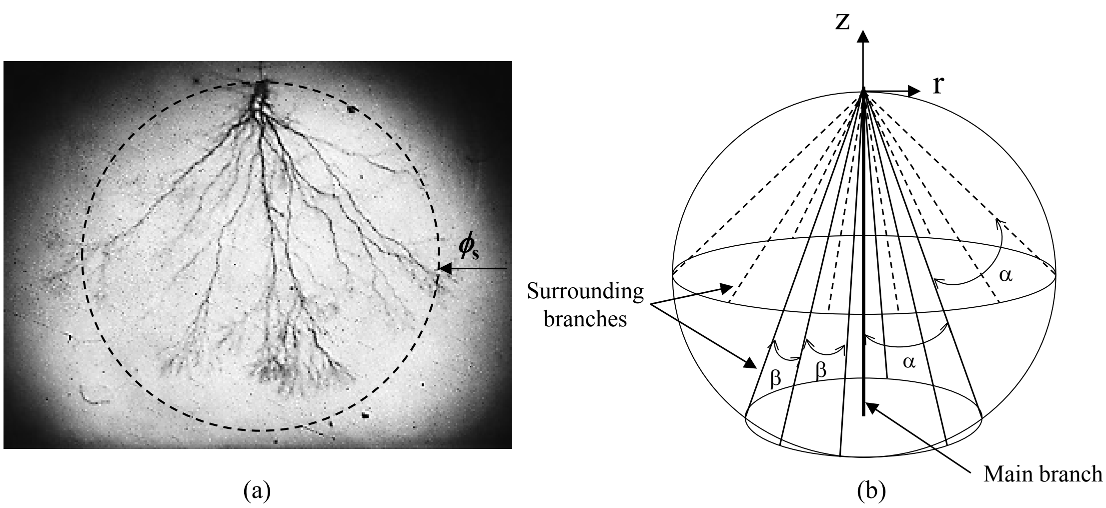

Figure A.10. The image of the 2nd mode streamers and the distribution of streamer branches.

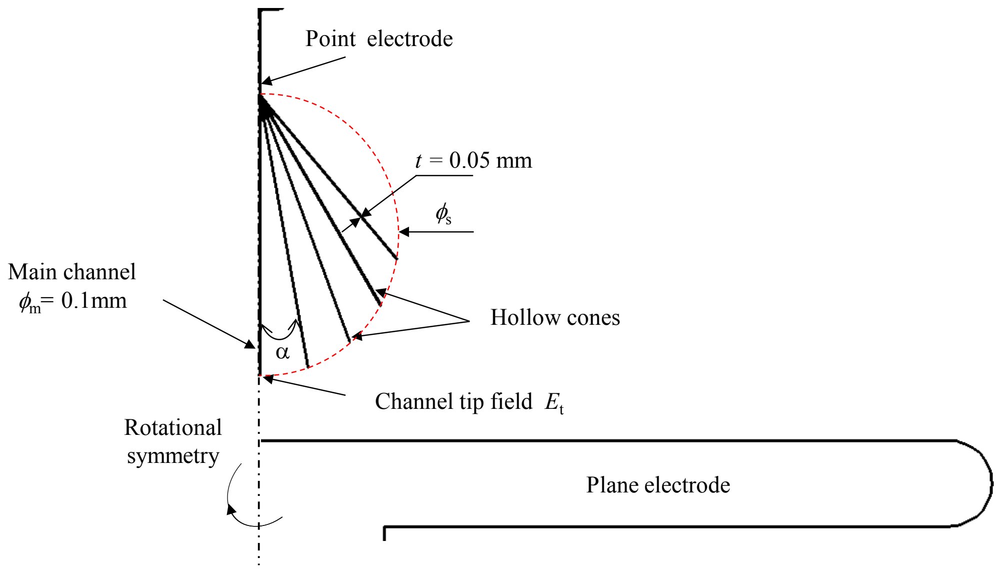

Figure A.11. The 2D axial symmetry model for simulation of shielding effect.

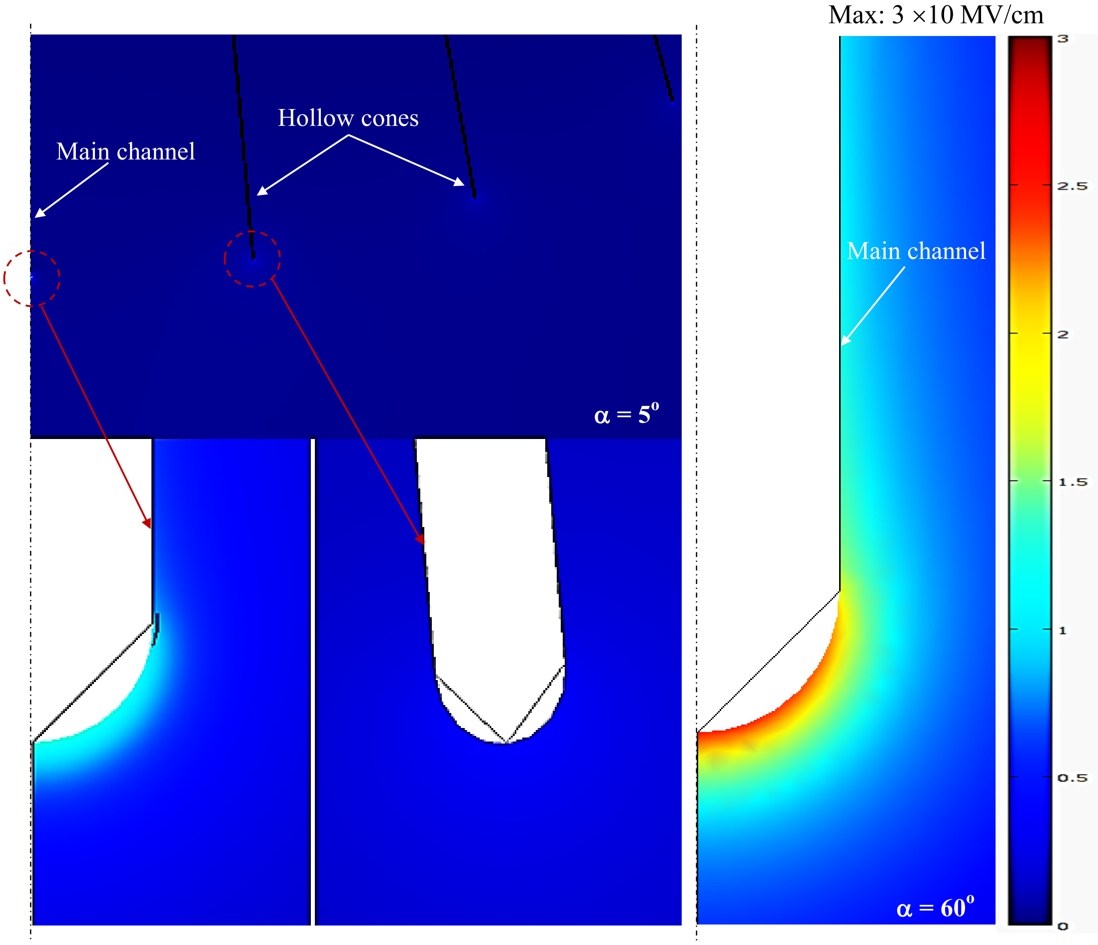

Figure A.12. Electric field distribution in case of ϕ_s = 75 mm.

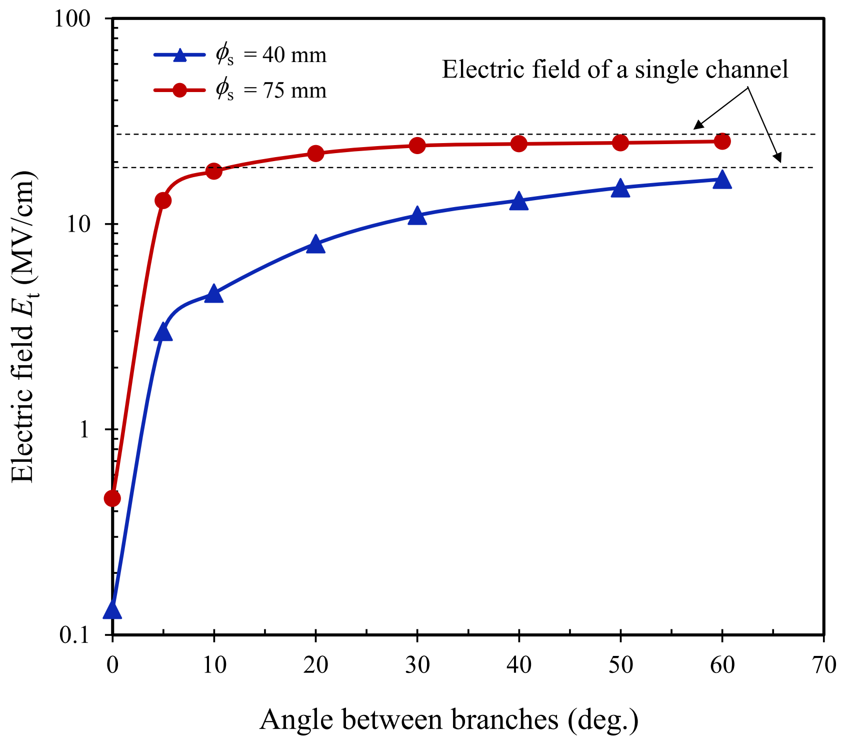

Figure A.13. The channel tip field versus angle between branches.

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Appendix B: Papers

Paper 1

Streamers in Large Paraffinic Oil Gap

N. V. Dung, F. Mauseth, H. K. Høidalen, D. Linhjell, S. Ingebrigtsen, L. E. Lundgaard and M. Unge

Proceeding of the IEEE International Conference on Conduction and Breakdown in Dielectric Liquids, 2011, paper no. 113.

Streamers in Large Paraffinic Oil Gap

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Abstract—**This paper focuses on studying characteristics of streamers in Exxsol D140. The experiments were carried out with 80 mm point-plane gap under step-voltage up to 540 kV.**

Inception delay time, stopping time and stopping length of streamers is voltage, polarity and impurity dependent. It is seen how increased voltage changes streamer shape and speed resulting in different propagation modes. Impurities markedly reduce inception, breakdown and acceleration voltage. A low ionization potential additive decelerates the positive streamers and accelerates the negative streamers.

In fast mode, positive streamers are approximately 5 times faster than negative streamers, and their velocities can reach the value of 110 km/s and 25 km/s at 540 kV for positive and negative polarities respectively. Besides, positive streamers accelerate at 240 kV, while 420 kV is the value of negative streamers.

Keywords-component; streamers; breakdown; stopping length; additive; velocity

I. INTRODUCTION

Streamers in mineral oil and hydrocarbon liquids for small gap as well as for long gaps have been studied for many years [1-7]. Beside pure liquid investigation, the effect of additives have been examined [8, 9].

The streamer structure and its characteristics depend on many parameters, especially the applied voltage, the electrode arrangement, hydrostatic pressure and the physio-chemical properties of the liquid [10].

However, the understanding of streamers in transformer oil has not been fully achieved yet, especially in the fast event phase and in large gaps. In addition, the branching mechanism of streamers is still unknown as well as their nature and physical mechanisms in fast modes. Therefore, it is necessary to investigate the streamer in varying composition of mineral oil.

In this study, streamers in one model oil of paraffinic type, Exxsol D140, were studied. The effect of voltage amplitude, polarity, filtration and degassing were investigated. In addition, the influence of a low ionization potential additive, N,N-Dimethyl aniline (DMA), was also investigated.

II. EXPERIMENTAL SETUP AND PROCEDURE

A. Experimental Setup

Fig. 1 shows the experimental setup. The test cell is a transparent borosilicate vessel containing the point-plane electrode system. The plane electrode was connected to ground and the point electrode to the Marx generator. A 76 Ω resistor was placed in series with the test cell to dampen oscillations and limit the breakdown current.

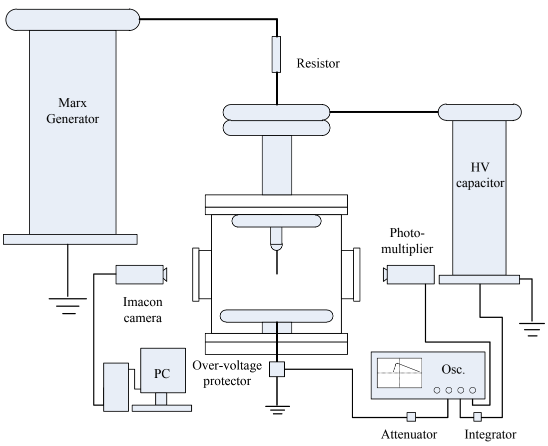

Figure 1. Experimental setup

The voltage across the test cell was measured by a high voltage capacitor combined with an integrator. An overvoltage protector connected with attenuators was used when measuring the streamer current. Still and streak images were recorded by an IMACON image converter camera. Light pulses are monitored with a photomultiplier. All signals were displayed on the screen of high bandwidth oscilloscope Tektronix DPO4104.

The tungsten point electrode is 0.15 mm in diameter, and 340 mm is the diameter of the aluminum plane electrode. Before experiments were carried out, the point electrode was conditioned with some ten shots of breakdown to remove edge effects. After this treatment, the point's tip resembles a hemisphere. All experiments were performed with an electrode gap of 80 mm.

The "step voltages" were short rise time (0.5 μs) impulses with long time to half value (1700 μs). Studies with both voltage polarities were performed.

B. Experimental Procedure

For investigating the effect of carbon particles on the inception voltage, the first oil sample was contaminated with 20 breakdowns prior to experiment, and the second oil sample was filtered in air.

To examine the influence of carbon particles on breakdown voltage and streamer propagation, oil was not cleaned during experiment. However, the impact of dissolved air was examined by filtering the oil either under vacuum or in air after 10 shots. When filtering in air, the oil will be circulated from the test cell to a filter (hole's size = 0.2 μm) through a pump and back to the test cell again. When filtering under vacuum, the oil will be sucked from the test cell to vacuum chamber and then forced to the test cell via the filter by the pump. Without filtering, the oil will contain 6.9×10^6 particles/100 ml with dominant particles of size 5 - 10 μm and air. However, filtered oil just shows 1.03×10^5 particles/100 ml with dominant particles within the size range 1 - 3 μm. Filtering under vacuum will remove carbon particles and degas the oil while filtering in air only removes carbon particles and will mix in some air including O_2, which is electronegative and has a large impact on gas discharges.

To investigate the influence of DMA on streamers in the oil, DMA was mixed into Exxsol to a mole concentration of 0.064M.

In order to determine inception and breakdown voltage, the voltage was increased in 5 kV steps and there were 10 shots per voltage level. All recorded data was analyzed with Weibull distribution. For measuring stopping length and velocity, voltage was increased in 30 kV steps with 10 repetitive shots at each step.

III. Results and Discussion

A. Streamer inception voltage

Fig. 2 shows the onset of streamers versus applied voltage. The probability increases rather steeply with the voltage. After removing carbon particles in the oil, streamers initiate at higher voltage under both positive and negative polarities. With carbon particles and dissolved air present, the negative inception voltage is reduced 9.9 kV, and the positive inception voltage is also decreased 32 kV. Moreover, there is a change on the effect of polarity on the inception voltage. With carbon particles and dissolved air present, the negative inception voltage is 7.5 kV lower than the positive inception voltage. On the other hand, when the oil is filtered in air, the negative inception voltage is 14.6 kV higher than the positive inception voltage. It is clear that carbon particles have a strong effect on streamer initiation. Because the number of particles (size range ≥ 1 μm) per 100 ml in the carbon particles polluted oil (6.05×10^5) is approximate six times higher than that in filtered oil (1.03×10^5), possibly a better condition for ionization is created, so streamers will initiate at lower voltage. The 50% probability of inception voltage is shown in table 1.

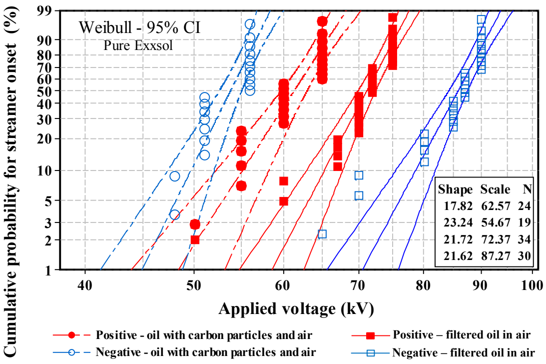

Figure 2. Streamer onset versus applied voltage

TABLE 1. 50% PROBABILITY INCEPTION VOLTAGE

Type of oil	Polarity	
	Positive	***Negative***
With carbon particles and air	61.3 kV	53.8 kV
Filtered oil in air	71.2 kV	85.8 kV

B. Inception Delay Time

Using shadowgraphic imaging, it was found that streamers appear with time delay from the voltage onset. Initiation of streamers in the size range of 0.5 - 1 mm was detected with 100 ns interval frame images. The average inception delay time, t_i, vs. voltage with both positive and negative polarity is shown in fig. 3. It is clear that t_i decreases with applied voltage, and eventually streamers will appear during the rise time of the impulse voltage. This result is qualitatively similar to mineral transformer oil [11]. For positive polarity, t_i decreases from about 2 µs to 0.1 µs as voltage is increased. In the negative polarity case, t_i drops from about 10 µs to 0.3 µs. Altogether, the negative inception delay time is more voltage sensitive than the positive one, and the inception delay time is polarity dependent. At low voltage, there is a large difference in t_i between voltage polarities. However, when the voltage is over 500 kV, there is no significant polarity effect. The effect of dissolved air is also investigated. In fig. 3, it is seen that the dissolved air has little impact on t_i at low voltage and no influence as the voltage is above 300 kV. The inception delay time can be fitted to an inverse power function, see (1) and (2). The time t_i is expressed in µs and V in kV.

Positive polarity for oil filtered in air:

$$t_i = 111.96V^{-1.028} \tag{1}$$

Negative polarity for oil filtered in air:

$$t_i = 3003.1V^{-1.453} \tag{2}$$

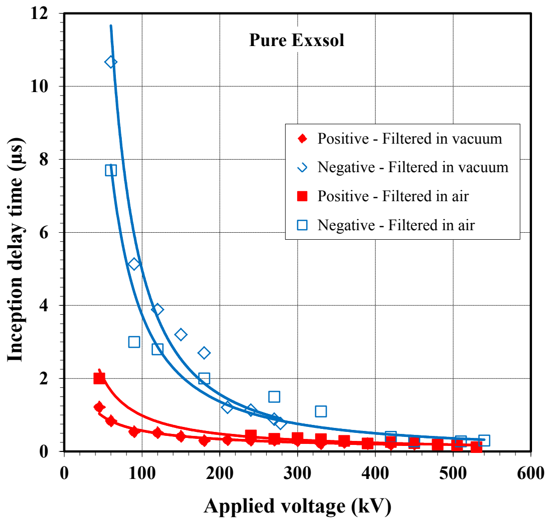

Figure 3. Average inception delay time correlated applied voltage

C. Breakdown Voltage

Fig. 4 and fig. 5 show the breakdown probability of oil under influence of filtration types and DMA for positive and negative polarities respectively. The breakdown voltage V_b is defined for a breakdown probability of 50%.

As seen from these figures, both carbon particles and air greatly reduce the breakdown voltage. However, carbon particles have a much stronger effect than air. The value of breakdown voltage V_b is shown in table 2. Breakdown voltages in Exxsol is similar to that in mineral transformer oil for both polarities [3, 12].

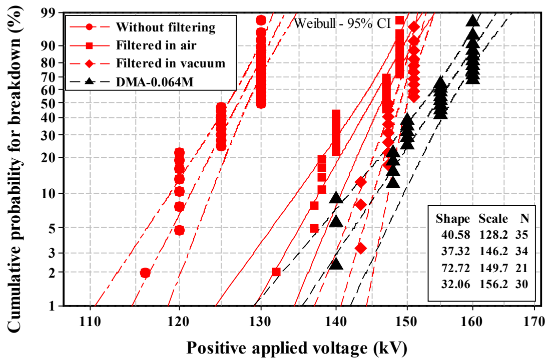

Figure 4. Positive breakdown probability

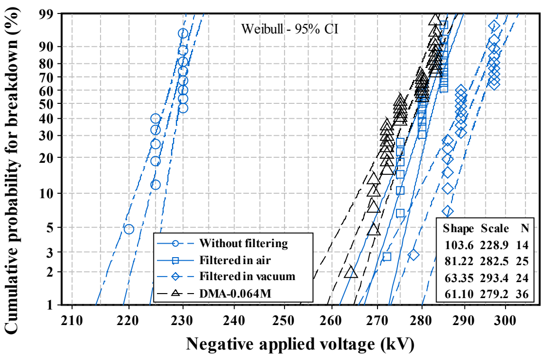

Figure 5. Negative breakdown probability

TABLE 2. 50% PROBABILITY BREAKDOWN VOLTAGE

Type of oil	Polarity	
	Positive	*Negative*
Without filtering	127.1 kV	228.1 kV
Filtered in air	144.7 kV	281.2 kV
Filtered in vacuum	149 kV	291.7 kV
DMA	154.4 kV	277.5 kV

When adding DMA, breakdown voltage increases 9.7 kV (6.7%) for positive streamers, but reduces 3.7 kV (1.3%) for negative streamers. The reason is that DMA has a lower ionization potential (7.14 eV) compared to Exxsol (paraffinic molecule ≈10 eV) [1, 13]. DMA will be easier to ionize, so it makes streamers branch more. For positive polarity, streamers get more branches at the needle tip as seen in fig. 6 (radial shape), and this will reduce the velocity leading to increase breakdown voltage. Under negative polarity, streamers will switch from a bushlike to a treelike shape as shown in fig. 6. This leads to higher velocity and lower breakdown voltage.

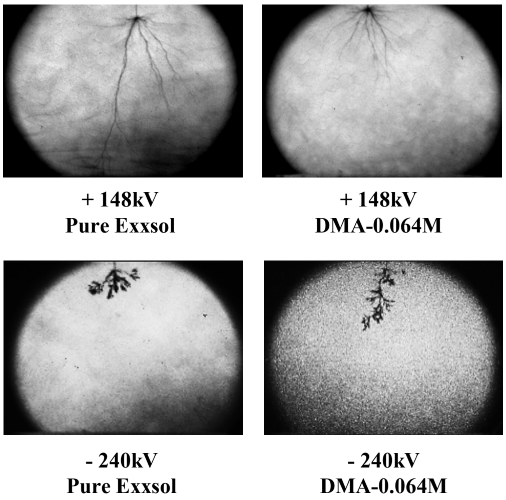

Figure 6. Effect of DMA on branching

D. *Stopping Time and Breakdown Time*

Stopping time and breakdown time versus voltage is shown in fig. 7. Streamer stopping time increases as voltage increases. When filtering the oil in air, the positive stopping time rises from 15 µs to 41 µs while the negative stopping time will go up from 18 µs to 178 µs. When breakdown occurs, the time to breakdown will be reduced with further increasing voltage. Breakdown time consists of a long time group for slow modes and a short time group for fast modes [2]. It is considerably longer for negative polarity than for positive polarity. At first, it reduces quickly from 40 µs to 16 µs, and then suddenly falls down to 1.6 µs at 240 kV before gradually decreasing to 0.7 µs at 530 kV under positive polarity. For negative polarity, times to breakdown are higher but show a similar trend. It reduces from 136 µs to 51.4 µs, and then suddenly drops to 7.5 µs at 420 kV before slightly decreasing to 3.5 µs at 540 kV. The reason is that streamers switch from slow mode to fast mode at V_a = 240 kV and 420 kV for positive and negative polarities respectively, where the "acceleration voltage" V_a is defined as the voltage where the short time group starts to appear.

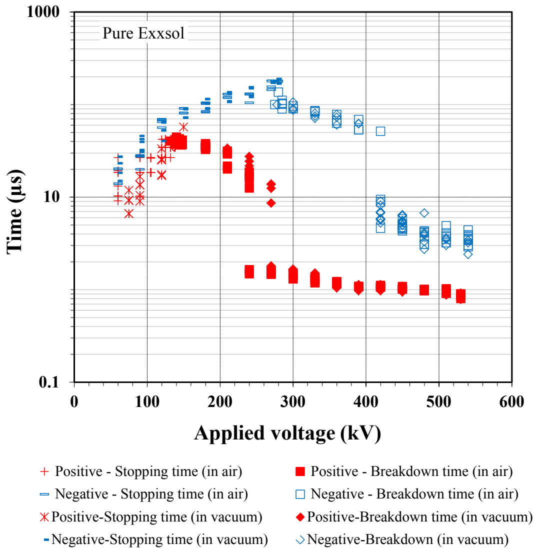

Figure 7. Stopping time and breakdown time versus applied voltage

When filtering the oil under vacuum, stopping time and breakdown time have similar characteristics to those for filtering the oil in air, and the values just slightly vary for positive polarity. It means that dissolved air has a slight influence on these times for positive polarity, and has no effect on them for negative polarity.

E. *Stopping Length*

Fig. 8 shows the average stopping length, L, versus applied voltage for both polarities. For positive streamers, L increases with the rate (expressed as the inverse of the $L(V)$ plot slope) of about 12 kV/cm. This rate is approximately 2/3 of the value 20 kV/cm reported for mineral transformer oil [3, 5]. For negative streamers, the shape of the $L(V)$ curves can be roughly decomposed in two parts: at low voltage the rate of increase is about 130 kV/cm. Above a critical voltage of about 200 kV, the streamer length increases 10 times faster with applied voltage at the rate of about 13 kV/cm.

From fig. 8, we can also see that carbon particles and dissolved air have an insignificant effect on the stopping length of positive streamers. However, it is not the case for negative streamers. For them, average stopping length is strongly affected by carbon particles, and little affected by dissolved air. Equation (3) and (4) are fits of the stopping length. L is expressed in mm and V in kV

Positive polarity for oil filtered in air:

$$L = 0.0045V^2 - 0.0119V - 11.318 \qquad (3)$$

Negative polarity for oil filtered in air:

$$L = 0.4766e^{0.017V} \quad (4)$$

Fig. 9 shows the influence of DMA on the stopping length. From this figure, it is seen that DMA reduces the stopping length for positive streamers, and slightly increases it for negative streamers. The change of the stopping length seen for both streamers can be related to DMA's effect on branching.

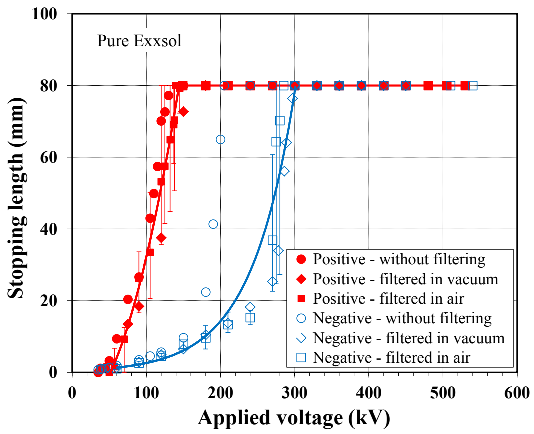

Figure 8. Average stopping length versus applied voltage

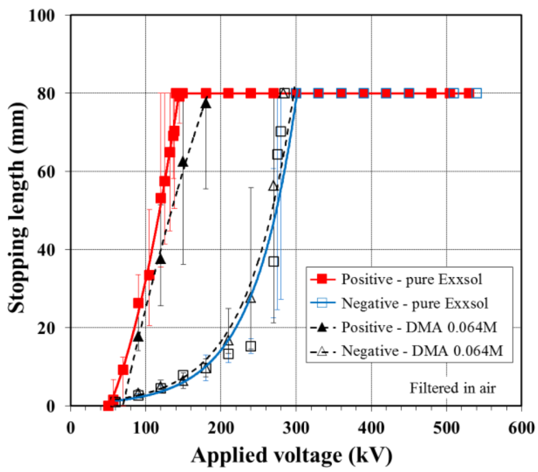

Figure 9. Effect of DMA on stopping length

F. Velocity

The average velocity versus applied voltage is illustrated in fig. 10. Below the breakdown voltage V_b, the velocity is calculated from the measured stopping length and the corresponding propagation time. Above V_b, the velocity is found by dividing the gap distance by the breakdown time.

In general, streamer velocity will rise as the applied voltage increases. For positive streamers, the average velocity measured at breakdown voltage, V_b, is about 2 km/s. From V_b to V_a, the velocity increases slightly. A very steep acceleration is observed at V_a, and velocity reaches a value of higher than 100 km/s as the applied voltage exceeds 500 kV. However, at V_a, the velocity is just around 3 - 4 km/s. V_a is about 1.7 times V_b.

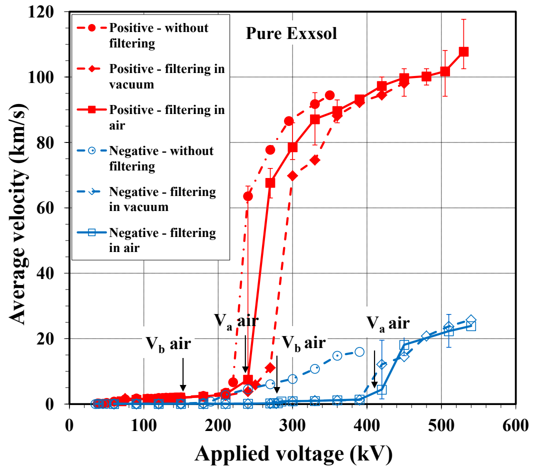

Figure 10. Average velocity correlated applied voltage

In case of negative streamers, below V_a, the velocity is about 100 - 200 m/s. Above V_a, the velocity increases quite rapidly, and reaches a value of approximately 25 km/s as applied voltage reaches 540 kV. Similar to the positive case, V_a is about 1.5 times V_b. It is clear that positive streamers are much faster than negative streamers, and the ratio is about 4 in fast mode when applied voltage is over 500 kV.

Types of oil filtration show different effects on velocity as voltage increases. At voltage below 200 kV, type of oil filtration has no effect on velocity. It means that at slow modes, carbon particles and dissolved air do not affect velocity. For positive polarity, above 200 kV, i.e. fast modes, both carbon particles and dissolved air strongly increase velocity. However, air has only little influence on velocity as applied voltage is higher than about 360 kV. For negative polarity, above approximately 200 kV, velocity is only affected by carbon particles.

Fig. 11 illustrates the effect of DMA on average velocity. DMA causes acceleration voltage to increase 60 kV and strongly reduces velocity for positive streamers, especially in the fast modes. It is different from the velocity development observed in Marcol and n-Hexane, but similar in acceleration voltage to Cyclohexane [1, 7, 8]. In contrast, V_a decreases 40 kV and velocity slightly increases in case of negative streamers. It is different from the n-Hexane case. In n-Hexane, DMA has no effect on negative streamers [8]. Again, the reason is the effect of branching for positive streamers, and branching reduction for negative ones as exhibited in fig. 12.

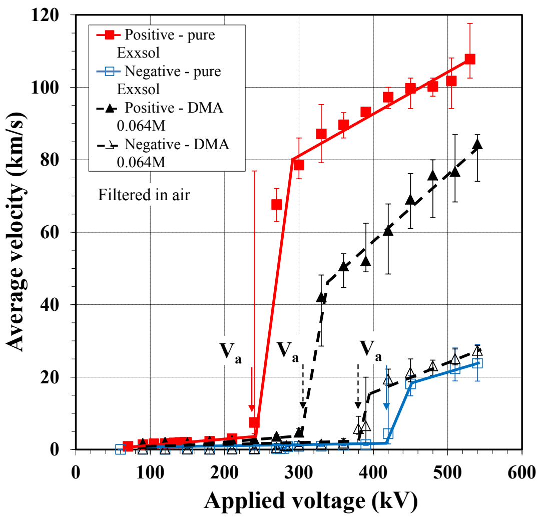

Figure 11. Effect of DMA on velocity

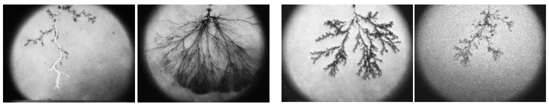

Figure 12. Effect of DMA on streamer shape

G. *Streamer Shape*

Typical shapes of streamers in Exxsol are shown in fig. 13 and fig. 14. In these figures, streamer shapes are voltage and polarity dependent.

Fig. 15 presents the streamer's area and average velocity versus applied voltage for pure Exxsol filtered in air. For positive streamers, area increases quickly from 72 mm^2 at 90 kV (fig. 13A) to the peak of 746 mm^2 at 210 kV (fig. 13B), and then drops drastically to 238 mm^2 at 270 kV (fig. 13C) before rising again to reach 1233 mm^2 at 540 kV (fig. 13D). It is clear that below V_a (V_a = 240 kV), streamers have multi-filamentary shape and the number of branches increases as voltage rises, so its velocity just gradually increases. Just above V_a, streamer's shape switches from multi-filamentary to tree-like form and thus the area reduces 3 times. This will make the streamer 20 times faster. Further increasing voltage above V_a, streamers start to branch again to get spherical shape, hence the area goes up fast and the rate of speed increase will be reduced.

For negative streamers, a similar trend is exhibited. However, the peak value for negative streamers is approximately twice that of positive. Therefore, negative streamers are slower than positive streamers. Although, in some ranges, the positive area is larger than the negative, positive streamers are still faster than negative streamers, especially, for voltages above 400 kV. These area curves show a similar trend as charge curves of streamers in mineral transformer oil [3, 6].

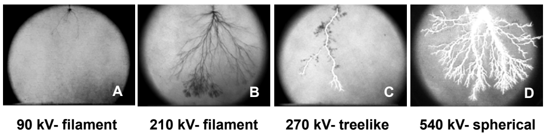

Figure 13. Positive streamer shape

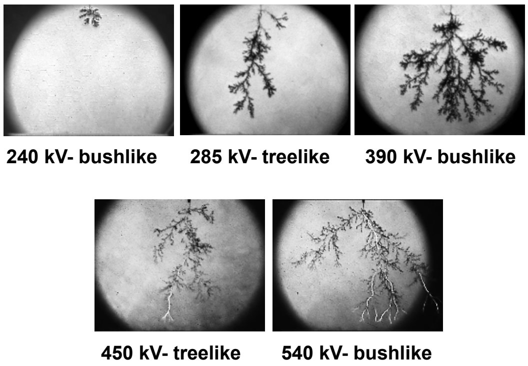

Figure 14. Negative streamer shape

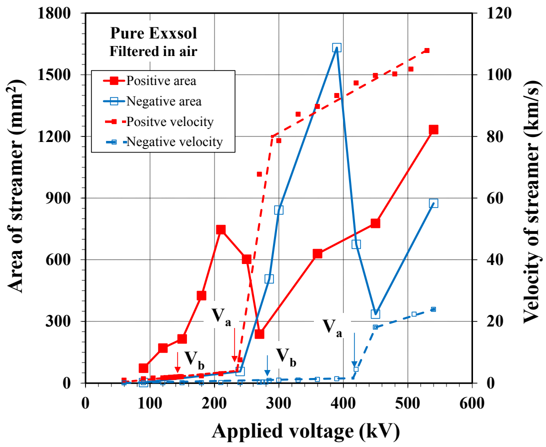

Figure 15. Streamer's area versus applied voltage

IV. CONCLUSIONS

Basic research on streamers in paraffinic oil has been carried out with the following main findings:

Carbon particles have a strong effect on streamers such as reducing inception, breakdown and accelerating voltage, increasing stopping length and velocity, especially for negative polarity. On the other hand, dissolved air has less influence on both polarities of streamers.

Streamers occur after an inception delay time, and they can appear during the rise time.

Streamer velocities show a jump at V_a and reach the values of 110 km/s and 25 km/s for positive and negative polarities in fast mode.

A streamer has to change its shape to accelerate. A positive streamer will change from multi-filamentary to treelike and end with spherical shape. Interestingly, negative streamers only switch between bushlike and treelike.

Low ionization potential additive increases breakdown voltage and acceleration voltage of positive streamers. This results from a decrease in velocity because of the additive's effect on branching. In contrast, it raises velocity in negative streamers because of branching reduction, so breakdown and acceleration voltage will decrease.

ACKNOWLEDGMENT

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Paper 2

Influence of Impurities and Additives on Positive Streamers in Paraffinic Model Oil

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Influence of Impurities and Additives on Positive Streamers in Paraffinic Model Oil

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ABSTRACT

This paper presents an experimental study of positive streamers in paraffinic model oil in a point-plane gap. The investigation was performed concerning the influence of voltage, impurities and additives. It was seen how increased voltage changes streamer shape and speed resulting in different propagation modes. Carbon particles markedly reduce inception, breakdown and acceleration voltages, while dissolved gases/air have little effect on these voltages. A low ionization potential additive decelerates the streamers, while an electron scavenger shows an increase in streamer velocity. The correlation between propagation velocity and streamer's branching is discussed.

Index Terms - **Streamer, initiation, breakdown, stopping length, velocity.**

1 INTRODUCTION

THE design of large oil/paper insulated transformers is based on more than a hundred year experience with the built-in voltage time characteristic of a liquid insulated system. The experience is that withstand voltages increased when changing stress from ac via switching impulse to lightning impulse (LI). During the last decennia, one has come to the conclusion that this increasing withstand voltage for short impulses stems from characteristic velocities for prebreakdown streamers. For moderate stresses these streamers grow at a limited velocity and will die out during the duration of a LI, and first at considerably increased stresses the velocities will sufficiently increase to cause breakdown [1, 2]. The fact that this voltage time characteristic is different for many of the new ester-based liquids - where the "streamer acceleration" occurs at much lower voltages - poses a challenge for the industry. One has to learn the behavior of these "new" liquids for different stresses and geometries, designs and tests have to be adapted. This study sets out to - via breakdown studies in model liquid - to reveal the electrochemical properties, the processes and the mechanisms that govern the V-T curve of an insulating liquid.

It is observed that the V-T curves are liquid dependent. The existence and behavior of fast event

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is one reason for this. The high acceleration voltage, at which the fast event appears, for mineral oils is possibly related to aromatic compounds. Therefore, Exxsol oil is a candidate of low aromatic model liquids. Many earlier studies on positive streamers in mineral oils, esters, and additives have been performed. However, studies on influences of additives on the fast event in long gaps are lacking. This will limit the identification of reasons for the good V-T properties of mineral oils.

The initiation and propagation of streamers in mineral oil as well as in hydrocarbon liquids have been studied by many researchers for many years [3-6]. In small gaps, streamer propagation is independent of dissolved gases [7]. In 2nd mode, carbon particles and other particles have an insignificant effect on streamers [8]. In [9], Chadband et al reported that N,N-Dimethyl aniline, a low ionization potential additive, had a significant effect on the growth of positive streamers, while Carbon tetrachloride, an electron scavenger, slightly influenced the growth. Besides, low ionization potential additives accelerate positive streamers, while electron scavengers only speed up negative streamers [10-12]. On the other hand, it has been found that N,N- Dimethyl aniline reduced the velocity of positive streamers and increased the breakdown voltage [13], and that Carbon tetrachloride increases the velocity of the positive streamers [14].

However, the effects of carbon particles and dissolved gases as well as of additives on positive streamers in fast modes in long gap in compositions of mineral oil as well as in other hydrocarbon liquids have not been elucidated yet.

In this paper, we will lean on streamer mode definition in [15, 16], in which positive streamers were classified into 1st, 2nd, 3rd and 4th modes according to the measured propagation velocities. The characteristics of positive streamers in paraffinic model oil, Exxsol D140, containing 99.4% paraffinic molecules and less than 0.6% aromatic molecules by weight were studied. The role of impurities comprising carbon particles and dissolved gases including air (dissolved gases/air) was also investigated. Another important part of this study was concerned with the influence of a low ionization potential (IP) additive, N,N- Dimethyl aniline (DMA), and of an electron scavenger, Trichloroethylene (TCE), on positive streamers because these additives can modify the streamer branching properties and thus vary velocity as well as breakdown voltage and acceleration voltage.

2 EXPERIMENT

2.1 EXPERIMENTAL SETUP

The experimental setup used in this work is shown in Figure 1. A point-plane electrode system, constituted of a high voltage tungsten wire (0.15 mm in diameter) facing a grounded plane (340 mm in diameter), is located in an insulated test cell. All experiments were performed with an electrode gap of 80 mm. A six-stage Marx generator was used to provide a positive step voltage with 0.5 µs rise time and 1700 µs time to half value. A 76 Ω resistor was placed in series with the test cell to dampen oscillations and limit the breakdown current. To remove edge effects the point electrode was initially conditioned with ten breakdowns. After this treatment, the point's tip resembles a hemisphere (0.18 mm in diameter) when observed under a microscope. Then the treated point electrode was used to run an experiment to determine inception, breakdown and acceleration voltages. When changing oil sample, the same procedure for treating the point electrode was repeated. So the tip of the point electrode is similar in radius among experiments with different oil samples.

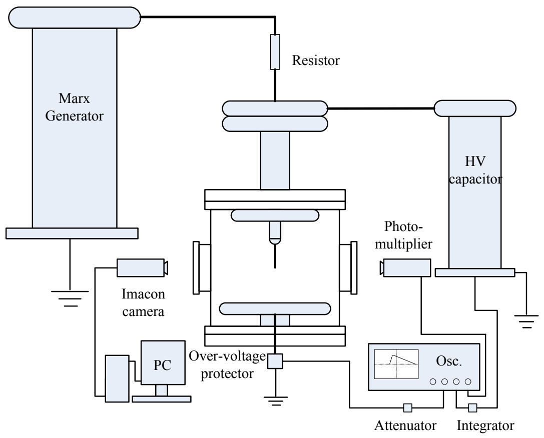


Figure 1. Experimental setup.

The positive step voltage was measured at the high voltage side of the test cell via a capacitor combined with an integrator giving good step response and slow decay. An overvoltage protector connected with attenuators was used when measuring the streamer current at the low voltage side of the test cell. Still and streak images were photographed by an IMACON 468 image type converter camera. A photomultiplier was placed close to a window of the cell to record light emission pulses. All signals were displayed on the screen of a high bandwidth oscilloscope Tektronix DPO4104.

2.2 PROCEDURE

There are two types of oil samples used in this study called the cleaned and the contaminated oils. The cleaned oil was formed by conditioning the new high purity oil taken from the drum by 10 shots resulting in breakdown. Then the oil was filtered in air for 30 minutes through a cleaning system consisting of a filter with pore's size of 0.2 µm. This particular treatment is to maintain the similar condition, i.e. carbon particles and dissolved gases/air, of oil for non-breakdown and breakdown experiments. The contaminated oil sample was formed by applying 20 shots resulting in breakdown to the cleaned oil sample prior to experiment. After these above treatments, both oil samples contain carbon particles and dissolved gases/air.

To investigate the effect of carbon particles on streamers, the contaminated oil sample was used. During this investigation, the oil was not filtered, so the carbon particles will increase during the experiment. After finishing this experiment, the particle content in oil was measured and compared with the cleaned and the contaminated oil samples. The particle content was determined by a particle counter SBSS-C following the ISO 4406 and NAS 1638 classes. The distribution of particle sizes is shown in Figure 2. Most of the particles are in the 1-4 µm size range. The total numbers of particles per 100 ml are 1.03×10^5, 6.05×10^5 and 33×10^5 for cleaned, contaminated and after investigation oil samples, respectively.

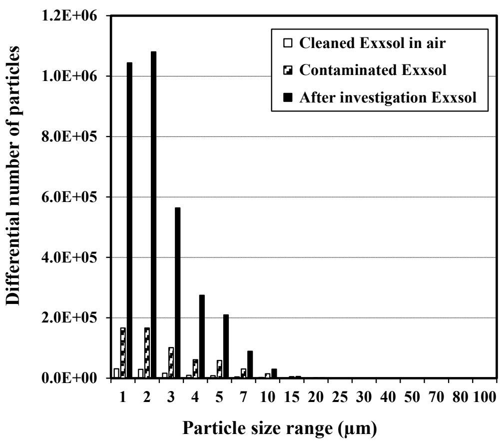


Figure 2. Particle size distribution.

The impact of dissolved gases/air was examined with the cleaned oil. The oil was filtered either under vacuum or in air through the cleaning system after 10 shots for 30 minutes. Filtering under vacuum will remove carbon particles and degas the oil while filtering in air only removes carbon particles and will mix in some air.

To investigate the influence of additives on streamers, DMA was mixed into the cleaned oil to a concentration of 0.064M, i.e. mol/l, while 0.064M and 0.128M are the concentrations of TCE. The oil was filtered in air after every 10 shots for 30 minutes. The reason is that when using DMA and TCE, degassing was not used in order to avoid depletion of these additives.

The experiment sequence consisted of four stages. The voltage was increased in different steps depending on the stage. Initiation phase was with 5 kV/step. From initiation to breakdown, the voltage was increased with 10 - 30 kV/step. During breakdown phase, 5 kV/step was used again, and finally 30 kV/step was used for propagation phase. Ten repetitive shots at each step were applied for all stages. All data of initiation and breakdown phases were analyzed with Weibull distribution. The expression for the cumulative distribution function for two parameter Weibull distribution is shown in (1). Here V_0 and β are the scale and shape parameters, and V is the peak voltage.

$$F(V) = 1 - exp\left[-\left(\frac{V}{V_0}\right)^{\beta}\right] \quad (1)$$

3 RESULTS

3.1 INCEPTION VOLTAGE

The onset of streamers was determined by using shadowgraphic imaging. Streamers in the minimum size range of approximately 1 mm were detected by 100 ns interval frame images, so the appearance of streamers within this size range was considered as streamer onset. Ten shots were applied at each voltage step and the number of streamer onsets was counted. We acknowledge that sizes of onset streamers can be smaller. Because the same magnification was kept between initiation and propagation phases, streamers whose sizes are smaller than 1 mm cannot be detected by our camera. Moreover, our current and light emission measurement systems are not sensitive enough to detect such streamers.

Figure 3 shows the influence of carbon particles on streamer initiation. Carbon particles possibly reduce inception voltage because a number of particles increase about 6× from 1.03×10^5 to 6.05×10^5 as seen in Figure 2. It means that these particles create a better condition for streamer initiation. After contacting with the needle electrode, the carbon particles will become positively charged. Because of the much smaller size of carbon particles than of the needle, the field around this particle will enhance greatly.

Therefore, this phenomenon may decrease the inception voltage. However, the lowest inception voltage measured for both cleaned and contaminated oil was 50 kV.

Additives affect the initiation of streamers as seen from Figure 4. DMA reduces inception voltage, but TCE increases it. A similar result was obtained when adding an electron scavenger, e.g. Carbon tetrachloride or Iodobenzene, into Tetraester [17]. The lower ionization potential of DMA (7.14 eV [10]) comparing to Exxsol oil, assumed to be approximately 10 eV, causes a reduction in the inception voltage. TCE, due to its electron scavenging property, will deplete the ionization process in oil and thus raise the inception voltage [10].

The 50% probability of inception voltage is shown in table 1. From this table, carbon particles show a stronger influence on streamer initiation than DMA and TCE.

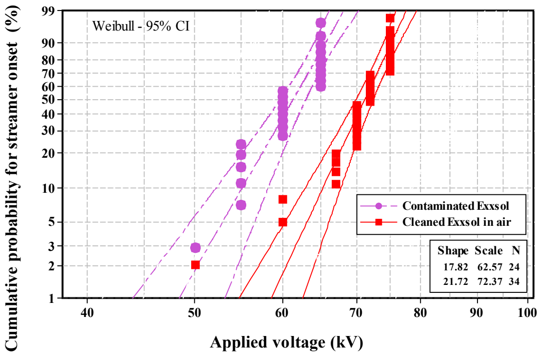


Figure 3. Effect of carbon particles on streamer initiation.

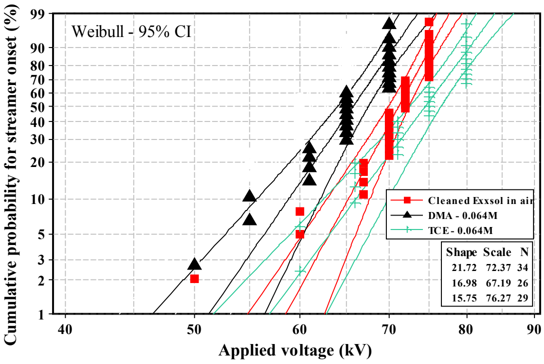


Figure 4. Streamer initiation under the influence of additives.

Table 1. 50% Probability Inception Voltage.

Types of oil	Value	Percentage compared to case (*)
Exxsol cleaned in air (*)	71.2 kV	100 %
Contaminated Exxsol	61.3 kV	86.1 %
DMA – 0.064M	65.8 kV	92.4 %
TCE – 0.064M	74.5 kV	104.6 %

3.2 BREAKDOWN VOLTAGE

The breakdown voltage, V_b, is defined as the applied voltage that yields 50% probability of breakdown. Figure 5 shows the influence of carbon particles and dissolved gases/air on breakdown voltage. Carbon particles greatly decrease V_b while dissolved gases/air just slightly reduces it. This is in agreement with what was reported in insulating oil [18]. Comparing with Figure 3, one can see that the smaller the inception voltage is, the lower the breakdown voltage. Similar to the inception voltage case (Figure 3) the breakdown voltage is approximately 14% lower for the contaminated compared to the cleaned oil.

It is clear that both DMA and TCE raise the breakdown voltage as seen in Figure 6. However, in some other liquids DMA reduces breakdown voltage and TCE has no effect [10, 12]. The effect of DMA is opposite to the decrease tendency in inception voltage. The reason is that the streamer is more branched at the streamer tips when DMA is added into Exxsol as seen in Figure 7. For TCE, again, its attribute of large electron trapping cross section will slow down the ionization process in oil. This results in a rise in breakdown voltage. The fact that electron scavengers increase the breakdown voltage was previously observed in [17].

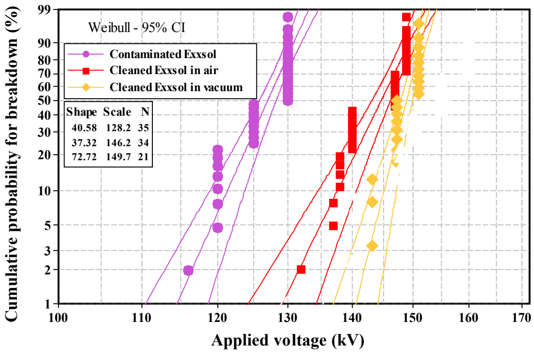


Figure 5. Effect of carbon particles and dissolve gases/air on breakdown voltage.

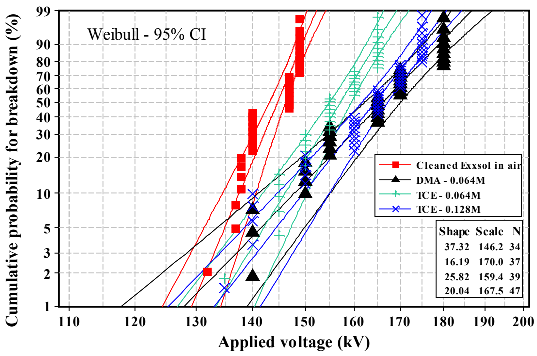
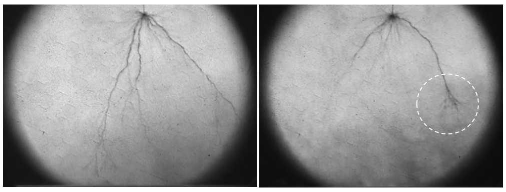


Figure 6. Effect of additives on breakdown voltage.



150 kV Cleaned Exxsol | 150 kV DMA - 0.064M

Figure 7. Effect of DMA on branching.

Table 2 shows the 50% probability of breakdown voltage. It can be seen that carbon particles and DMA show the strongest impact on breakdown voltage, while dissolved gases has the lowest influence. However, the effect of carbon particles on the breakdown voltage is opposite to that of DMA.

Table 2. 50% Probability Breakdown Voltage.

Types of oil	Value	Percentage compared to case (*)
Exxsol cleaned in air (*)	144.7 kV	100 %
Exxsol cleaned in vacuum	149.0 kV	103 %
Contaminated Exxsol	127.1 kV	87.8 %
DMA – 0.064M	166.2 kV	114.9 %
TCE – 0.064M	157.2 kV	108.6 %
TCE – 0.128M	161.4 kV	111.5 %

3.3 TIME TO BREAKDOWN

We next examine time to breakdown, t_{BD}, correlated to applied voltage as illustrated in Figure 8. In general, the time to breakdown decreases with increasing applied voltage. A sudden drop can be observed as voltage is increased beyond the acceleration voltage, V_a, and the streamers switch to fast mode from slow mode. Hence the time can be divided into two groups based on V_a. The short time group represents fast modes, and the long time group refers to slow modes. It is seen that the value of the short time group ranges from 0.5 to 2 μs and 10 - 40 μs for the long time group. Most likely, there is a change in propagation mechanisms between the two groups. In the short time group, DMA slightly increases the time while TCE reduces it a little.

3.4 STOPPING LENGTH

Figure 9 indicates that contaminated oil, containing both carbon particles and dissolved gases/air, causes the stopping length of non-breakdown streamers to increase. It means that these impurities form a better condition for streamer propagation. However, carbon particles show a stronger effect than dissolved gases/air as one should expect from the effect upon initiation and breakdown voltages. For all three cases, the rate of increase is approximately 11 kV/cm, which is about 3/5 of what it is in mineral oil [19].

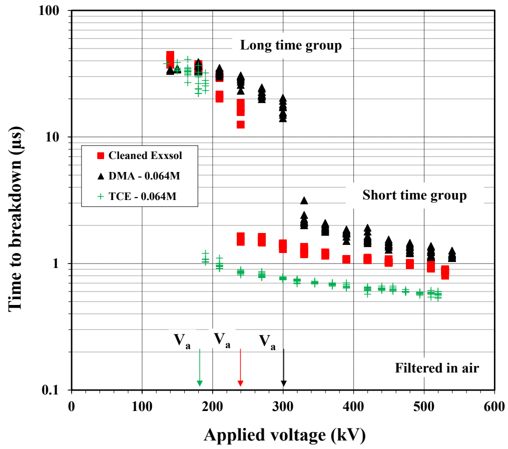


Figure 8. Effect of additives on time to breakdown.

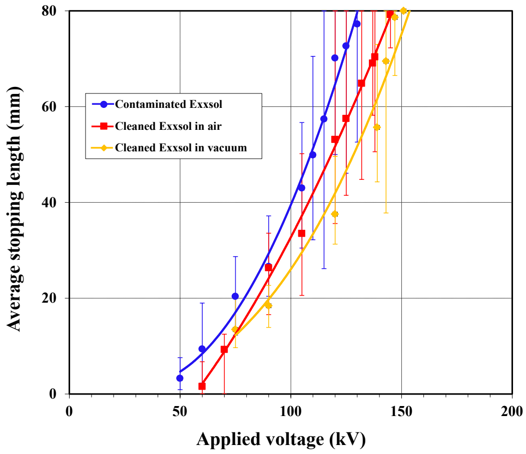


Figure 9. Influence of carbon particles and dissolved gases/air on stopping length. Non-breakdown streamers, all being 2[nd] mode.

In Figure 10, the stopping length for cleaned Exxsol increases quasi linearly with increasing applied voltage. With DMA and TCE added a slight non-linear relation is seen. The average rate of increase is 11 kV/cm, 16 kV/cm, and 13 kV/cm for cleaned Exxsol, DMA and TCE, respectively. It means that streamers find it harder to propagate with the presence of DMA. The stopping length has a large scatter from one shot to another, and the scattering increases when the applied voltage is increased.

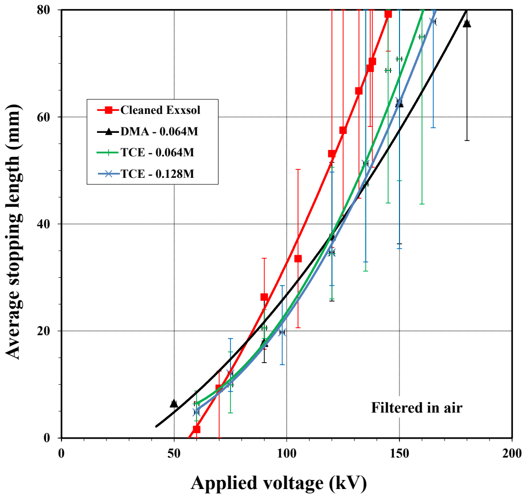


Figure 10. Influence of additives on stopping length. Non-breakdown streamers, all being 2nd mode.

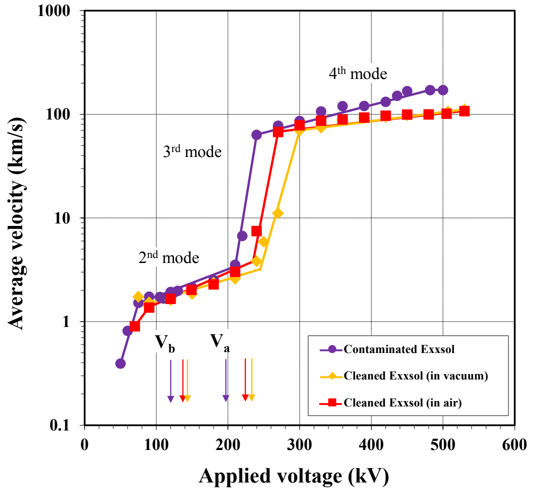


Figure 11. Influence of impurities on velocity.

3.5 VELOCITY

The average velocity increases in steps with increasing applied voltage as shown in Figures 11 and 12. Below V_b, the velocity is determined from stopping length and corresponding stopping time. Above V_b, it is calculated from the gap distance and breakdown time. It shows a jump when applied voltage is just higher than V_a, i.e. streamers change from slow mode to fast mode.

Carbon particles significantly increase streamer velocity leading to reduced V_b and V_a as seen in Figure 11. Dissolved gases/air also increase streamer velocity and thus decrease V_b and V_a. It means that streamers propagate faster with oil contaminated by carbon particles or dissolved gases/air. However carbon particles have a stronger effect on streamers than dissolved gases/air.

The streamer velocity is reduced, leading to increased V_a when DMA is added into cleaned Exxsol as seen in Figure 12. The reason is that DMA causes the streamers to branch more, i.e. creating mutual shielding effect among filaments as seen in Figure 13. This feature is similar to what was observed in cyclohexane [11, 12].

Contrary to previous results in Cyclohexane [12], TCE raises the streamer velocity and reduces the acceleration voltage V_a. This can be explained by the reduction of the number of branches as seen in Figure 13.

Moreover, while having little effect on the 2nd mode streamers, both carbon particles and additives, i.e. DMA and TCE, dramatically affect the streamers in 3rd and 4th modes. However, the reasons for these effects are unclear.

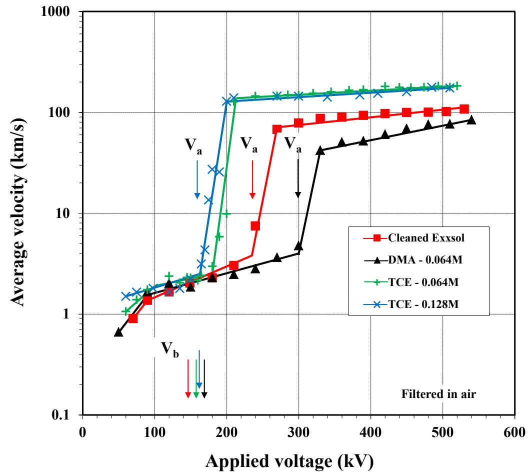


Figure 12. Influence of additives on velocity.

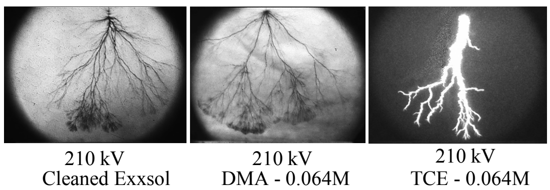


Figure 13. Effect of DMA and TCE on branching.

The ratio between V_a and V_b (given in table 2) is summarized in Table 3. It can be seen that carbon particles and dissolved gases/air have almost no effect on the ratio, but DMA and TCE greatly change the ratio. Amazingly, while DMA increases the ratio to 1.8, similar to that of mineral oil [2], TCE reduces this ratio to 1 at concentration of 0.128M. It means that streamers immediately accelerate when the applied voltage is just slightly above V_b. A possible explanation is that TCE neutralizes the property of low ionization potential of pre-existing aromatic content in Exxsol. The effect of DMA on the increase of the ratio V_a/V_b is in agreement with what was observed from the influence of pyrene in cyclohexane [11] because of an increase in aromatic content leading to more branching and thus the ratio V_a/V_b.

Table 3. Acceleration voltage and the ratio V_a/V_b.

Types of oil	V_a	V_a/V_b
Exxsol cleaned in air	240 kV	1.66
Exxsol cleaned in vacuum	245 kV	1.64
Contaminated Exxsol	210 kV	1.65
DMA – 0.064M	300 kV	1.8
TCE – 0.064M	180 kV	1.15
TCE – 0.128M	161 kV	1.0

Instantaneous velocity correlated to streamer growth is indicated in Figure 14. This velocity was calculated from framing image sequences. These velocity curves can be categorized into a slow mode group and a fast mode group. The slow mode group shows a minimum value of about 2 km/s in the 40-60% gap distance and is faster at approximately 3-10 km/s at both ends of velocity curves, i.e. near the electrodes. In contrast, there is no observation of a minimum range in the middle of the gap for the fast mode group except possibly at 270 kV. The reason is that with increased applied voltage, the time to breakdown is reduced. Eventually, the time will be approximately 1 µs or less as seen in Figure 8, and this means that at voltages above 300 kV, most of the streamer development takes place during the rise time of the impulse and thus under a continuously rising voltage leading to continuously increased instantaneous velocity. In this group, streamers start with some tens of kilometers per second and then their velocities increase continuously to reach a value of 100-200 km/s as streamers approach the plane electrode. Comparison between streamers at the higher voltage levels becomes somewhat difficult since one effect of increasing voltage level is simply to move the streamer initiation and development to an earlier part of the rising time. This figure does not show the instantaneous velocity from the 240 kV measurement because at this voltage, the velocity fluctuates between the slow and the fast mode groups.

3.6 SHAPES

Typical shapes correlated to modes of streamers in cleaned Exxsol are shown in Figure 15. These images were captured just before breakdown except Figure 15A, captured at stopping length. It is clear that shapes are voltage dependent. Streamers show multi-filamentary shape as applied voltage is lower than V_a (V_a = 240 kV), and the number of filaments will increase when raising the voltage as seen in Figure 15B. Just above V_a, e.g. 270 kV, streamers switch to treelike shape and a jump will be observed in the velocity as seen in Figure 17. When increasing applied voltage, streamers again start branching into spherical shape constituted from numerous bright branches as seen in Figure 15D.

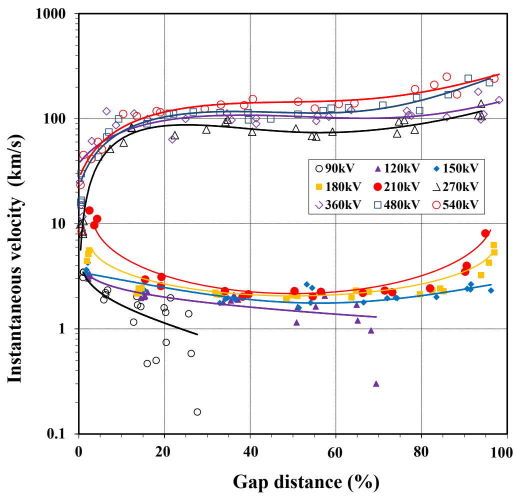


Figure 14. Instantaneous velocity versus streamer position. Cleaned Exxsol in air.

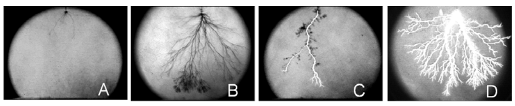


Figure 15. Typical streamer shapes.

The transition process from multi-filamentary (Figure 15B) to treelike shape (Figure 15C) of streamers with a sudden increase in the velocity can be seen in detail in Figure 16. First, streamers reduce to some main branches with numerous side-branches (240 kV). The side-branches decrease their length to some millimeters as the applied voltage is increased to 260 kV and their shortest length can be achieved at 270 kV, i.e. treelike shape.

Figure 17 shows the relationship between the streamer's apparent area mimicing the number of branches for both non breakdown and breakdown streamers and the velocity and applied voltage in cleaned Exxsol. The area of all streamer channels was measured by a program named ImageJ. The area increases quickly from 72 mm^2 at 90 kV to the peak of 746 mm^2 at 210 kV because of branching, so the velocity just gradually increases. Then it drops drastically to about 1/3 at 270 kV at the same time as the velocity increases 20 times. Further increasing voltage, the area continuously rises resulting from the branching of the fast streamer, leading to a reduced rate of speed increase. At 4th mode, e.g. 540 kV, although streamers get spherical in shape composed of very luminous branches with very large area of 1233 mm^2, they still reach the very high velocity of around 110 km/s. It can be deduced that with luminous branches, streamers channels are more conducting, being responsible for higher electric field at the streamer tip. This results in stronger ionization process and streamers will propagate with higher velocity. This area curve shows a similar tendency to the charge curve reported in mineral oil [2].

3.7 STREAMER PROPAGATION

The propagation of streamers in cleaned Exxsol can be described with streak images and associated oscilloscope traces of voltage, light emission and current pulses.

Below V_b, streamer starts and terminates with continuous luminosity in the 2nd mode as shown in Figure 18. From previous studies on other liquids, streamer's charge continuously increases during propagation time until streamers die out [20]. It can be deduced that streamers are in continuous propagation.

Up to the acceleration voltage, V_a, the 2nd mode is the only one recorded as seen in Figure 19. The streamer starts with weakly continuous luminosity during most of the propagation, and then fast flashes in the channels, i.e. reilluminations, occur just before breakdown. Corresponding to reilluminations, light emission and current pulses are recorded. However, there is no light and current observed during the non-reillumination phase. This is due to the low sensitivity of photomultiplier set to avoid over-exposure during reilluminations, and similarly low sensitivity of current measurement system. The first current pulse is the displacement current charging up the system because of the capacitance of the point-plane system.

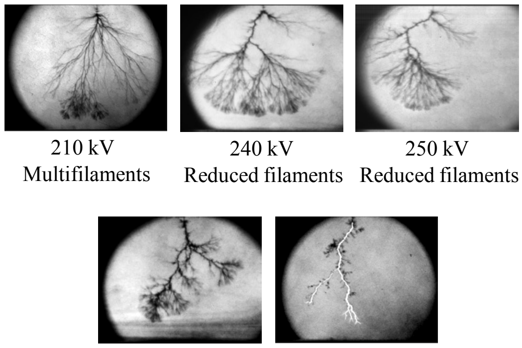


Figure 16. Transition process of shape.

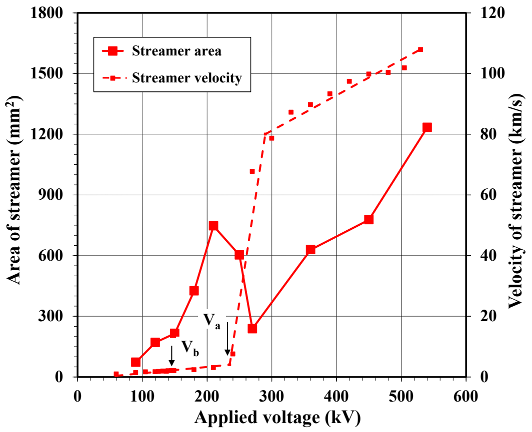


Figure 17. Streamer's area and velocity versus applied voltage. Cleaned Exxsol in air.

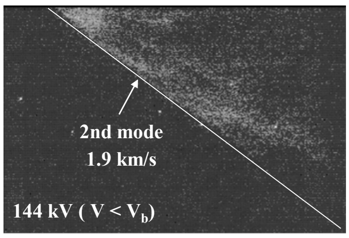


Figure 18. Typical streak image at V = 144 kV < V_b.

Just below V_a, a burst of reilluminations with similar length and high repetition rate appears at the onset of streamers, and some flash channels can be seen just before breakdown as shown in Figure 20. Streamers begins with 3rd mode and travel in 2nd mode.

At V_a, streamers also start with very luminous reillumination in 3rd mode and then propagate in 2nd mode. However, there is still a time of approximately 6 µs between two groups of reilluminations as seen in Figure 21.

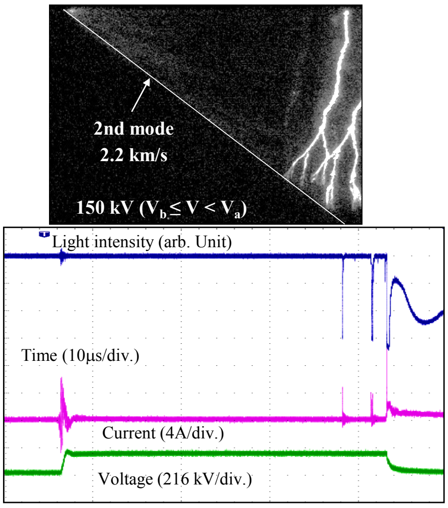


Figure 19. Typical streak image at V = 150 kV < V_a and corresponding signals.

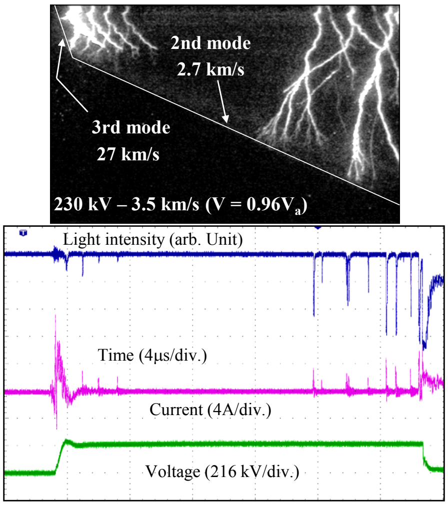


Figure 20. Typical streak image at V = 230 kV ≲ V_a and corresponding signals.

Just above V_a, reilluminations repeat after some µs during propagation time as shown in Figure 22. The streamer stem reilluminations are much more luminous than its head. This is in agreement with what was seen in mineral oil [19]. Streamers start and move in the 3[rd] mode with onset velocity being 12 times higher than propagation velocity. Because the over-voltage protection on the current measurement operates as applied voltage is over 240 kV, the second current pulse is suppressed and the values of consecutive pulses are reduced.

As the voltage is further increased above V_a, only high continuous luminosity was recorded in streak photographs (Figure 23). It can be stated that the streamer is in continuous movement. During propagation, streamer exhibits 4[th] mode despite beginning with 3[rd] mode as seen in Figure 14.

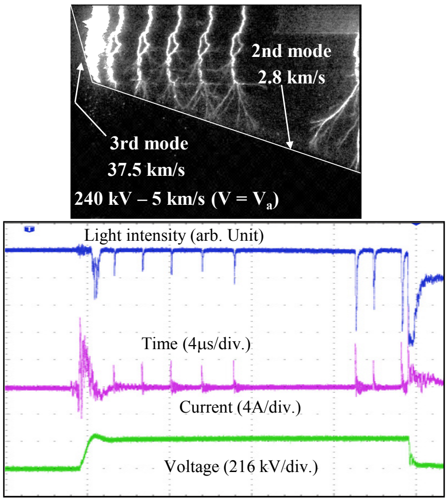


Figure 21. Typical streak image at V = 240 kV = V_a and corresponding signals.

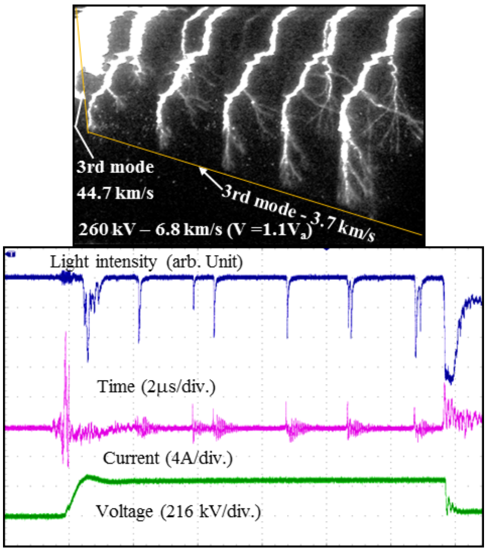


Figure 22. Typical streak image at V = 260 kV ≳ V_a and corresponding signals.

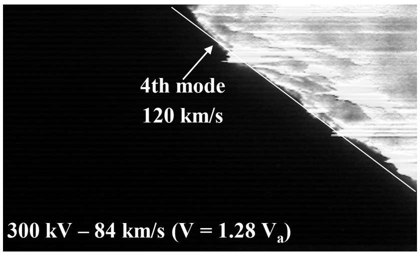


Figure 23. Typical streak image at V = 300 kV > V_a.

Although there are no light and current pulses detected between reilluminations, weak continuous glow can be observed (Figures 19-22). In addition, it is hard to detect the background luminosity and small pulses between reilluminations, which are easily observed in mineral oil [2, 4], even though the sensitivity of the photo-multiplier was adjusted to maximum value as shown in Figure 24. Other authors believe that streamers possibly propagate in step throughout reillumination phase since no current or light pulses are found in between [21-23]. However, this may be a sensitivity problem. It is difficult to determine whether streamer propagation is continuous or stepwise during this phase because saturation of measured signals during reilluminations must be avoided.

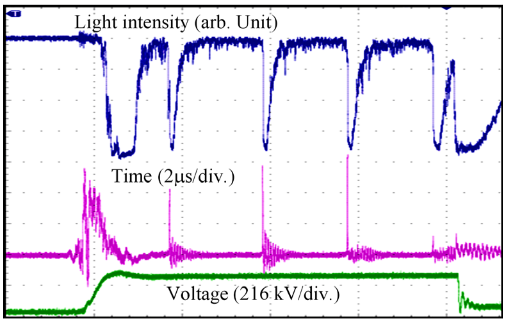


Figure 24. Light emission signals at 260 kV. Maximum sensitivity.

The development of reillumination appearance when increasing voltage is monitored by the light emission trace as schematized in Figure 25. At first, they occur only slightly before breakdown (Figure 25A), and then their numbers rise as the start of reilluminations move towards voltage onset point as seen in Figure 25B. With further increasing voltage, they are present at both points (Figure 25C). Eventually, with high enough voltage, they repeat fairly periodically (Figure 25E) during development before turning into only continuous flash as seen in figure 25F. The nature of reilluminations and their repetition were explained qualitatively in the papers [2, 4]. However, these explanations are not in agreement with each other.

The number of reilluminations varies as the applied voltage is increased as shown in Figure 26. It begins with zero and rises quickly to reach the peak of 12 just below V_a before falling down to one. Simultaneously, time between reilluminations gradually decreases except for peaking at 260 kV, and gets the value of approximately 1 - 2 μs in fast mode, i.e. 3rd mode. This suggests that below V_a, reilluminations easier repeat with increasing applied voltage, so the number of reilluminations will increase and the time will reduce. Just above V_a, t_{BD} greatly decreases with increasing applied voltage leading to lower number of reilluminations and increased time between reilluminations. Further higher than V_a, i.e. 270 kV, t_{BD} is about 1 μs as seen in Figure 8. It seems that repeating reilluminations require at least 1 μs intervals.

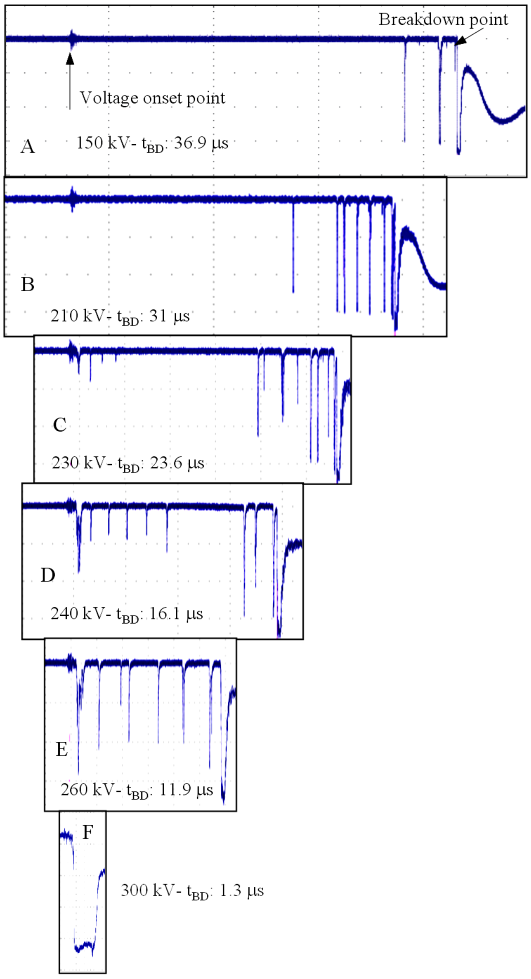


Figure 25. Typical sequence of reilluminations.

4 DISCUSSION

Massala et al [24] suggested that the streamer shape, determined by its tendency to subdivide and form branches, is a very important factor in establishing the macroscopic field of the envelope around the streamer tips. It means that an increase in branching will reduce the field and vice versa or one can say that the branching governs the macroscopic field. This hypothesis was shortly mentioned by Lundgaard et al [1, 25].

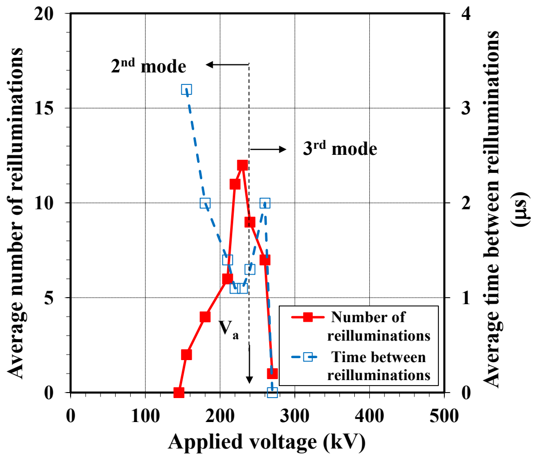


Figure 26. Number of reilluminations versus applied voltage. Cleaned Exxsol in air.

Moreover, the connection between the macroscopic field and the streamer tips will depend on the "density" of tips, the shape, and the voltage drop along the streamers.

It is generally accepted that branching increases with voltage amplitude except around V_a as one can see in this study (Figure 15) and elsewhere [2, 24]. The branching, correlating with an increase in streamer's apparent area, can appear in the 2nd mode as well as in the fast mode streamers (Figures 15 and 17). Branching can occur at the needle tip [11] and streamer tips as shown in Figure 13.

It is also observed that at certain voltages named acceleration voltage V_a the streamers may accelerate into faster modes as shown in Figure 11. When this occurs the streamer envelope shape changes from spherical to elongated (Figures 15B and 15C). This phenomenon is also recorded in cyclohexane [11, 12] and in mineral oil [2, 4]. In particular, the low IP additives will increase V_a because of the effect on branching as seen in Figures 12 and 13. This impact of additive was clearly observed in cyclohexane when varying the additive's concentration [11]

To explain the correlation between the tip field and the streamer propagation, the simple model for macroscopic field based on approximations with simple geometry, i.e. growing sphere, was proposed [1, 26]. In more detail, the field, calculated with spherical and cylindrical models, was compared between the 2nd mode and the fast modes in [24]. From these calculations, increasing sphere diameter, i.e. more branching, will reduce the tip field. The existence of the minimum field during propagation of the growing sphere in inter-electrode gap may provide an explanation for the lowest value of the instantaneous velocity observed in 2nd mode streamers in the present study as seen in Figure 14 and elsewhere [1, 26].

Streamer propagation is defined by conditions at the tip such as electric field, energy input into liquid, liquid state, temperature, etc. However, most of these conditions have not yet been verified with experiment.

As mentioned above, in 2nd mode the macroscopic field is strongly controlled by the branching because of the so called shielding effect among streamer branches, leading to quasi-constant velocity [24]. At 3rd mode, streamers have elongated shape comprising only one filament with numerous small ramifications (Figure 15C), so there is hardly any shielding and the field reduction at the tip is only a consequence of the voltage drop along the streamer channel. In mineral oil, this is about 1 kV/cm under similar conditions [24]. However in 4th mode at sufficiently high voltage above V_a, there is again considerable branching and thus shielding, resulting in a decrease in increase rate of velocity as applied voltage is increased. This can be observed in Figures 15D and 17.

The development process of streamers at 210 kV can be seen in Figure 27. Streamers first start with high speed (45 km/s) and almost no ramifications can be detected around the main filament. Then they reduce to lower speed (6.1 km/s) because of lower streamer field tip or the less favorable conditions at the main filament tip in general perhaps and many ramifications can be observed. The development of ramifications results in shielding effect. In turn, this effect will further decrease the speed as seen in Figures 27C and 27D.

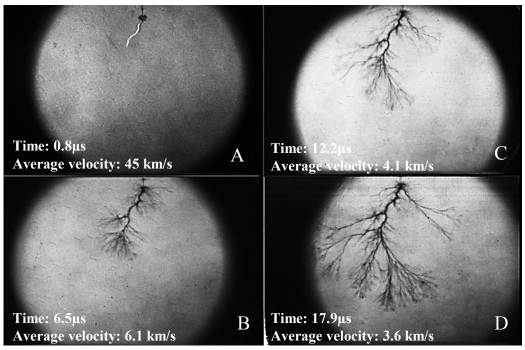


Figure 27. Streamer development at 210 kV. Cleaned Exxsol in air.

More observations of streamer development were done at 270 kV as seen in Figure 28. Streamers start and propagate with high speed of 48 km/s and about 75 km/s respectively.

Numerous ramifications exist around a unique filament, but most of them are unable to propagate and stop with short length.

From these above observations on correlation between velocity and the branching, we suggest that slow speed allows ramifications to grow. When the speed increases, the ramifications get less chance to develop because field drops behind streamer tip. This means that the ramifications are hindered and the macroscopic as well as the microscopic field increases in front of the dominating branch. Hence, the speed is further increased, i.e. auto-accelerated.

The validity of the hypothesis is tested for the 2nd mode streamers in presence of easily ionizable molecules. At low voltage these molecules ease inception and streamer propagation resulting in higher velocity. With increasing voltage the velocity becomes lower than in pure liquids due to shielding effect from branching at the needle tip as seen in Figure 12 and in [11]. In turn, lower-speed streamers will be more branched with longer and denser ramifications to form a spherical shape as one can see in Figure 13 and in [11, 12] or in detail in Figure 29. It is in accordance with the hypothesis. Logically, lack of low ionization molecules gives higher inception voltage and therefore higher speeds afterward and fewer ramifications, e.g. Figure 13 in the present study and in [11, 12].

Also note that at sufficiently high voltage, e.g. at 540 kV, the speed is high despite the increased branching, seen in Figures 14 and 15D, so the propagation mechanism must be assumed to be different or somehow at least much more efficient than in lower modes.

5 CONCLUSIONS

The general characteristics of positive streamers in Exxsol were examined. Carbon particles have a strong effect on both streamer initiation and propagation while dissolved gases/air shows a little impact on streamers. This study also confirms that streamers show their electronic properties because of being strongly influenced by both a low IP additive and an electron scavenger. The macroscopic observation that is influenced is the branching, which plays an important role to control breakdown as well as acceleration voltages on the account of changing velocity. Moreover, streamer propagation contains reilluminations, requiring at least 1 μs intervals, as well as weak continuous glow among them. However, at fast modes only continuous strong luminosity was observed. We found that streamers with low speed have more branching. Conversely, we have also observed that more branching results in low speed. It means that the relationship between speed and branching is mutual.

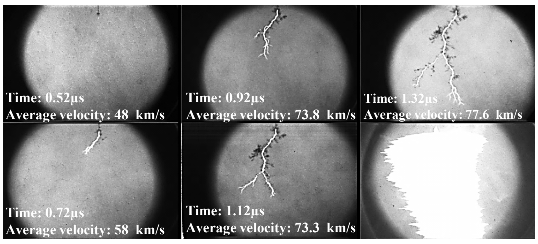


Figure 28. Streamer development at 270 kV. Cleaned Exxsol in air.

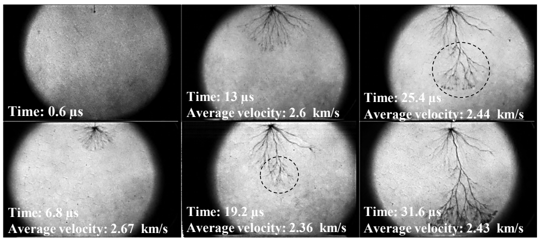


Figure 29. Streamer development at 180 kV. DMA - 0.064M.

ACKNOWLEDGMENT

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Paper 3

Influence of Impurities and Additives on Negative Streamers in Paraffinic Model Oil

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Influence of Impurities and Additives on Negative Streamers in Paraffinic Model Oil

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ABSTRACT

The non-breakdown and breakdown streamers in paraffinic model oil were investigated under negative "step" voltages. Experiments were performed with the point-plane gap of 8 cm and voltage up to 540 kV. Streamer behaviors were observed with shape, stopping length, velocity, current and light emission pulses. Carbon particles markedly reduce inception and breakdown voltages of streamers, while dissolved gases have a little effect on these voltages. Both low ionization potential and electron scavenging additives accelerate the streamers. However, the electron scavenger shows a much stronger influence on streamers than the low ionization potential additive.

Index Terms — **Streamers, initiation, propagation, stopping length, velocity.**

1 INTRODUCTION

THE positive streamers in paraffinic model oil were presented in an earlier paper [1]. Although positive streamers are much more severe than negative streamers, the study on negative streamers is still needed both for its own sake and for improving the understanding of streamers in liquids. The behavior of negative streamers depends on voltage level, chemical composition, and hydrostatic pressure as reported in a review paper [2]. In small gaps, dissolved air or oxygen has no appreciable influences on negative streamers while metallic particles significantly increase the speed of propagation [3]. Carbon particles decrease ac, trapezoidal and impulse breakdown voltages [4-6]. Electron scavenger additives raise the velocity of negative streamers in n-hexane [7], in cyclohexane [8], and in Marcol oil [9], while low ionization potential additives had no significant impact [9]. Similar results for additives were obtained in long gaps in cyclohexane [10]. Propagation of negative streamers has been investigated thoroughly with long gaps in mineral oils [11, 12] and in ester oil [13, 14]. In these studies, negative streamers show common properties: reilluminations with associated light and current pulses, continuous light from streamer extremities, and fast terminating event.

To better describe and develop the understanding of the negative streamers, studies should be performed with model oils, representative for components of mineral transformer oil. Exxsol oil is one such model oil with very low aromatic content. Moreover, experiments with long gaps and voltages

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above breakdown value have been rarely carried out with negative polarity. A previous investigation was done with the same setup in cyclohexane, i.e. naphthenic molecules [10]. In this paper, what are studied are the basic features of negative streamers in paraffinic model oil, Exxsol-D140, containing 99.4% paraffinic molecules and less than 0.6% aromatic molecules by weight. The influences of both a low ionization potential (IP) additive, *N,N*-Dimethylaniline (DMA), and an electron scavenger, Trichloroethylene (TCE), on streamers shapes and velocities were investigated. Effects of carbon particles and dissolved gases including air - dissolved gases/air - were also studied.

To distinguish among streamers with very different shapes and velocities with increasing applied voltage, we use the classification of streamers in [15]. We are fully aware that this classification is developed for positive streamers and may be ambiguous. However, in lack of better descriptors we feel that it is still useful.

In this paper, a filamentary streamer contains a single, thin channel. The streamer is bush-like if there are several channels originating from what look like a common root point on the electrode. A tree-like streamer has one dominant channel enclosed by numerous smaller side channels. A spheroidal streamer has an overall shape like a sphere composed of multiple tree-like channels.

2 EXPERIMENT

2.1 EXPERIMENTAL SETUP

Figure 1 shows the experimental setup used in this study. A point-plane electrode system, with a high voltage tungsten wire (0.15 mm in diameter) opposing a grounded plane (340 mm in diameter), is located within a test cell made from borosilicate glass. All experiments were performed with an electrode gap of 80 mm. A six-stage Marx generator was used to provide a “step” voltage (0.5/1700 μs). A 76 Ω resistor was placed in series with the test cell to dampen oscillations and limit the breakdown current. To remove effects from sharp cut wires the point electrode was initially conditioned with ten breakdowns. After this treatment, the point’s tip resembles a hemisphere (0.18 mm in diameter) when observed under a microscope. Then the treated point electrode was used to run an experiment to determine inception, breakdown and acceleration voltage. This treatment was repeated for every new oil sample to keep the shape as equal as possible.

The impulse voltage was measured at the high voltage side of the test cell using a capacitive differentiator by a low voltage integrator, giving good step response and slow decay.

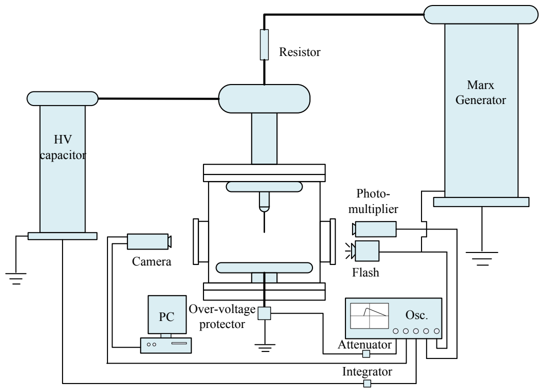


Figure 1. Experimental setup.

Streamer current was measured at the low voltage side of the test cell in an arrangement with a gas gap overvoltage protector and attenuators were used in the connection to the oscilloscope.

Framing and streak images were captured by an IMACON 468 image converter camera. A photomultiplier was placed close to a window of the cell to record light emission pulses. All signals were displayed on the screen of a high bandwidth oscilloscope Tektronix DPO4104. A Xenon flash was used that allowed for back illumination of the streamers.

2.2 PROCEDURE

The oil used in the experiments was conditioned in two different ways; either filtered (cleaned) or non-filtered (contaminated). The treatment procedures for both oil samples are the same as used earlier [1]. After treatment, the cleaned oil sample will contain a small amount of carbon particles while much higher concentration of carbon particles is present in the contaminated oil sample.

To investigate the effect of carbon particles on streamers, the contaminated oil sample was used. During this investigation, the oil was not filtered, so the density of carbon particles will increase during the experiment. The particle content in oil after finishing this experiment (after investigation oil) was measured and compared with the cleaned condition and a sample of contaminated oil from before the experiment series. The particle content was measured by a particle counter (PAMAS SBSS-C) according to the ISO 4406 and NAS 1638 classes. Most of the particles are in the 1-3 μm size range. The total numbers of particles per 100 ml are 1.03×10^5, 6.05×10^5 and 12.8×10^5

for cleaned, contaminated and after investigation oil samples, respectively.

The impact of dissolved gases/air was investigated in the cleaned oil sample. The oil was passed through a degassing column and a particle filter under vacuum or in air. This was done for 30 minutes after 10 shots for non-breakdown streamers and after each shot when breakdown occurred. Filtering under vacuum will remove carbon particles and degas the oil, while filtering in air only removes carbon particles and will mix in some air.

To investigate the influence of additives on streamers, DMA and TCE were separately mixed into the cleaned oil to a concentration of 0.064M, i.e. mol/l. The same cleaning condition as cleaned oil case was applied. However, after filling the additives, the oil was only filtrated in air because degassing, i.e. cleaning in vacuum, will deplete these additives.

The experiment sequence was divided into four stages. The voltage was increased in different steps depending on the stage. The 1st stage, initiation stage, was performed with 5 kV/step. In the 2nd stage, from initiation to breakdown, voltage was increased with 30 kV/step. During the 3rd stage, breakdown stage, 5 kV/step was applied again, and finally 30 kV/step was used for the propagation stage, i.e. the 4th stage. Ten repetitive shots at each step were applied for all stages except the 4th stage. Only five shots were used at this stage because of time consumption for cleaning the oil after each breakdown. All data of initiation and breakdown phases were analyzed using the Weibull distribution. Equation 1 is the expression of the cumulative distribution function for two parameter Weibull distribution. Here V_0 and β are the scale and shape parameters, and V is the peak voltage.

$$F(V) = 1 - exp\left[-\left(\frac{V}{V_0}\right)^{\beta}\right] \qquad (1)$$

3 RESULTS

3.1 INCEPTION VOLTAGE

The onset of streamers was determined by using shadow graphic imaging. The smallest observable streamers were approximately 0.5 - 1 mm in cross section and were detected by 100 ns interval frame images, defining the streamer onset. Ten shots were applied at each voltage step and the number of streamer onsets was counted.

Figure 2 shows the influence of carbon particles and additives on streamer initiation. Carbon particles reduce the inception voltage. It means that these particles create a better condition for streamer initiation. Possibly, after contacting with the needle electrode, the carbon particles will become negatively charged. Because of the much smaller curvature of carbon particles than of the needle, the field around these particles will be greatly enhanced and hence they cause a reduction in the inception voltage. Both DMA and TCE also decrease the inception voltage. This is quite similar to what was obtained in small gaps in cyclohexane [16]. However DMA has a stronger impact on the inception voltage than TCE. A possible explanation for a reduction of inception voltage with additives in Exxsol is the lower IPs of DMA (7.12 eV [17]) and TCE (9.46 eV [17]) than of the Exxsol oil, whose IP is assumed to be equal to that of hydrocarbon liquids (10 eV [18]). Higher IP correlates with higher inception voltage.

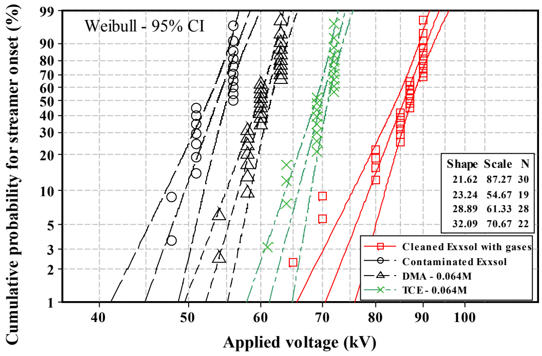


Figure 2. Influence of carbon particles and additives on streamer initiation.

The 50% probability of inception voltage is shown in table 1. From this table, carbon particles give a reduction of 37.3%, while DMA and TCE decrease the inception by respectively 29.4 % and 18.5%. This shows that carbon particles have a stronger influence on the inception voltage than DMA and TCE.

Table 1. 50% Probability inception voltage.

Types of oil	Value	Percentage compared to case (*)
Cleaned Exxsol with gases (*)	85.8 kV	100 %
Contaminated Exxsol	53.8 kV	62.7 %
DMA – 0.064M	60.6 kV	70.6 %
TCE – 0.064M	69.9 kV	81.5 %

3.2 STOPPING LENGTH

Figure 3 shows the average stopping lengths of non-breakdown streamers. The three plots have the same tendency, with an abrupt change of length at the “knee” points, occurring at a threshold voltage, V_{th}. Carbon particles strongly reduce V_{th} from 265 kV to 190 kV, while dissolved gases/air only results in a slight reduction from 265 kV to 260 kV. Below V_{th}, the stopping length increases slowly with voltage. Assuming that (the inverse of) the increase in stopping length with voltage can be used to quantify the voltage drop along the streamer channels, this is about 100 kV/cm for all conditions. Above V_{th}, the stopping lengths increase steeply with much smaller voltage drop being about 4 - 5 kV/cm. Macroscopically, one can see that when the voltage is increased above V_{th}, streamers switch from a slow bush-like shape to a tree-like shape (Figure 4), which propagate more efficiently. The filamentary shape will greatly enhance the tip field, leading streamers to travel easier. Therefore, streamers require less voltage increase to extend 1 cm than before or with the same voltage increase, streamers will reach further. This results in raising the rate of length increase. The "knee" point V_{th} is quite analogues to that of propagation voltage, V_p, where positive streamers switch from slow "bush-like" streamers to filamentary streamers [19].

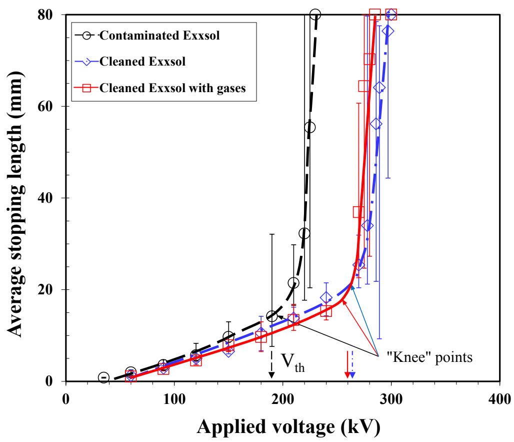
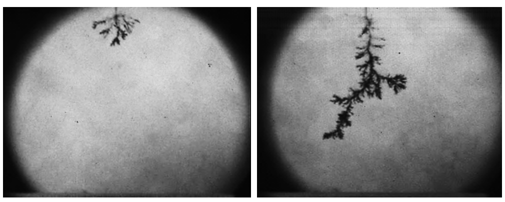


Figure 3. Effect of carbon particles and dissolved gases/air on stopping length of non-breakdown streamers.



240 kV
Bushlike

270 kV
Treelike

Figure 4. Shapes of non-breakdown streamers. Cleaned Exxsol with gases. "Knee" point at 260 kV. Images were captured around stopping length.

The effects of DMA and TCE on the stopping length are shown in Figure 5. Adding DMA does not change behavior much from what is seen for cleaned condition with a "knee" point of around 210 kV. However, a larger data scatter can be seen in the DMA case. Again a switching of type of streamer shape is seen just above the "knee" point. For the TCE case, there is no observation of the "knee" point. The stopping length line shows a gradual change of the increase rate because streamers propagate without an obvious change of the shape's type (Figures 6a and 6b). The negative streamers become more filamentary when TCE is added into Exxsol (Figure 7). A similar observation was made for cyclohexane in a long gap [10]. The shapes of negative streamers in this case resemble those of positive streamers seen in the cleaned Exxsol [1]. This result confirms what was observed by Devins et al. in Marcol oil in small gaps [9]. Both DMA and TCE increase the stopping length. However, the impact of TCE on the stopping length is much more pronounced than that of DMA since TCE makes the streamers more filamentary (Figure 7), and thus eases the propagation.

3.3 BREAKDOWN VOLTAGE

Both carbon particles and dissolved gases/air affect the breakdown voltage, V_b, which is defined as 50% probability of breakdown voltage as presented in Figure 8. Carbon particles greatly reduce V_b, while dissolved gases/air only results in a small reduction. This is in line with what was found for positive streamers [1].

Figure 9 shows the impact of both DMA and TCE on the breakdown voltage. DMA has a little effect on the breakdown voltage, while TCE decreases it significantly. This result is in line with what has been reported in cyclohexane [10]. The reduction of breakdown voltage can be explained from the macroscopic observation of streamer shapes in Figure 7. It seems that with more elongated or filamentary shape of streamers, the stopping length will be increased (Figure 5). Therefore the breakdown voltage will be reduced. From the microscopic viewpoint, the electron trapping properties of TCE will confine hot electrons close to the streamer tip, and hence enhances the local field and favors ionization in the oil [9].

Table 2 shows the 50% probability of breakdown voltage. It can be seen that TCE shows the strongest impact on the breakdown voltage with 27.1% of reduction, while DMA has the lowest influence with only 1.3% of decrease.

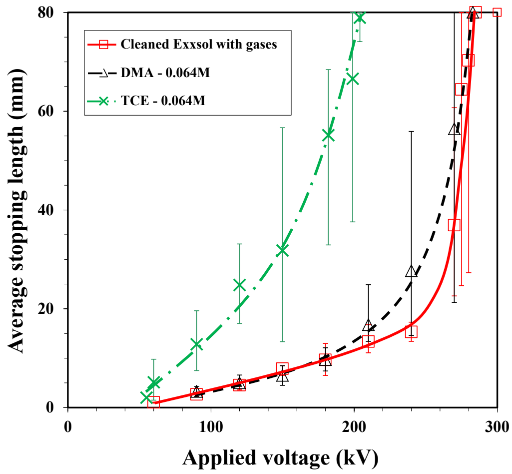
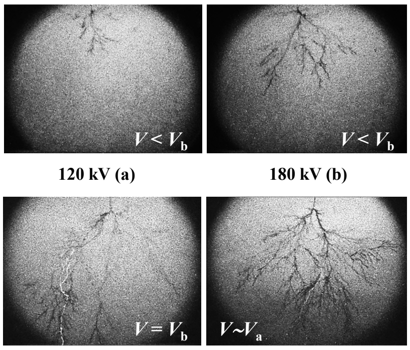


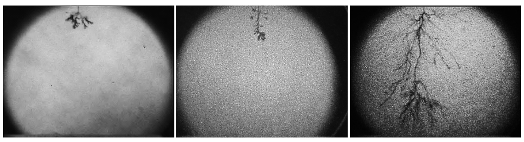
Figure 5. Effect of DMA and TCE on stopping length.



120 kV (a) 180 kV (b)

205 kV (c) 240 kV (d)

Figure 6. Shapes of streamers in TCE case.



210 kV Cleaned Exxsol with gases | 210 kV DMA-0.064M | 210 kV TCE-0.064M

Figure 7. Effect of additives on streamer shape. Images were captured at around stopping length for the cleaned Exxsol and DMA. For TCE, image was taken just before breakdown.

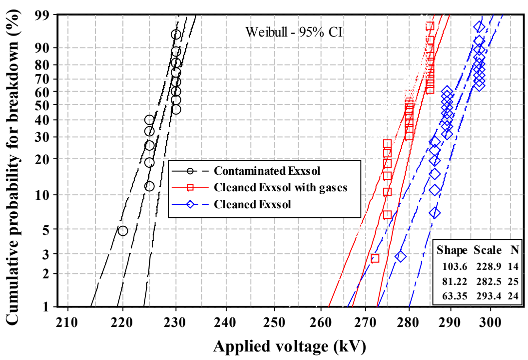


Figure 8. Effect of carbon particles and dissolved gases/air on breakdown voltage.

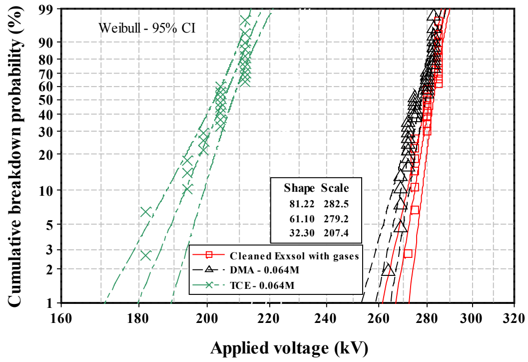


Figure 9. Impact of DMA and TCE on breakdown voltage.

Table 2. 50% Probability breakdown voltage.

Types of oil	Value	Percentage compared to case (*)
Cleaned Exxsol with gases (*)	281.2 kV	100 %
Cleaned Exxsol	291.7 kV	103.7 %
Contaminated Exxsol	228.1 kV	81.1 %
DMA – 0.064M	277.5 kV	98.7 %
TCE – 0.064M	205.1 kV	72.9 %

3.4 TIME TO BREAKDOWN AND VELOCITY

In general, time to breakdown, t_{BD}, will be reduced with increased voltage as seen in Figure 10. A sudden drop can be observed as voltage exceeds a critical value (acceleration voltage V_a), and the streamers switch to a faster mode. Hence the time to breakdown can be divided into two groups based on V_a; the shorter time group representing fast modes, and the longer time group referring to slow modes. At V_a, t_{BD} distributes between these two groups. The breakdown times for the faster streamers ranges from 2 to 10 µs, while slower needs 40 - 140 µs to cross the gap. Average velocities may be calculated from this. As seen, DMA and TCE reduce both V_b and V_a. TCE has the biggest impact. Because of the lowering of V_b and V_a, i.e. shifting of these voltage amplitudes to the left, DMA and TCE reduce the time of both groups. With smaller value of V_b and V_a, TCE will reduce the times more than DMA.

The average velocity of streamers in cleaned and contaminated Exxsol is shown in Figure 11. Generally, the velocity increases in steps when the voltage is raised. Two acceleration voltages, named V_{th*} (knee point) and V_a (acceleration), occur in cases of cleaned Exxsol (with and without degassing), while only V_{th*} is present in contaminated Exxsol. V_{th*} is smaller than the breakdown voltage V_b whereas V_a is higher than it. It can be seen that carbon particles strongly increase the velocity while dissolved gases/air has little impact on it. However, over 450 kV, i.e. at 3rd mode, the velocity seems to be unaffected by the carbon particles. V_{th} in Figure 3 is compared with V_{th*} of Figure 11. Clearly, for cleaned Exxsol with and without gases, the two voltages are the same (as one naturally would expect), but this is not so for contaminated Exxsol, destroying a clear connection between speed and stopping length.

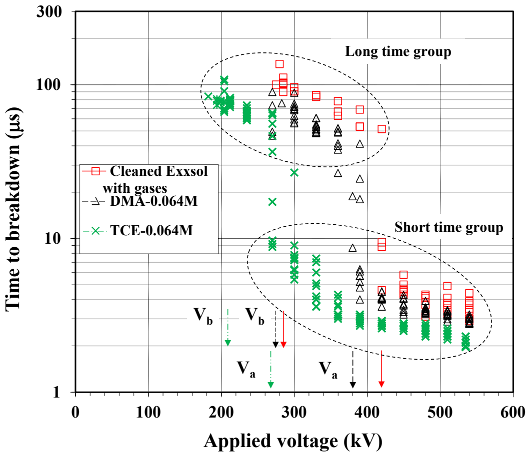


Figure 10. Effect of DMA and TCE on time to breakdown voltage.

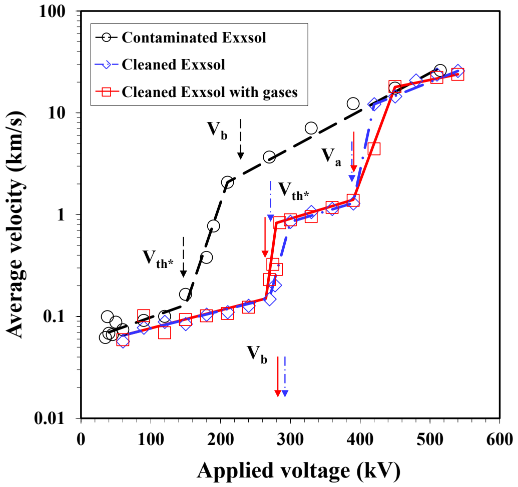


Figure 11. Effect of carbon particles and dissolved gases/air on average velocity.

A possible explanation of the velocity characteristics can be based on the observation of shape changing as seen in Figure 12, e.g. in the case of cleaned Exxsol with gases. The streamer shape can be represented by its apparent area, which is measured by using ImageJ program. The velocity, correlating with the area, is shown in Figure 13. Below V_{th*}, streamers are in the 1st mode with bush-like shape (Figure 12a) and streamer area increases about 20 times, so the velocity gradually increases. From V_{th*} to V_b, streamers switch from the bush-like shape to tree-like shape (Figure 12b) to propagate and breakdown, and thus accelerate the velocity as well as increase the area. From V_b to V_a, the velocity again gradually increases because streamers are the most branched (Figure 12c) with an area increase of approximately 300 %. Just above V_a, because of reduction in number and diameter of branches (Figure 12d), the area drops to about a fifth. Therefore streamers accelerate the second time. Further above V_a, with more branching again (Figure 12e), streamers will decrease their rate of velocity increase.

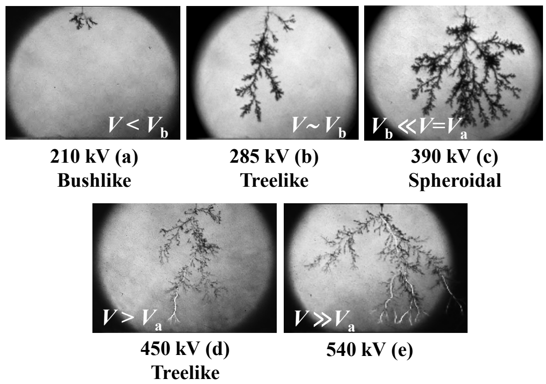


Figure 12. Streamer shapes versus applied voltage. Cleaned Exxsol with gases.

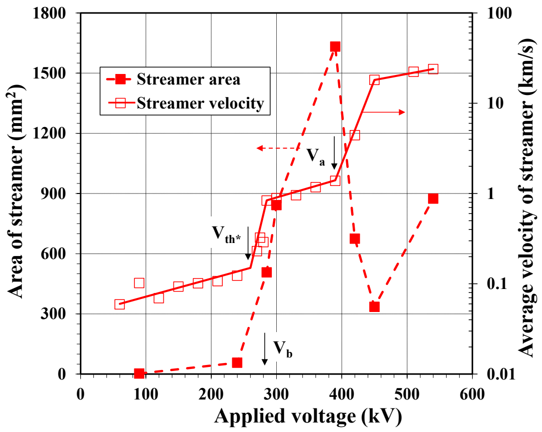


Figure 13. Streamer area and average velocity versus applied voltage. Cleaned Exxsol with gases.

The effect of carbon particles on streamer velocity relates to the shape change as seen in Figure 14. Below 450 kV, e.g. at 360 kV, the 1st shot streamers have a spheroidal envelope shape constituted from dense branches with velocity of about 0.93 km/s, while the 2nd shot streamers are much more filamentary shaped and composed of less and thinner branches, and hence their velocity increase to approximately 7.5 km/s. It means that after only one breakdown in the sample oil, streamers switch from 2nd mode to 3rd mode, i.e. their velocity can increase many times. This phenomenon could be explained by a small increase in the amount of carbon particles in the stagnant oil in the gap. The phenomenon is reproducible. However, the shape and the velocity of the 6th shot streamers are similar to those of the 2nd shot streamers. It can be deduced that the effect on streamers of introducing carbon particles in the pure oil is significant but saturates quickly, directly after the first shot. From 450 kV, shape and velocity of the streamers are similar from the 1st to 6th shots for all oil conditions. They have filamentary shape composed from some main branches. Many side branches along the main stems can be seen but most of them stop in small bush-like shapes. At this voltage level, the streamers are in the 3rd mode with the velocity of around 16-18 km/s. Clearly, the shape and velocity of the streamers do not change with the ordinal number in the sequence. Carbon particles have little or no impact on the 3rd mode streamers.

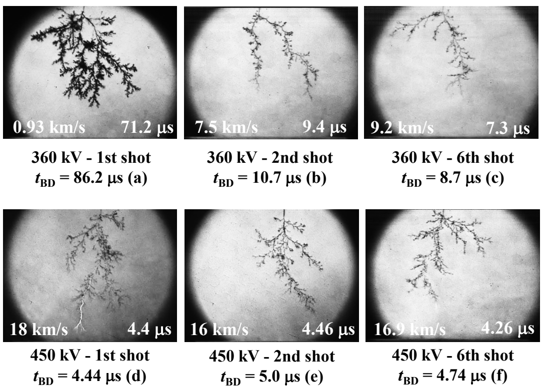


Figure 14. Influence of the ordinal shot on streamer shape. Cleaned Exxsol with gases. Filtered after 6 shots.

Figure 15 shows the impact of DMA and TCE on the average velocity. Only TCE has a strong and significant effect on the velocity, increasing it about a decade in the lower voltage ranges. Also TCE changes the velocity in only one step compared to cleaned Exxsol and Exxsol with DMA, which show two steps. The reduced branching correlates with increased speed for the 2nd mode as seen at the 210 kV level in Figure 16, mainly for TCE, but also to some extent for DMA. However, in 3rd mode, e.g. at 540 kV (Figure 16), streamers with much more branching in TCE case still reach the highest velocity. The speculation is that electron trapping shows a stronger effect on propagation of the 3rd mode streamers than branching.

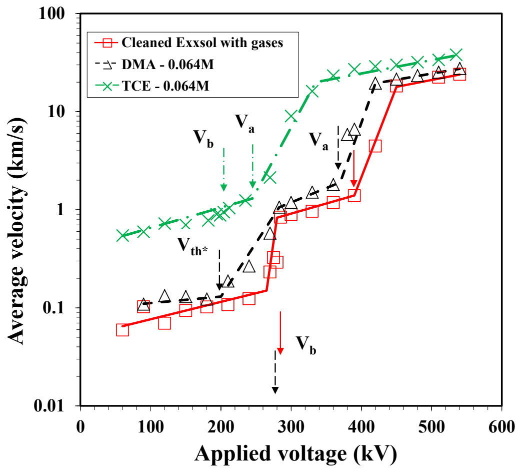


Figure 15. Impact of DMA and TCE on average velocity.

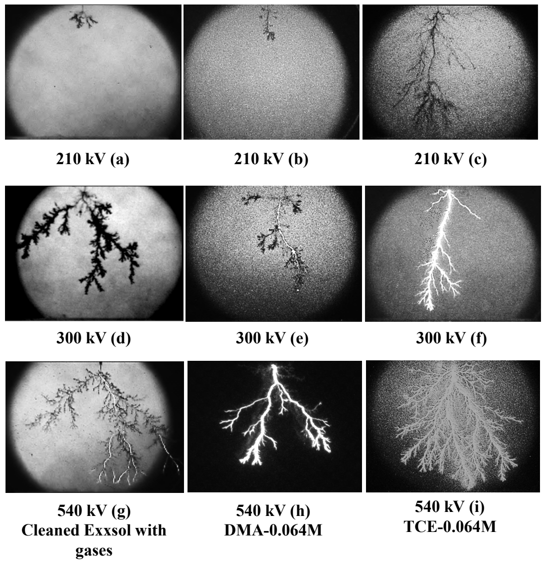


Figure 16. Impact of DMA and TCE on streamer shape.

The instantaneous velocity of cleaned Exxsol is shown in Figure 17. For non-breakdown streamers, i.e. at 240 kV and 270 kV, the velocity decreases continuously as the streamers are dying out. For the breakdown streamers, two groups of velocity curves are seen. The low value group is for the 2nd mode streamers and high value group stands for the 3rd and 4th mode streamers. Both groups show minimum values at mid-gap position. The low velocity group shows a wide flat minimum of about 0.8 km/s from 20% to 70% of gap distance. The minimum velocity seems to be unaffected by applied voltage. However, the high value group exhibits a sharper minimum value at about 40% of gap distance, and the minimum value varies proportionally to applied voltage.

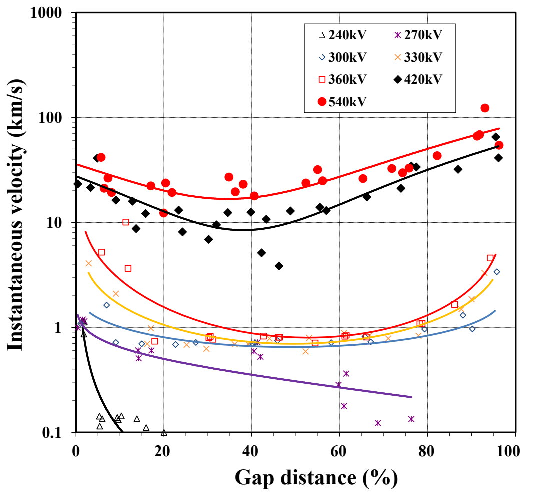


Figure 17. Instantaneous velocity versus gap distance. Cleaned Exxsol.

3.5 PROPAGATION AND MODES

Generally, streamer propagation in cleaned Exxsol was investigated with streak images and light intensity and current measurements showing correlated pulses. The first current pulse when the step is applied is the capacitive charging current.

A typical streak image of streamer stopping before crossing is shown in Figure 18. It starts with a short flash channel, followed by a weak continuous background during the propagation at 0.2 km/s. Two big diffuse flashes correlating to strong light pulses are observed. The currents associated with the flashes are small. We have denoted this as a 1st mode streamer.

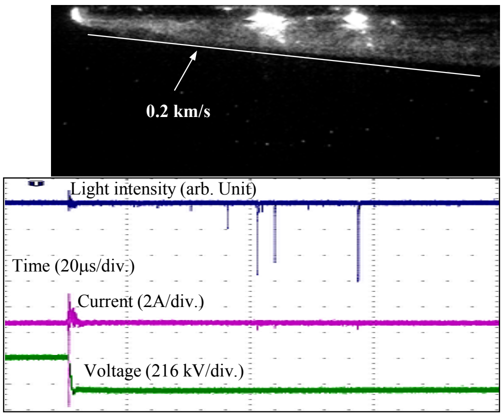


Figure 18. Typical streak image at V = 270 kV < V_b and corresponding signals. The 1st mode streamers.

Around breakdown voltage, the streak image remains similar to that in Figure 18, but velocity has increased to 0.8 km/s. Some channel like reilluminations superimposed on the continuous background were captured as seen in Figure 19. We consider this as a 2nd mode streamer.

Just above breakdown voltage, the speed is still about the same, but we now see numerous repetitive reilluminations with similar light intensity occur just before breakdown (Figure 20). The reilluminations are repeated flashes of a main branch while the background light comes from discrete lights from the many side branches. The first flash channel correlating to light pulses can be seen both in framing and streak images.

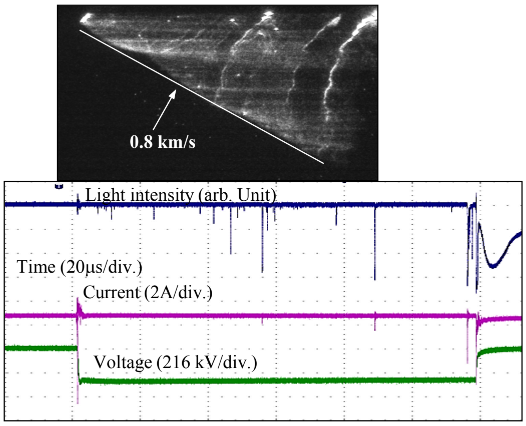


Figure 19. Typical streak image at V = 285 kV ~ V_b and corresponding signals. The 2nd mode streamers.

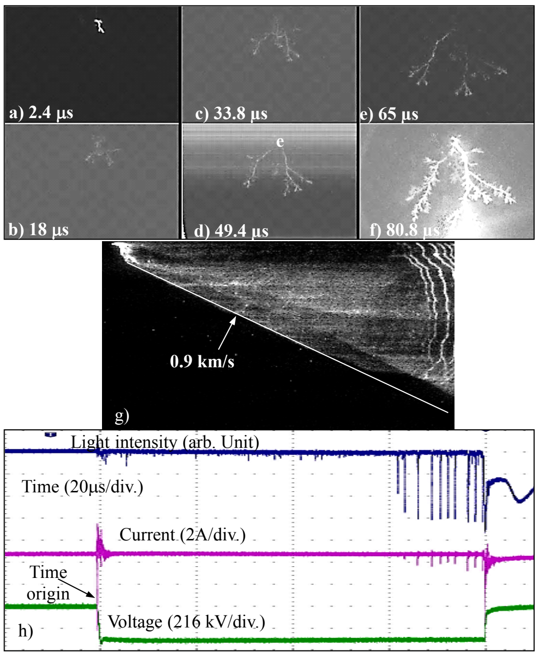


Figure 20. Propagation of the 2nd mode streamers at V = 320 kV > V_b; a-f) framing images; g) streak image; h) oscilloscope signals

When further raising the voltage, speed increases about tenfold in the first 2.5 μs of the crossing, and then falls off to what was seen for lower voltages. Figure 21 shows many reilluminations with high repetition rate. The light intensity and current amplitude gradually increase during the first part but then die out. Streamers begin with the 3rd mode and propagate with the 2nd mode.

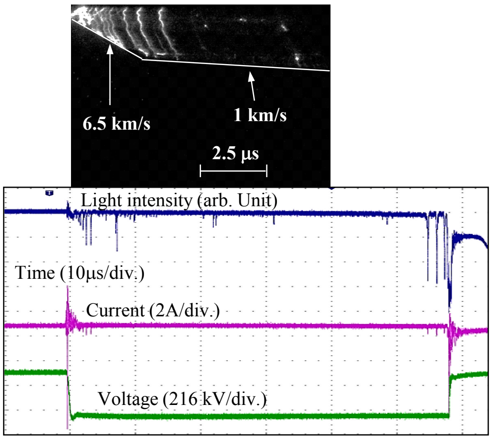


Figure 21. Typical streak image at V = 375 kV >> V_b and corresponding signals. The 3rd mode + the 2nd mode streamers.

Above acceleration voltage, propagation is now always above the sonic speeds seen for lower voltages, and strong reilluminations repeat throughout the propagation as shown in Figure 22. In the start it is difficult tell whether the light is pulsed or not. The current measurements did not work as the overvoltage gas gap triggered on the initial capacitive pulse and short-circuited the current shunt. Between reilluminations, weak continuous background and continuous light emission from the streamer heads may still exist although no light can be recorded because sensitivity was set low now. The continuous lights from the streamer heads have comparable intensity to that of streamer stems. Compared to Figure 21, streamers start with much higher velocity of 30 km/s during a much shorter time of 500 ns, and then velocity falls more than three times to 8.6 km/s before increasing again to 11.2 km/s during the final stage. Streamers start with 4th mode and traverse in the 3rd mode. The 4th mode streamer, having filamentary shape, can be observed at the beginning and the end of propagation (Figure 23).

When further increasing voltage the general behavior did not change. However, the continuous light from the tips got more pronounced. The ratio of the beginning stage's velocity to that of the second stage is reduced, and the relative duration of the beginning stage is increased.

The effects of DMA and TCE on streamer propagation are shown in Figure 24. The main features are similar to those in cleaned Exxsol. Nevertheless at V_b<V<V_a in the DMA case, reilluminations repeat in groups during the whole propagation time (Figure 24a). At V >V_a in the TCE case, the fast terminating event is easily observed, starting at about half the gap distance (Figures 24d and 24e).

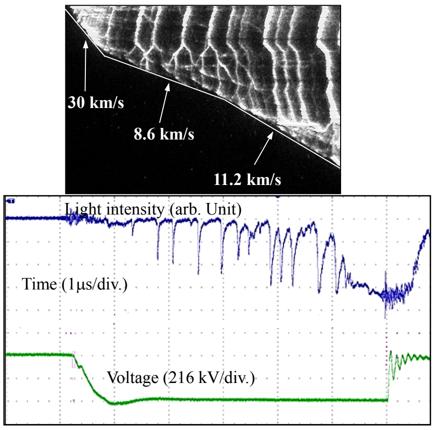


Figure 22. Typical streak image at V = 420 kV > V_a and corresponding signals. Camera closed 1.2μs before breakdown. The 4th mode + the 3rd mode streamers.

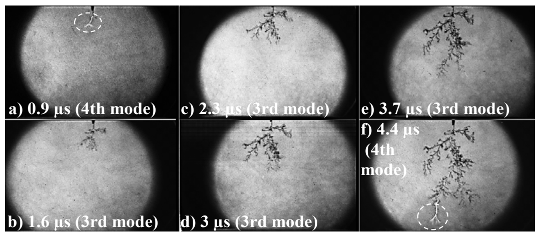
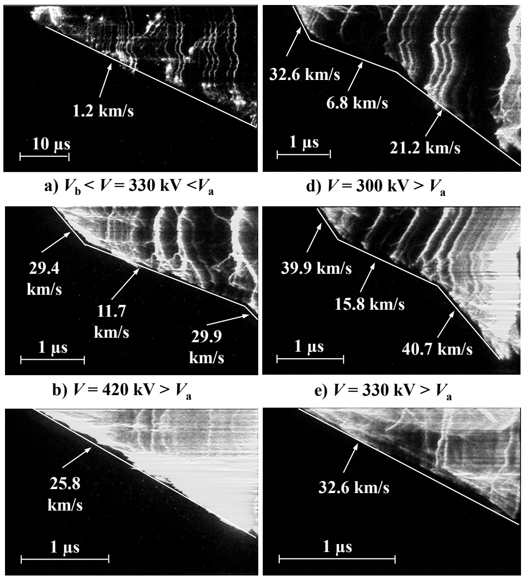


Figure 23. Shapes of the 3rd and 4th mode streamers at V = 450 kV > V_a.

4 DISCUSSION

Devins et al. observed that electron scavengers strongly accelerate the negative streamers in Marcol oil in small gaps while low ionization potential additives had insignificant effects on them [9]. Moreover, an electron scavenger, ethyl chloride, will make negative streamers more filamentary. These above observations are largely confirmed by this study. However, we see that a low ionization potential additive, i.e. DMA, can slightly increase streamer's velocity with a little change in streamer shape (Figures 15 and 16). In addition, we can clarify modes and propagation of streamers from low to very high voltages. This was not studied in [9].



a) $V_b < V = 330$ kV $< V_a$ d) $V = 300$ kV $> V_a$

b) $V = 420$ kV $> V_a$ e) $V = 330$ kV $> V_a$

c) $V = 510$ kV $\gg V_a$ DMA – 0.064M f) $V = 480$ kV $\gg V_a$ TCE – 0.064M

Figure 24. Effects of DMA and TCE on streamers propagation.

In mineral transformer oil, negative streamers showed bush-like shape with very low velocity of around 100 m/s just above the inception voltage. Filamentary streamers were seen far above the inception voltage when they reach more than 10% of a gap distance. At even higher voltages, streamers became more and more filamentary and cross the gap distance with much higher velocity of about 1 km/s. Above a threshold voltage, this velocity suddenly accelerated [12]. Most of these features are in line with those seen in this study in a blend of Exxsol and TCE, except that we did not observe the slow streamers having bush-like shapes. Mineral transformer oils had lower negative breakdown voltages than pure hydrocarbons and highly refined mineral oils [9, 12, 20] because of a content of aromatic molecules resulting in more filamentary streamers. This specific characteristic is reproduced in this study by adding TCE, representing the electron scavenging property of aromatic compounds, into Exxsol oil (Figure 15).

Influences of DMA and TCE on streamers in this study are similar to what have been reported for cyclohexane in a long gap. DMA did not have any pronounced influences on negative streamers while TCE greatly enhances the velocity of streamers as well as increasing the stopping length, resulting in a reduction in breakdown voltage [10]. Our results also support earlier observations in cyclohexane in a small gap [8, 16]. Both DMA and TCE slightly reduced the negative inception voltage. An electron scavenger, perfluoro-*n*-hexane, increased the stopping length as well as the velocity. This scavenger also made negative streamers more branched with thinner filaments.

Like described for positive streamers in [1], carbon particles have an effect on negative streamers stronger than dissolved gases/air had. However, carbon particles show a more pronounced influence on negative streamers than positive streamers. Compared to negative streamers, additives behaved quite differently for positive streamers [1]. For positive polarity, both DMA and TCE strongly affected streamers. DMA decreased the velocity, and thus increased the breakdown and acceleration voltages. TCE raised the velocity and hence reduced the acceleration voltage but still enhanced the breakdown voltage. In cleaned condition, the 1st mode positive streamers and the corresponding transition "kneepoint" to 2nd mode seen for negative polarity were not observed, whereas the fast 4th mode negative streamers, i.e. 100 km/s, seem nonexistent. The 2nd mode positive streamers are more filamentary than negative streamers leading to an increase of velocity by two times. Just above a threshold acceleration voltage, both positive and negative streamers largely reduce their number of branches to speed up, but there is a transition from dark channels to bright channels in positive streamers while dark branches of negative streamers become thinner.

As can be seen in tables 1 and 2, DMA and TCE decrease both inception and breakdown voltages. Although DMA lowers the inception voltage more than TCE due to low IP, the effect of DMA on the breakdown voltage is much less. Thus, the breakdown voltage would be determined by streamer propagation. Both DMA and TCE increase the velocity and reduce the acceleration voltage but TCE shows a more pronounced influence on streamers than DMA. From Figure 15, the ratios V_a/V_b for cleaned Exxsol, DMA, and TCE cases are 1.4, 1.3, and 1.2 respectively. As seen in Figures 6 and 12, there is much more branching in the cleaned Exxsol case leading to an increased value of the acceleration voltage, and hence also the ratio V_a/V_b. As one might expect the ratio depends on the degree of branching. This behavior is in accordance with that of positive streamers in Exxsol [1] and in cyclohexane [10, 21]. Compared to positive streamers [1], negative streamers have a lower V_a/V_b. This is in agreement with the result obtained in mineral transformer oil [12].

As mentioned above, the "knee" point seen for negative streamers appears when streamers switch from the 1st mode to the 2nd mode, i.e. from the bush-like shape to tree-like shape. This point is easy to determine from the stopping length line in cleaned Exxsol. However, the point becomes unclear in the DMA case, and it totally disappears in TCE case because streamers first start and propagate in the 2nd mode with more filamentary shape instead of the 1st mode with a bush-like shape.

In this study, we observe four kinds of streamers. The 1st mode streamers, seen below the breakdown voltage, have a bush-like shape with low velocity of about 60-200 m/s. The 2nd mode streamers are recorded from just below the breakdown to the acceleration voltages. They show tree-like shape around the breakdown voltage and become more branched into spheroidal shape with velocity of approximately 1 km/s. The 3rd mode streamers, being detected above the acceleration voltage, exhibit similar shapes to the 2nd mode streamers but have thinner branches and much higher velocity of 5-20 km/s. The 4th mode streamer, a filamentary structure, grows at a velocity of 30-40 km/s. If only the average velocity of streamer is considered, the mode classification for negative streamers here is in line with that for positive streamers in [15].

In this study, carbon particles were seen to reduce the inception and breakdown voltages 37.3 % and 18.9 % respectively for negative streamers while 13.9 % and 12.2 % are the corresponding numbers for positive streamers [1]. Lesaint et al. used carbon powder for experiment with a rod-plane gap of 35 cm while we carbonize the oil by breakdown shots. They did not measure the actual particle content before and after experiment series. They found that carbon particles had insignificant effects on stopping lengths of both the 2nd mode positive and negative streamers in ac even though large concentrations of carbon power was mixed into the oil (the oil became black) [22]. This is quite similar to our results for positive streamers [1], but very different from negative streamers presented here. Carbon particles influence the stopping length, the velocity, and the breakdown voltage.

In the 2nd mode, after one single breakdown, the velocity of negative streamers increases by a factor of eight and their shape become less branched with thinner stems in the 2nd shot as shown in Figures 14a and 14b. An interval time between shots of around five minutes was used. After the 1st breakdown shot, the stagnant oil will contain carbon particles, dissolved gases/air, bubbles, space charges, excited atoms, etc. The parameter causing the observed change in the 2nd shot cannot be exactly identified. However, if the interval time is increased to 24 h or more, much faster streamers are still recorded in the 2nd shot. On the other hand, we see that if the oil is filtered either in air or in vacuum for 20-30 minutes after one breakdown shot, streamers have the same velocity as in the 1st shot, and are thus independent of the ordinal number of shot. From these observations, we suggest that carbon particles are the main factor impacting streamers in the 2nd shot. It is suggested that because of suspending in the oil, carbon particles would greatly enhance the local electric field around them. This will favor the propagation of streamers. Such a phenomenon cannot be observed in positive streamers [1]. It means that in 2nd mode, negative streamers are much more sensitive to carbon particles than positive streamers.

It has been observed that when pyrene was added into cyclohexane, a lower inception voltage was recorded. This resulted in more branched and filamentary positive streamers correlating to an increased velocity and reduced breakdown voltage [21]. The density of branches increased with applied voltage leading to form a "space charge" shielding effect of neighbouring tips. This effect would regulate the macroscopic field of a streamer envelope, and thus reduced the increase rate of velocity and raised the acceleration voltage [21]. In this study, when mixing TCE into Exxsol, we obtained some similar results as described above. TCE reduces the inception voltage so it makes negative streamers more filamentary. With more filamentary shape (less branches), the streamer tip field is expected to increase. This field is one of the most important factors to drive streamers [23-25]. Thus, the velocity of streamer increases, and hence the breakdown voltage is reduced. However, unlike pyrene, it seems that TCE reduces the branching degree. Moreover, TCE causes streamer branches to become thinner than those in pure Exxsol. Therefore the shielding effect is considered to decrease, and a lower acceleration voltage can be observed.

From Figures 18 to 22, it is seen that the streak image constitutes of the background light (at the beginning phase and between reilluminations), the reilluminations (being correlated with light and current pulses), and the continuous light from streamer tips. The background light is constituted by all streamer branches while reilluminations are almost regularly repeated flashes of main branches. This means that the background light exists without regard to the presence of reilluminations or one can state that streamers propagate continuously to cross the electrode gap. Such continuous light is less visible in positive streamers [1], and the 3rd mode positive streamers always start with very fast luminous channels instead of the strong background light in this study. Quite similar streak images have been observed in mineral oils [11, 12], with the exception of the following features: The continuous light coming from the streamer tip seems to be more pronounced in mineral oils. The background light between reilluminations was not easy to observe in mineral oils. Well above the breakdown voltage, streamers propagate with a quite constant velocity in the initial phase (10-20 km/s), and velocity increases 2-3 times in the second phase (~50 km/s) in mineral oils. Such a fast terminating event can be seen when TCE is added into Exxsol (Figure 24). It means that negative streamers propagating in a blend of Exxsol and TCE behave more similarly to those in mineral transformer oils.

5 CONCLUSIONS

The characteristics of negative streamers in paraffinic model oil, Exxsol-D140, were investigated. The effects of carbon particles, dissolved gases, DMA, and TCE on streamers were also studied. Carbon particles show a strong influence on negative streamers because of largely increasing the local electric field, especially on the 2nd mode streamers. TCE greatly increases the velocity of streamers because it makes streamers more filamentary, and hence removes the 1st mode streamers. This result supports the hypothesis of electronic avalanches as the nature of negative streamer propagation. A “knee” point in the stopping length diagram only appears when streamers switch from the slow bush-like shape to the tree-like shape. Below the “knee” point, the propagation of streamers is less efficient. We consider this “knee” point a specific feature of pure Exxsol. With more bush-like shape and bigger channels, negative streamers show lower velocity than positive streamers in slow modes. In faster mode, with smoother and brighter channels, positive streamers propagate with several times higher velocity than negative streamers. It is observed that negative streamers in a blend of Exxsol and TCE exhibit many similarities with those in mineral transformer oils.

ACKNOWLEDGMENT

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Paper 4

A Study on Positive Streamer Channels in Marcol Oil

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A Study on Positive Streamer Channels in Marcol Oil

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***Abstract*- The streamer channels in Marcol oil have been studied under the positive "step" voltages. Experiments were performed with a point-plane gap of 8 cm. Three kinds of streamer channels were observed around breakdown voltage. These are dark, partly illuminating, and fully illuminating (reillumination) channels. No current could be detected for the dark channels. The partly illuminating channels correlate with small current pulses in some hundreds of milli-amperes. However, the reilluminations are associated with much higher current pulses of some amperes. All kinds of channels occur simultaneously and propagate almost equally fast. Streamers with reilluminations almost always terminate with breakdown. On the other hand, streamers with dark or partly illuminating channels have much lower probability for breakdown. Reilluminations do not have significant effects on the propagation of non-breakdown and breakdown streamers as well as the time to cross the gap and breakdown. In the 2nd mode streamers, 30 - 50% of their branches are able to become illuminated, and the number of reilluminations as well as illuminating branches is proportional to the applied voltage. The effects of vacuum on streamers were also investigated. With vacuum, streamers travel with much lower voltage drop along the streamer channel. Therefore stopping length greatly increases, and the breakdown voltage drastically drops. All crossing streamers result in breakdown. The number of reilluminations in vacuum is lower than that in ambient pressure. The physics of the above streamer channels is discussed.**

I. INTRODUCTION

Optical observations of positive streamers have been performed during the last decades. Usually, shadowgraphic or schlieren techniques are utilized to capture the frame images of streamers while the streamer propagation is recorded with streak photographs. The shadow portion in the frame images is considered streamer channels or branches. The channel diameter was measured in [1, 2]. In [2, 3], the conductivity of channels was estimated.

In the streak photographs, one can see channels flashing more or less periodically. This phenomenon was named reilluminations. The detailed description and properties of reilluminations were reported in [4, 5]. However, their roles in streamer propagation and breakdown were not investigated.

In shadowgraphic images, only the structure of the channels is seen whether the channels are reilluminations or not, although strong reilluminations may sometimes be seen even in the shadowgraphs. In streak images, both a continuous luminosity at the beginning and reilluminations has been observed [5, 6]. Moreover, this luminosity was still present between reilluminations [6]. We believe that different types of channels exist: those where reilluminations occur, and the larger number of channels where reilluminations do not occur but the nature of the difference between them was not clear. In this study, a special technique is employed to record both shadowgraphic and non-shadowgraphic images within the recording sequence of single streamers. Therefore, both the overall channel structure and reilluminations can be observed for the same growing streamer. In this paper, channels are termed "dark" except during the brief reilluminations.

The plasma state of channels was suggested in [7]. However, the nature of streamer channel was evidenced to be gaseous by investigating the influence of the hydrostatic pressure on streamers, and the dynamic of expansion and collapse of streamer channels [1, 8]. Streamer channels sometimes touched the plane electrode without current measured [5, 9] while reilluminations always correlated with high current pulses [4-6]. Thus, streamer channels become conductive only during reilluminations [5]. On the other hand, with Kerr effect measurements, it was found that streamer channels were quite good conductors [10]. Clearly, it is essential to clarify the physics of streamer channels.

The physical mechanisms being responsible for reilluminations were proposed as gaseous discharge [5] or the process of plasma cooling and redistribution of the electric field along the streamer channel [4]. If the gas discharge theory is relevant, the internal pressure of streamer channels will affect the existence of reilluminations. Hence, in vacuum, possibly reducing the internal pressure, reilluminations are expected to easily appear. The hydrostatic pressure suppresses streamer propagation [8], so vacuum perhaps favors streamer propagation. However, the impact of vacuum on streamers is unknown.

The purpose of this study is to classify and describe streamer channels, investigate the effect of reilluminations on streamers, briefly examine the influence of vacuum on streamers, and discuss the physics of streamer channels.

II. Experimental Setup and Procedure

Fig. 1 illustrates the experimental setup. A point-plane electrode system consists of a high voltage tungsten wire (ϕ = 0.15 mm) and a grounded plane (ϕ = 340 mm). The electrode distance was 80 mm. The positive step voltages (0.5/1700 μs), provided by a Marx generator, was applied to the point electrode through a damping and limiting current resistor of 76 Ω.

The impulse voltage was measured at the high voltage side of a test cell via a capacitor combined with an integrator giving good step response and slow decay. Streamer current was measured at the low voltage side of the test cell. The current was monitored through a 50 Ω cable system with attenuators, ending in a Tektronix DPO4104 oscilloscope.

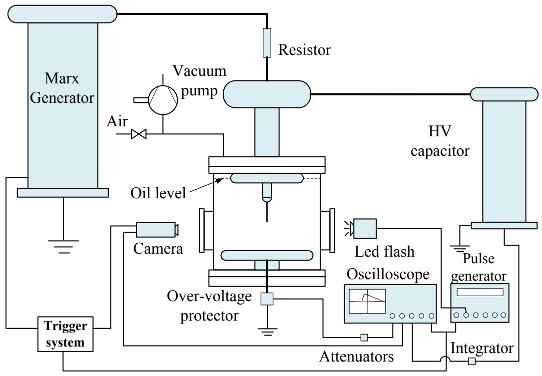

Fig. 1. Experimental setup

To capture frame images both with and without flash simultaneously, we use a diode flash controlled by a pulse generator. The flash can be switched on or off within 500 ns. The Marx generator, the pulse generator and the image converter camera, Imacon 468, were synchronized by a trigger system.

A 50% probability of breakdown voltage, V_b, was first determined. To do this, we applied voltage in steps of 5 kV with 10 consecutive shots for each step. A number of breakdown shots were counted, and V_b was found by Weibull statistics. V_b is 162 kV. To investigate the types of streamer channels, a critical voltage which is lower than V_b, i.e. 150 kV, was used. This critical voltage results in low probability for breakdown (around 10%), so we can observe all types of streamer channels. The differences among kinds of channels were recorded with images and current measurements. To examine the effect of reilluminations on streamers, three hundred tests at 155 kV were performed. All occurring events were recorded. The oil was filtered after every 10 shots. For examining the influence of vacuum on streamer channels, the vacuum of 152 mmHg, being created by a vacuum pump, was applied on the oil during experiment. Again, the oil was filtered after every 10 shots under vacuum condition. All results were obtained in white oil, Marcol-52, containing 67% paraffinic molecules and 33% naphthenic molecules by weight.

III. Results

A. Streamer channels

At 150 kV, three types of streamer channels were observed; dark, partly illuminating, and fully illuminating channels. The dark channels are recorded when streamers stop before touching the plane electrode or they cross the electrode gap without breakdown as shown in Fig. 2. No current can be detected around touching time. However, a DC current of 20 mA is measured during most of the propagation. It means that the dark channels may have low conductivity, so they are unable to cause a breakdown. The streak image of dark channels shows only weak light spots as seen in Fig. 3. There are more light spots detected at streamer tips than its stems because numerous ramifications present at streamer tips (Fig. 2). These light spots form a continuous trace at streamer tips during propagation (Fig. 3). It means that streamers continuously cross the electrode gap.

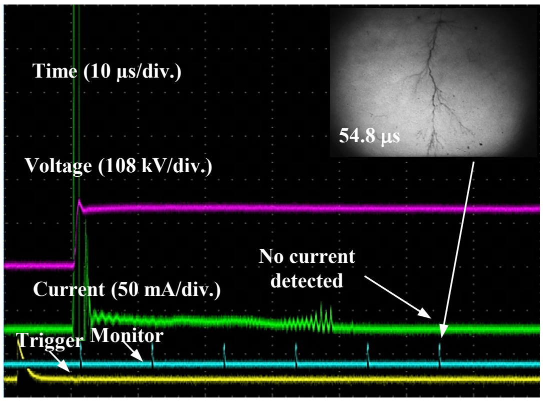

Fig. 2. Dark channels and correlated signals. 150 kV

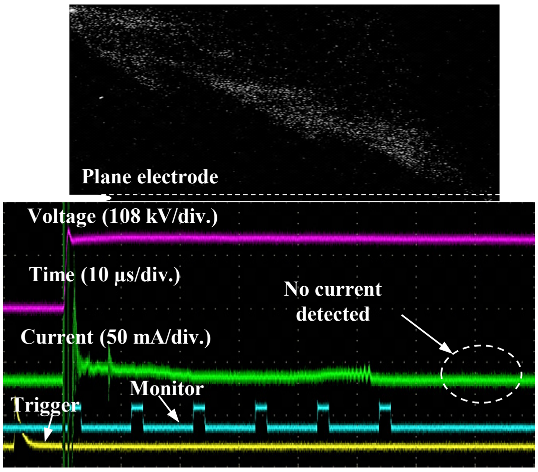

Fig. 3. Streak image and related signals. 150 kV

In some rare cases, partly illuminating channels are seen when streamers touch the plane electrode without causing breakdown. A small current of about 190 mA is recorded, and a channel section at the tip electrode strongly illuminates as shown in Fig. 4. Similar phenomena were previously reported in [5, 9]. Compared to dark channels, partly illuminating channel seems to be more conductive. However, they still cannot cause a breakdown.

Fully illuminating channels are mostly observed for breakdown streamers, but sometime also for non-breakdown streamers. They are accompanied by a higher current pulse of about 3 A as seen in Fig. 5. These channels are able to repeat to form the so called reilluminations (Fig. 6). Moreover, we observed that a breakdown process always took place when reilluminations touch the plane electrode. It is suggested that channels become highly conductive during reilluminations.

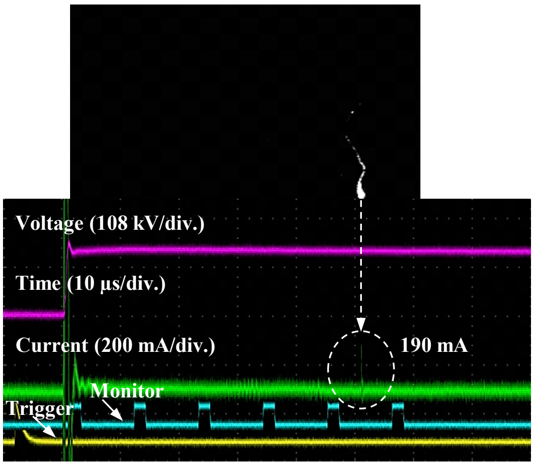

Fig. 4. Streak image of partly illuminating channels and related signals

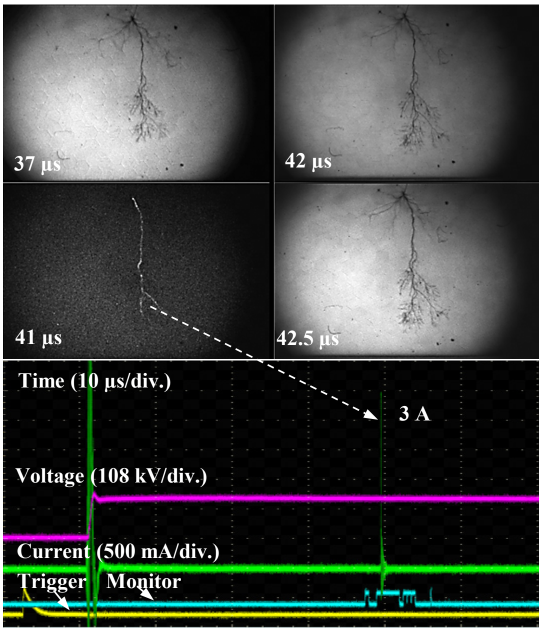

Fig. 5. Fully illuminating channels and related signals. 150 kV

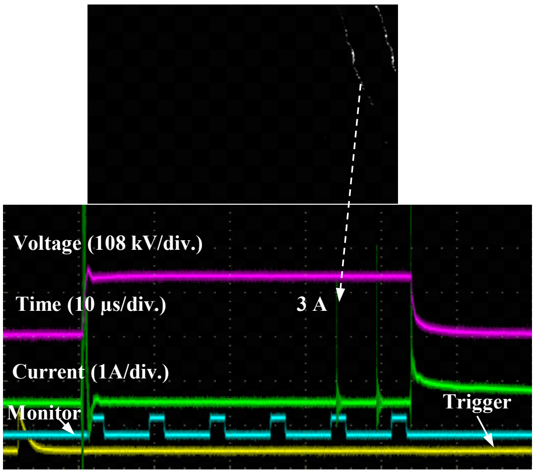

Fig. 6. Repetition of fully illuminating channels. 150 kV

When the applied voltage was increased well above V_b, i.e. 190 kV, both dark channels and reilluminations were observed in frame images as seen in Fig. 7. Reilluminations always appear within the streamer envelope. The channels can be illuminated during a very short time. It means that the dark channels are channels in the low illuminating state while reilluminations are channels in the high illuminating state. Besides, it was found that a breakdown channel coincides with the position of one of the reilluminations.

To count the number of streamer channels, the applied voltage was increased in steps from 150 kV to 210 kV. The number of channels against the applied voltage is shown in Fig. 8. It is quite linear fit for three cases. However, the largest discrepancy is for the case of reilluminations. It is found from the Fig. 8 that about 30 - 50% of total channels are able to illuminate, and a channel can illuminate several times.

B. *Effect of reilluminations*

Table 1 shows the outcome and probability of six types of events. We can see that breakdown with reilluminations has 6 times higher probability than breakdown without reilluminations. The probability for non-breakdown with reilluminations is only 2.34%.

From table 1, data extraction for all crossings, both breakdown and non-breakdown streamers, is shown in table 2. It is inferred that streamers with reilluminations have about 2.6 and 2.3 times higher probability for crossing and breakdown respectively than streamers without reilluminations.

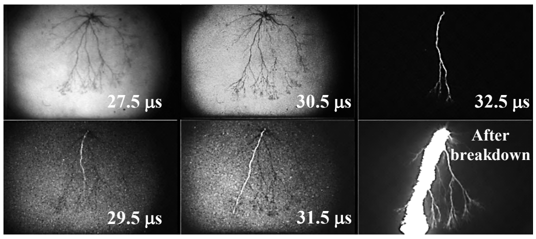

Fig. 7. Dark channels and reilluminations. 190 kV

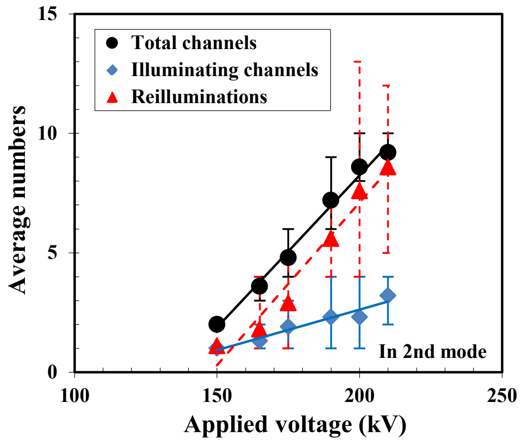

Fig. 8. Number of channels and number of reilluminations versus applied voltage

TABLE I
TYPE OF OCCURING EVENTS (155 kV)

No	Events	Outcomes	Probability (%)
1	Non-breakdown without crossing (no reilluminations)	167	55.67
2	Non-breakdown without crossing (reilluminations)	2	0.67
3	Non-breakdown with crossing (no reilluminations)	21	7
4	Non-breakdown with crossing (reilluminations)	5	1.67
5	Breakdown (no reilluminations)	15	5
6	Breakdown (reilluminations)	90	30
	Total	300	100

TABLE II
ALL CROSSINGS (BREAKDOWN AND NON-BREAKDOWN, 155 kV)

No	Events	Outcomes	Probability (%)	Number of BD	Probability for BD (%)
1	Crossing (no reill.)	36	27.5	15	41.7
2	Crossing (reill.)	95	72.5	90	94.7
	Total	131	100		

Fig. 9 and 10 show the average stopping length and streamer growth of non-breakdown streamers. Although, the average stopping length of streamers with reilluminations is larger than that of streamers without reilluminations, error bars partly overlap. Moreover, the distribution of streamer growths is fully over each other. The time to cross the gap of non-breakdown streamers is shown in Fig. 11. Streamers with reilluminations have smaller average time than streamers without reilluminations. However, their time ranges are nearly the same. This means that they will propagate with similar velocity. From these results, it is inferred that reilluminations have insignificant influences on propagation of non-breakdown streamers.

Reilluminations do not seem to affect the time to breakdown as shown in Fig. 11. However, the data scatter is slightly larger for streamers with reilluminations. Again, reilluminations do not have significant effects on propagation of breakdown streamers because of the overlap of the growth as seen in Fig. 12.

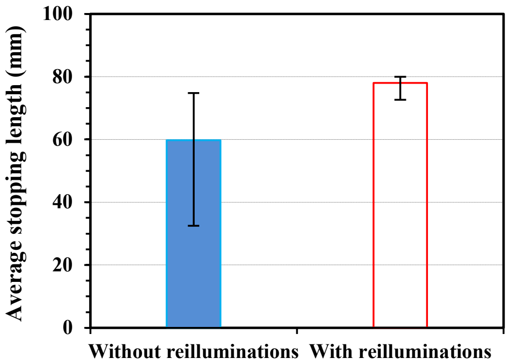

Fig. 9. Average stopping length. 155 kV

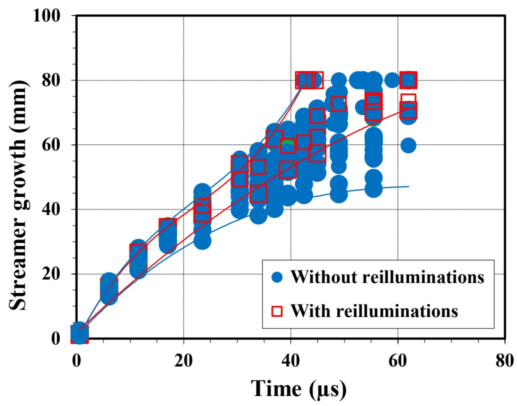

Fig. 10. Streamer growth versus time. Non breakdown streamers. 155 kV

C. *Effects of vacuum*

Fig. 13 shows the influence of vacuum on stopping length. Clearly, vacuum greatly increases the length. Assuming that (the inverse of) the increase in stopping length with voltage can be used to quantify the voltage drop along the streamer channels, this reduces about fourfold from 12.5 kV/cm to 3 kV/cm. Therefore, streamers more easily propagate under vacuum condition. From shape observation, with vacuum applied, streamers seem to become less branched at streamer tips excluding those near the plane electrode as exhibited in Fig. 14. Therefore, streamers will propagate more efficiently.

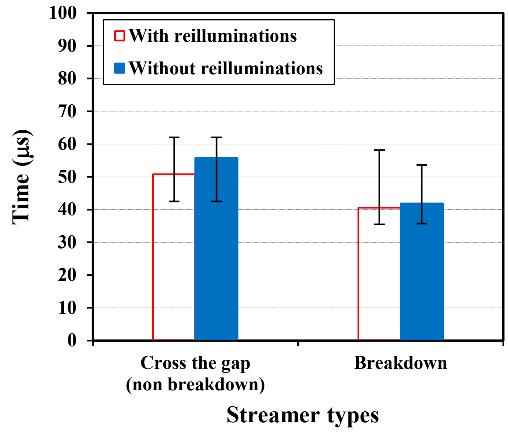

Fig. 11. Time to cross the gap and time to breakdown. 155 kV

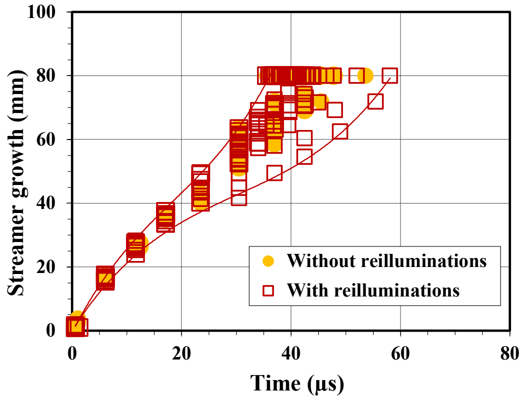

Fig. 12. Streamer growth against time. Breakdown streamers. 155 kV

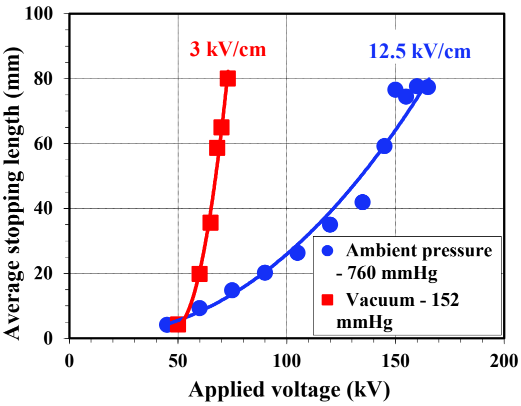

Fig. 13. Effects of vacuum on stopping length

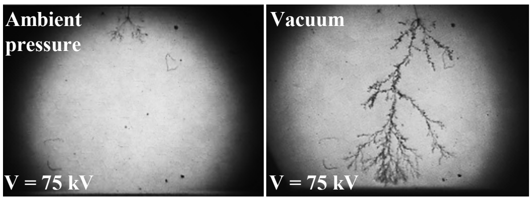

Fig. 14. Effects of vacuum on shape. Images were captured around stopping length (ambient pressure) and just before breakdown (vacuum)

Vacuum drastically reduces V_b as seen in Fig. 15. V_b decreases more than half from 162 kV to 70 kV. A possible explanation is that the decrease in V_b is due to an increase in stopping length as mentioned in an above section.

Although streamer channels were not investigated as detailed as in section A, we still observed that around V_b all crossing channels are dark and result in breakdown. Morever, there are no reilluminations recorded. High above V_b, some reilluminations appear. It means that under vacuum, breakdown more easily occurs but reilluminations are harder to be generated.

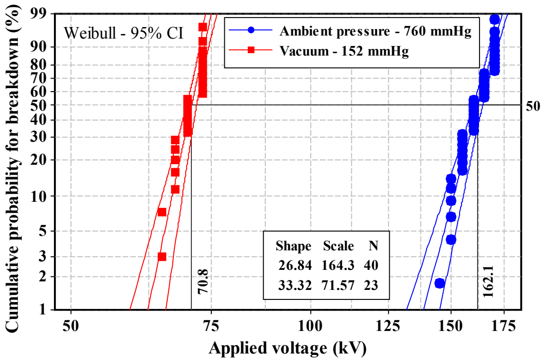

Fig. 15. Effects of vacuum on breakdown voltage

IV. Discussions

In [7], a model of the positive streamer was proposed as follows. Plasma state is inside the streamer channel, and space charges of 3-4 pC are at the streamer tips. The tip field to keep the propagation of streamer channels is estimated about 10^9 V/m [7]. The nature of the streamer channel considered plasma was supported by Linhjell et al. [4], and they speculated that this plasma state is well-conducting. With well-conducting channel, streamers should create a breakdown every time when touching the plane electrode. This is not the case as shown in this study and in [5, 9].

On the other hand, Gournay and Lesaint evidenced that streamer channels are composed of vapor of liquid [1]. This proof is supported by the effects of pressure [8] and of vacuum on streamers here (Fig. 13, 14, and 15). However the precise nature of these gaseous channels, e.g. chemical compositions, pressure, and temperature, is still unknown [11]. The idea of streamer channels filled with vapor of liquid can be used to explain why dark channels are low conductive and touch the plane electrode without inducing breakdown (Fig. 2 and in [5, 9]).

The voltage drop along streamer channel is estimated to about 10-20 kV/cm for mineral oil [12] and 12.5 kV/cm for Marcol in this study. Moreover, Kerr effect measurements show that streamer channel are rather good conductors [10]. This may indicate that the gaseous channels are filled with charges or the charges accumulate at the gas/liquid interface. However, the concentration of charges has not yet been quantified.

The fact that reilluminations do not have significant effects on propagation of streamers in this study can be explained by assuming the existence of critical space charges at streamer tips. These charges possibly create high enough magnitude of the electric field to drive the streamers. The presence of critical charges at streamer tips was mentioned in [7]. With this idea, we can also explain the phenomenon that streamers hit the plane electrode without causing breakdown but a bright luminous section existing at the channel tip and a small current pulse is recorded (Fig. 4).

As stated in a previous section, streamers with reilluminations expose 2-3 times higher probability for crossing the gap and breakdown than those without reilluminations. The reason is that after illuminating, the streamer channels may become more conductive because of the increase in the charge concentration inside the channels or at the gas/liquid interface. The increased conductivity of channels can lead to two effects. In the first one, with more conductive channels, the electrical connection between the space charges at the streamer tips and the needle electrode become stronger, thus enhancing or maintaining the tip field. Therefore the ability of streamer channels to cross the electrode gap will increase. In the other effect, more highly conductive channels will more easily result in breakdown when channels impinge on the plane electrode.

The fact that in vacuum, all crossing channels result in breakdown as mentioned in section C can be explained by both the voltage drop and the internal pressure. From Fig. 13, the voltage drop reduces from 12.5 kV/cm to 3 kV/cm when vacuum is applied. It could indicate that streamer channels are more conductive under vacuum leading easier to breakdown. With vacuum applied, the internal pressure may decrease. Thus, this pressure reduction will favor the breakdown in gaseous channels.

A decrease of about 4 times in the voltage drop may cause a large increase in conductivity of streamer channels as mentioned in above section. Thus there is never a sufficient voltage build-up within the channels to generate the gas discharge. If the gas discharge is a mechanism behind the reilluminations, the reilluminations will also have difficulty with occurring under vacuum. Our experimental results comply with this requirement, so the gas discharge could be responsible for appearance of reilluminations.

IV. Conclusions

An investigation of positive streamer channels has been performed. The results obtained from this study show that streamer channels can switch between low illuminating state (dark channels) and high illuminating state (reilluminations). Streamer channels are dark channels during almost the entire propagation time. Reilluminations show crucial effects for triggering breakdown although they do not play a significant role on streamer propagation, i.e. streamers propagate continuously to cross the electrode gap. The data support the idea that the critical charges presenting at the channel tips will control streamer propagation. It seems that processes occurring at the streamer tips are more important than those inside its channels. We also believe that the charges may exist inside the gaseous channels or at the gas/liquid interface. Vacuum facilitates both the stopping length and breakdown.

Acknowledgment

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Paper 5

Effects of reduced pressure and additives on streamers in white oil in long point-plane gap

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Effects of reduced pressure and additives on streamers in white oil in long point-plane gap

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Abstract: New experience tells that modern dielectric liquids behave differently from traditional mineral oil, particularly with respect to breakdown voltages for lightning impulse. This paper describes an experimental investigation addressing underlying reasons for this. The influences of reduced pressure and additives on streamers in white oil were investigated under both positive and negative polarities using an 8 cm long point-plane gap. Reduced pressure significantly accelerates streamers, thus increasing stopping length and reducing both breakdown and acceleration voltages. With increasing applied voltage, different typical propagation modes of streamers were recorded for both polarities. A low ionization potential additive strongly affects positive streamers. It significantly changes streamer velocity and reduces the breakdown voltage but increases the acceleration voltage where breakdown streamer velocity increases drastically. Adding an electron scavenger influences streamers of both polarities, but mainly increases the velocity of negative streamers and results in a reduction of both the breakdown and the acceleration voltages. The propagation mechanisms of streamers are also discussed.

1. Introduction

In earlier studies, streamers in hydrocarbon liquids, mineral oils, and additives have been investigated [1-7]. However, we still do not fully understand the phenomena. Recently, studies on biodegradable liquids, e.g. ester fluids, have been carried out to find new liquids that can replace mineral transformer oil in the future [8, 9]. Thus a better description and knowledge expansion of streamers are essential.

Mineral transformer oil has good electrical insulation properties because of high acceleration voltages for fast event streamers. The high acceleration voltage for mineral oils is possibly related to presence of polyaromatic compounds. With steadily changing and harder refining of mineral oil, the content of the electronically active compounds such as aromatics may change leading to potentially different dielectric behavior as a consequence. Hence, white oils, being highly refined and hydrogenated mineral oils virtually free from polyaromatic compounds, are suitable candidates of very low aromatic model liquids. A blend of white oil and additives can be considered a model of mineral transformer oil. The effect of additives on streamers in both small and long gaps has been reported in numerous papers [1-3, 10-12]. Nevertheless, studies on influences of additives on the fast event in long gaps are few. Furthermore, it is necessary to confirm reasons for the good *V-t* characteristics of mineral oil, i.e. with a high withstand for over-voltages of short duration due to the low probability of 4th mode streamers occurring for these short duration stresses.

Both gaseous and electronic processes involved in the pre-breakdown and breakdown phenomena in small gaps were evidenced by the influences of hydrostatic pressure and electron scavengers on negative streamers [1, 13].

In small gaps, increased hydrostatic pressure raises inception voltage, and suppresses the propagation of streamers leading to an increase in breakdown voltage [14]. However, influence of pressure changes on long gap breakdown has not earlier been studied. For cost reasons, experiments at elevated pressures were impossible, but our test vessel allowed for tests at reduced pressures.

In small gaps in n-hexane, the fact that *N,N*-dimethylaniline (DMA), a low ionization potential additive, had a significant effect on the growth of positive streamers, while carbon tetrachloride, an electron scavenger, slightly influenced the growth was reported in [2]. Moreover, low ionization potential additives markedly accelerate positive streamers, while electron scavengers only speed up negative streamers (in Marcol oil [1] and in cyclohexane [10, 11]). Similar results were also obtained in cyclohexane in long gap experiments [12]. Contradictory to this, in some studies in n-hexane in small gaps, DMA was found to reduce the velocity of positive streamers [3], and carbon tetrachloride increased the velocity of the positive streamers [15]. However, the impacts of low ionization potential additives and electron scavengers on streamers in white oils in long gaps have not yet been studied.

Long gaps are often considered to be longer than 5 cm [16, 17]. For small gaps and quasi-uniform distribution of electric field, the breakdown of streamers is governed by initiation [18]. However, for long gaps or non-uniform field, streamer propagation will control the breakdown [18, 19]. In addition, breakdown in long gaps is more relevant for the oil-solid insulation system in practical high voltage transformers. Thus, the investigation of streamer characteristics should be performed with long gaps.

In this study, we investigated the influences of reduced pressure and additives on streamer propagation and breakdown in white oil under both polarities. Both a low ionization potential additive, *N,N*-dimethylaniline (DMA), and an electron scavenger, trichloroethylene (TCE), were employed. Streamer characteristics are documented with stopping length, breakdown voltage, acceleration voltage and velocity. The different shapes that a streamer may take are also shown. Finally, the mechanism behind streamers is discussed.

To distinguish between different streamers types resulting from various applied voltages, we use the classification of streamer modes first introduced by Hebner (1988) [20] and then modified by Lesaint (1996) [21]. In this study streamer modes are first roughly classified as follows. The 1st mode streamers propagate with velocity of below 200-300 m/s while the 2nd mode streamers are faster (1-3 km/s). The 4th mode streamers are as fast as 100-200 km/s and 10-40 km/s for positive and negative polarities, respectively. The 3rd mode streamer is the transition between the slow 2nd mode and the fast 4th mode. The 3rd mode streamers have velocities of 5-20 km/s and 5-8 km/s for positive and negative polarities respectively.

In this paper, filamentary streamers are those containing smooth and thin channels. The streamer is bush-like if there are numerous branches originating from a common root point on the electrode. These branches are further subdivided into smaller branches. A tree-like streamer has one dominant channel enclosed by numerous smaller side channels.

2. Experimental setup and procedure

Figure 1 shows the experimental setup. An electrode system is comprised of a high voltage tungsten wire (ϕ = 0.15 mm) and a grounded plane (ϕ = 340 mm) with the electrode gap of 8 cm. A six-stage Marx generator was used to supply pulses resembling step voltages with 0.5 µs front time and 1700 µs for the time to half value. The waveform of a non-breakdown voltage pulse is illustrated in Figure 2. Within the maximum experienced duration of streamer propagation, the maximum voltage drop will be about 2% for positive polarity and 10% for negative polarity. A series resistor of 76 Ω was added to dampen oscillations and limit the breakdown current. To remove edge effects, the point electrode was initially conditioned with ten breakdowns. After this treatment, the point's tip resembles a hemisphere with radius of 75 µm when observed under a microscope. Then the treated point electrode was used to run experiments. When changing either voltage polarity or oil types, the same procedure for treating the new point electrode was repeated. Therefore the tip of the point electrode is similar in radius between experiments with different polarities or oil types.

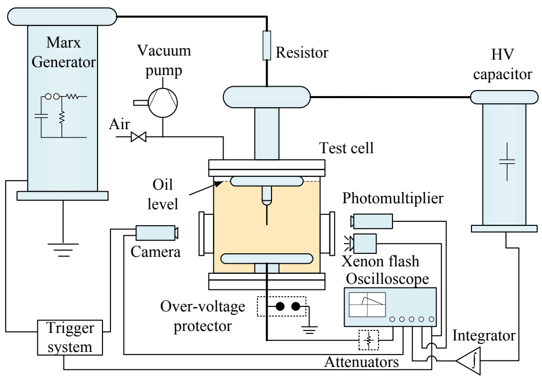

Figure 1. Experimental setup.

The step voltage was measured at the high voltage side of a test cell via a capacitor combined with an integrator giving good step response and slow decay [22]. It means that a current signal through the high voltage capacitor (representing the differentiation of the applied voltage) will be integrated into a voltage pulse observed by an oscilloscope (Tektronix DPO 4104). Streamer current was measured at the low voltage side of the test cell. The schematic of current measurement is shown in Figure 3. Light emission pulses from streamers were recorded by a photomultiplier (Philips 56 AVP) located close to a window of the test cell. The photomultiplier has a rise time of 2 ns, a response pulse width of 3 ns and a transit time of 35 ns.

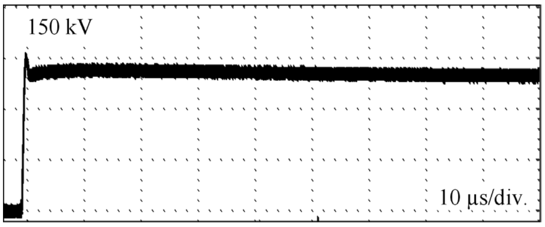

Figure 2. The waveform of a non-breakdown voltage pulse.

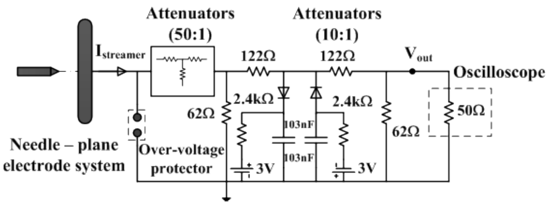

Figure 3. Schematic of current measurement.

Framing and streak images were captured by an image converter camera - Imacon 468. This camera has a resolution of 576 × 385 pixels per frame, the maximum framing rate is 10^8 frames per second, and the minimum exposure time is 10 ns. The Xenon flash was employed to produce shadowgraphic images. The Marx generator, the flash, and the camera were synchronized by a trigger system.

All results were obtained in pharmaceutical grade white oil, Marcol-52. From the datasheet, this oil contains 67% and 33% carbon atoms in paraffinic and naphthenic structures, respectively. The maximum concentration of polyaromatic molecules is about 0.05 wt% declared by the manufacturer; and it has a viscosity of 7 mm^2/s at 40^0C and a boiling point of 316^0C.

For examining the influence of reduced pressure, the tests were made either under ambient or low pressure. The reduced pressure (RP) was achieved by connecting a vacuum pump to the lid of the test cell to create a vacuum of 3 mbar above the oil surface during experiments, giving a pressure in the gap of 21-30 mbar due to the oil depth. The oil was degassed under 3 mbar for 30 minutes before experiments and filtered after every 10 impulses at each voltage step under vacuum condition for 30 minutes using a filter having a pore size of 0.2 μm.

To investigate the influence of additives on streamers, either DMA or TCE was mixed into the oil to a concentration of 0.064M, i.e. mol/l, which is similar to that used in a study on cyclohexane in a long gap [12]. The mixture of oil and DMA (or TCE) was filtered after every 10 impulses under ambient pressure.

The experimental sequence consisted of three stages; the voltage was increased in different steps depending on the stage. First, from initiation to breakdown, the voltage was increased with 15 and 30 kV steps for positive and negative streamers respectively. Then around breakdown voltage, 5 kV steps were used, and finally 30 kV steps were employed for voltages above this. Ten impulses were repeated at each step and applied for all stages except the propagation phase of negative streamers. Only five impulses were used at this stage because of the time consumption for cleaning the oil after each breakdown. Data of breakdown were analyzed by using a Weibull distribution. The expression for the cumulative distribution function for two parameter Weibull distribution is shown in (1). Here V_0 and β are the scale and shape parameters, and V is the peak voltage.

$$F(V) = 1 - \exp\left[-\left(\frac{V}{V_0}\right)^{\beta}\right] \quad (1)$$

3. Results

3.1. Positive streamers

3.1.1. Stopping length. Figure 4 shows the average stopping length, i.e. maximum length of non-breakdown streamer channels, versus the applied voltage. Reduced pressure (RP) greatly increases the stopping length that develops quite linearly with voltage with a rate of growth of about 0.33 cm/kV. However, under ambient pressure, streamers first develop with a much lower rate of 0.036 cm/kV in the lower voltage range, and then the rate increases with voltage to about 0.09 cm/kV. Reduced pressure makes channel propagation easier. From shape observations, with reduced pressure, streamers seem to become less branched at streamer tips excluding those near the plane electrode as exhibited in Figure 5. Neither DMA nor TCE does alter the nonlinear stopping length plot shape. DMA increases the stopping length for the streamers crossing more than half the gap whereas TCE has an insignificant effect on the stopping length. It is seen that data scattering is quite large and increases with applied voltage. The relative standard deviation (RSD) is around 20% for all cases except reduced pressure. A reduction in pressure will increase RSD to 46%.

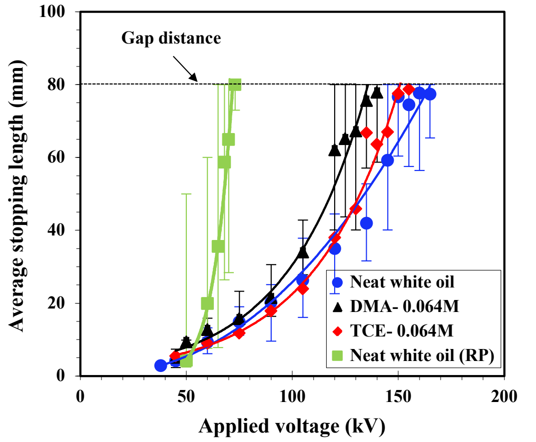

Figure 4. Stopping length of positive streamers versus applied voltage. Streamers reaching the plane electrode usually cause breakdown.

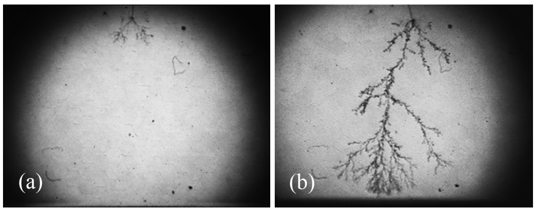

Figure 5. Effect of reduced pressure on streamer shape at 75 kV: (a) Neat white oil; (b) Neat white oil at reduced pressure. Images were captured around stopping length (a) and just before breakdown (b).

3.1.2. Breakdown voltage. Reduced pressure reduces the breakdown voltage, V_b, about a factor of two as seen in Figure 6. V_b is defined as 50% breakdown probability. DMA and TCE also reduce V_b; TCE less than DMA. The reduction in V_b reflects the increase in stopping length shown in Figure 4. The Weibull shape parameters are comparable among the four cases demonstrating similar data dispersion.

3.1.3. Time to breakdown and velocity. Stopping time, t_s, and time to breakdown, t_{BD}, are presented in Figure 7. Both inception delay time (t_i) [23, 24] and the time from onset of applied voltage to breakdown (t_{total}) were measured. Then, t_{BD} was determined by subtracting t_i from t_{total}. All time plots have a similar trend. Generally, t_s increases proportionally to applied voltage up to breakdown, after which t_{BD} is reduced with increasing applied voltage. At a threshold voltage (V_{th}), t_{BD} falls from some tens of µs to some µs, and it again gradually decreases when further raising the applied voltage. This result has been reported in cyclohexane, Exxsol oil, and mineral transformer oil [4, 12, 20]. Little effect on t_s is seen for additives, but it is strongly affected by reduced pressure. Reduced pressure not only increases t_s but also causes a steep increase with voltage. However, it does not significantly alter t_{BD}. For the 2nd mode streamers (below V_{th}), TCE decreases t_{BD} by 20-30% while DMA first reduces t_{BD} and then greatly increases it. For the 4th mode streamers (above V_{th}), TCE has no significant effects on t_{BD} whereas DMA increases it by a factor of two. RSD has a similar tendency and similar values with increasing applied voltage for all cases. Below V_{th}, RSD of t_{BD} is about 10% and increases to 100% around V_{th} where both slow and fast streamers occur. Above V_{th}, RSD drastically drops to about 6%.

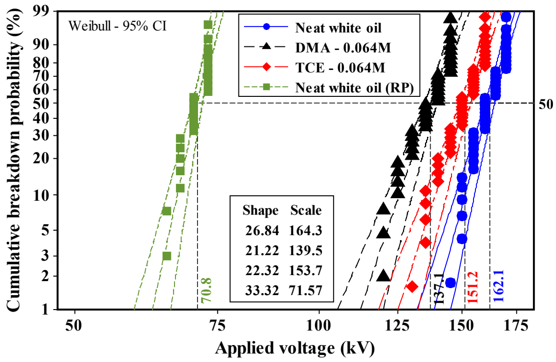

Figure 6. Weibull plots of breakdown voltages for positive streamers.

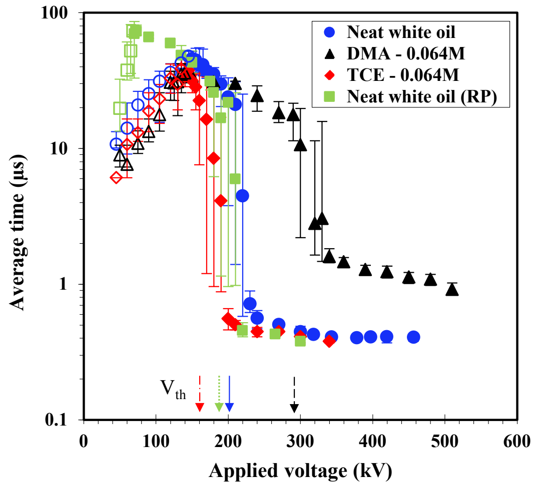

Figure 7. Average times to stopping and to breakdown for positive streamers versus applied voltage. Empty symbols for stopping time. Filled symbols for time to breakdown.

Figure 8 summarizes average velocity against applied voltage. Below the breakdown voltage V_b, the velocity is calculated from the measured stopping length and the stopping time. Above V_b, the velocity is determined from the gap distance and the time to breakdown. Generally, the velocity increases in "steps" as applied voltage is raised. The velocity measured at V_b is about 1-2 km/s. The rate of velocity increase is 0.022 (km/s)/kV in neat white oil. Reduced pressure does not significantly alter this, whereas DMA about halves it, and TCE raises it by a factor of approximately four. At a threshold voltage V_a, the velocity has increased to 3-4 km/s, and either slow or fast streamers randomly occur. V_a has a similar value to V_{th} in Figure 7.

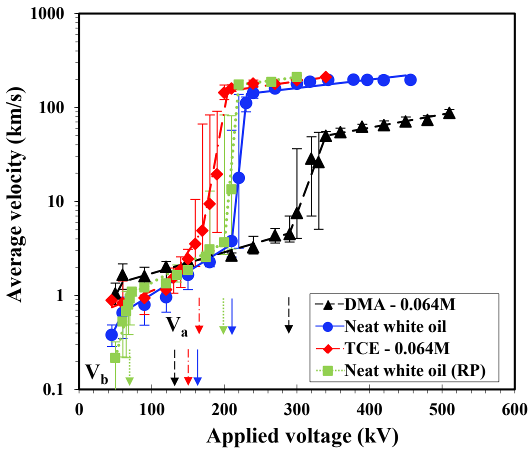

Figure 8. Average velocity of positive streamers versus applied voltage.

A sudden acceleration takes place when the applied voltage is just above V_a. This phenomenon has previously been observed in many kinds of liquids [4, 5, 8, 12, 19, 25]. Further above V_a, the velocity reaches a value of approximately 200 km/s except with DMA added, where streamer velocity for fast event is as low as 50-90 km/s. DMA markedly increases the velocity of non-breakdown streamers while TCE raises it a little. Thus, a reduction of V_b can be seen in Figure 6. However, while TCE continuously increases the velocity of breakdown streamers, DMA lowers it. Consequently, TCE decreases V_a while DMA increases it. Reduced pressure insignificantly raises the velocity, but it reduces V_b by a factor of about two as seen in Figure 6. Both TCE and reduced pressure decrease V_a, and increase the velocity of the 4th mode streamers. Nevertheless, DMA acts contrary. Thus, V_a is increased, and the velocity is reduced.

Below V_a, RSD of the velocity is approximately 20% and drops to about 6% when applied voltage is higher than V_a for all cases. Around V_a, RSD reaches a value of about 110% for neat white oil under ambient and reduced pressure while 52% and 76% are the values of RSD for the DMA and the TCE cases, respectively.

Table 1 presents the influence of reduced pressure, DMA, and TCE on the values of V_b, V_a, and V_a/V_b for positive streamers. Despite reducing V_b about 56%, reduced pressure only causes a decrease in V_a of approximately 5%. It means that reduced pressure has insignificant impact on the transition between slow and fast mode streamers. Both DMA and TCE strongly affect V_a and thus the formation of fast modes. DMA increases the ratio V_a/V_b to 2.1, while TCE reduces the ratio to 1.1, which is comparable to that of cyclohexane and ester oils [8, 12]. It means that a blend of white oil and TCE acts more like these simpler fluids. Similar to DMA, vacuum also raises the ratio to 2.8, but that is as a consequence of the reduction in V_b.

Table 1. Ratio V_a/V_b of positive streamers versus the types of oil and condition.

Types of oil	V_b (kV)	V_a (kV)	V_a/V_b
Neat white oil	162.1	210	1.3
DMA-0.064M	137.1	290	2.1
TCE-0.064M	151.2	160	1.1
Neat white oil (RP)	70.8	200	2.8

3.1.4. Streamer mode, shape and propagation. In [16], modes of positive streamers were defined. Streamers were classified into 1st, 2nd, 3rd and 4th modes according to streamer propagation velocities. The aim was to investigate the influences of reduced pressure and electronic active additives (DMA and TCE) on streamer modes. In this study, the 1st mode streamers were not observed, possibly because of the low optical magnification, but more likely because a large tip radius of the point electrode suppresses this streamer mode [26].

Up to V_b, only the 2nd mode streamers were seen with velocities of 1-2 km/s. Typical shapes of these streamers are shown in Figure 9. These streamers consist of some main channels with lateral branches being seen along main stems. Numerous ramifications appear at the tips of channels. It seems that DMA makes ramifications thinner while TCE reduces the number of ramifications. This may explain the fact that DMA and TCE increase the velocity of the non-breakdown streamers as seen in Figure 8. From the light emission recordings seen in Figure 10, DMA increases the number and magnitude of light pulses while TCE dramatically reduced these parameters. Although reduced pressure favors more branching, correlating with increasing both number and magnitude of current pulses (Figure 11), it still increases the velocity. It means that streamers propagate more efficiently under reduced pressure.

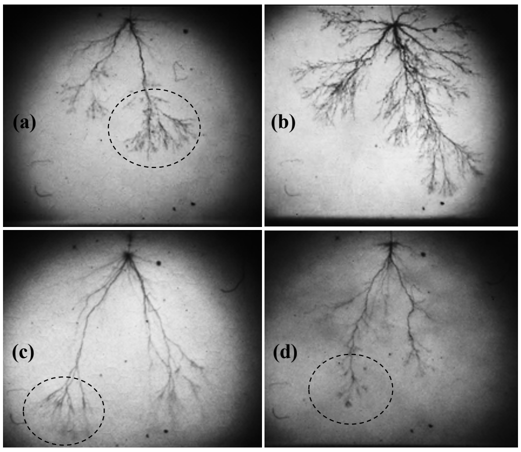

Figure 9. Shapes of the positive 2nd mode streamers at 145 kV: (a)-Neat white oil; (b)-Neat white oil at reduced pressure; (c)-DMA; (d)-TCE. All images taken just before breakdown except (a) photographed around stopping length.

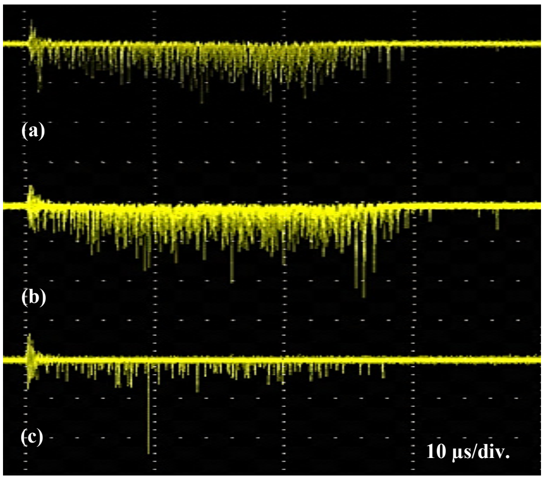

Figure 10. Light emission recordings of non-breakdown streamers at 135 kV: (a) Neat white oil; (b) DMA; (c) TCE.

In the range from V_b to V_a, the 2nd mode is still the normal propagating mode. The velocity reaches a higher value of approximately 3-4 km/s. Streamers become more branched as voltage is raised. As compared to neat white oil, DMA make streamers more branched at both the point tip and channel tips. However, only an increase in the number of ramifications at the channel tips can be clearly seen in Figure 12 because more than half of channels originating from the point tip die out around the middle of electrode gap. In contrast, TCE decreases the number of both channels and ramifications (Figure 12). For this reason, the velocity of breakdown streamers will be reduced by DMA but increased by TCE (Figure 8).

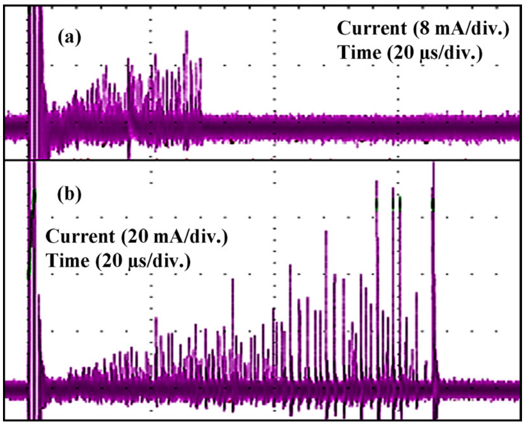

Figure 11. Streamer current recordings of non-breakdown streamers at 70 kV: (a) Neat white oil; (b) Neat white oil at RP.

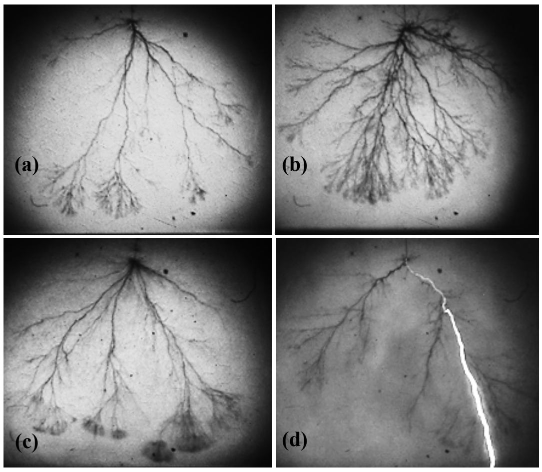

Figure 12. Shapes of the positive 2nd mode streamers at 180 kV: (a)-Neat white oil; (b)-Neat white oil at reduced pressure; (c)-DMA; (d)-TCE. All images taken just before breakdown.

A typical streak image of the 2nd mode streamers in neat white oil is shown in Figure 13. Streamers start with numerous weak light spots, forming a background light, created by "dark channels". Dark channels have a low conductivity and emit weak light [27]. Reilluminations appear just prior to the end of propagation. Fast current and light emission pulses correlate well with reilluminations. The measured velocity of about 2.5 km/s was seen during propagation. It was observed that streak images of reduced pressure, DMA and TCE cases have similar characteristics as described above except for the number of reilluminations. Both DMA and TCE boost the numbers of reilluminations while reduced pressure suppresses the appearance of reilluminations in the same voltage range.

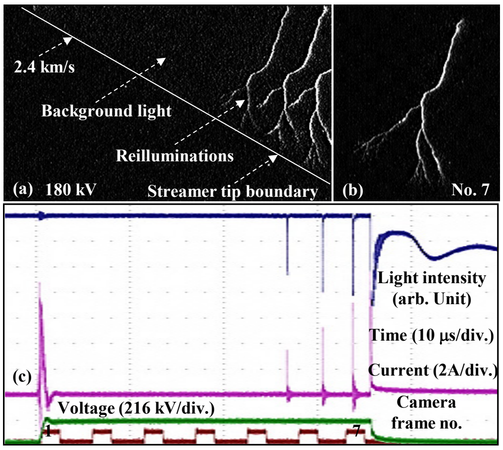

Figure 13. (a)-Typical streak image of the positive 2nd mode streamers in neat white oil; (b)-Frame image of (a); (c)-Corresponding signals of (a).

Around V_a, the 3rd mode, the transition mode, appears. The velocities vary between 3.5 and 21 km/s. Streamers consist of one or two main channels surrounded by numerous lateral branches as shown in Figure 14. DMA does not change the general shape of streamers but it causes denser branching and finer lateral branches. Figure 15 presents a typical streak photograph of this streamer mode in neat white oil. In the first stage, streamers begin with a very bright channel having the velocity of 50-100 km/s. However, they only propagate with velocity of 2.5-4 km/s in the later stage. One can see that reilluminations appear after the first bright channel, and they repeat fairly periodically. The background light is still detected between reilluminations. Similar characteristics as described above were also seen for streak images of reduced pressure, DMA and TCE cases.

Well above V_a, the 4th mode streamers were observed. Streamers consist of only a main bright channel with some lateral branches (Figure 16 (a) and (b)). Similar streamer shape was also seen with TCE added. As compared to the 2nd and 3rd mode streamers, the 4th mode streamers have much lower numbers of branches. This mode streamer is as fast as 100-200 km/s. However, with DMA, the velocity is only about 50 km/s, possibly due to the presence of numerous dark lateral branches reducing the macroscopic field [6]. Only high continuous luminosity was observed in streak images (Figure 17). The streamer velocity for the 4th mode directly measured from the streak image (Figure 17) roughly doubles that calculated from the electrode gap and time to breakdown (Figure 16) except the DMA case. This is possibly due to a delay time for breakdown after streamers cross the gap [28]. This delay time could be a significant part of the total time when time to breakdown is short.

If the applied voltage is increased to about $2\times V_a$, streamers will be more branched as seen in Figure 18. Despite more branches, streamers in neat white oil are approximately 3 times faster than those in a mixture of the neat white oil and DMA.

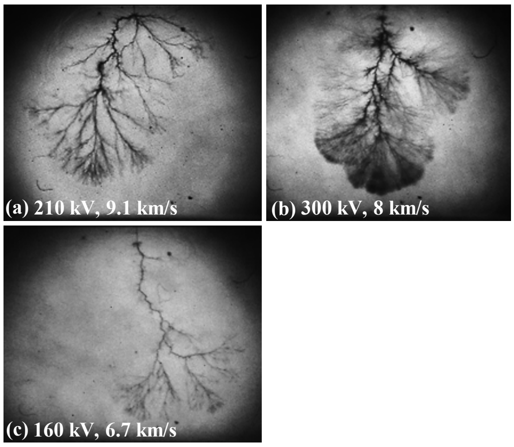

Figure 14. Shapes of the positive 3rd mode streamers; (a)-Neat white oil; (b)-DMA; (c)-TCE. All images taken just before breakdown.

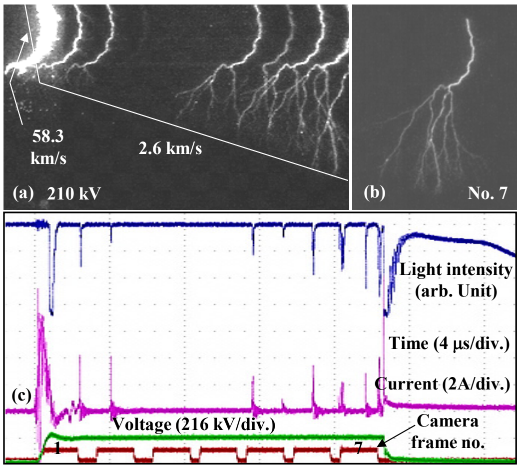

Figure 15. (a)-Typical streak image of the positive 3rd mode streamers in neat white oil; (b)-Frame image of (a); (c)-Corresponding signals of (a).

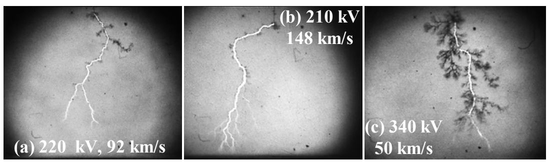

Figure 16. Shapes of the positive 4th mode streamers; (a)-Neat white oil; (b)-Neat white oil at reduced pressure; (c)-DMA. All images taken just before breakdown.

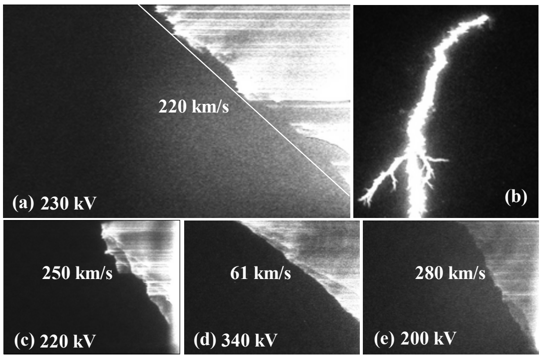

Figure 17. Streak images of the positive 4th mode streamers; (a)-Neat white oil; (b)-Frame image of (a); (c)-Neat white oil at reduced pressure; (d)-DMA; (e)-TCE.

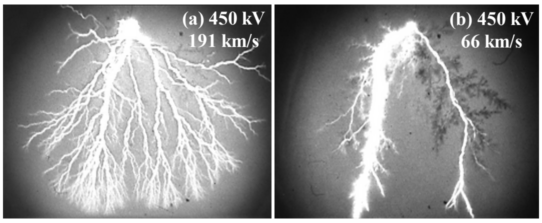

Figure 18. Branching of the positive 4th mode streamers; a)-Neat white oil; (b)-DMA. All images taken just before breakdown.

3.2. Negative streamers

3.2.1. Stopping length. In Figure 19, we have reported the stopping length of negative streamers versus applied voltage. The stopping length is pressure dependent. As for positive streamers, reduced pressure dramatically increases the stopping length of negative streamers. When streamers first appear they have a growth rate of 0.01 cm/kV, increasing to 0.11 cm/kV when they approach the plane electrode. Under ambient pressure, the rate is reduced to about one third (0.003 cm/kV) in the beginning, and streamers again reach a high rate of 0.08 cm/kV for later propagation.

The stopping length also depends on TCE content. Contrary to what was experienced for positive streamers, DMA has no significant effect on the stopping length while TCE greatly increases it. It may be noted that the effect of TCE on the stopping length of negative streamers now is similar to the effect of pressure reduction. RSD is approximately 18% for all cases.

3.2.2. Breakdown voltage. As for positive streamers, reduced pressure decreases V_b about 45% as shown in Figure 20. Different from what was seen for positive streamers, TCE has a much stronger effect on V_b than DMA. While TCE reduces V_b by a factor of about two, DMA slightly increases it. Again, a decrease in V_b in cases of reduced pressure and TCE can be associated with the increase in the stopping length (Figure 19).

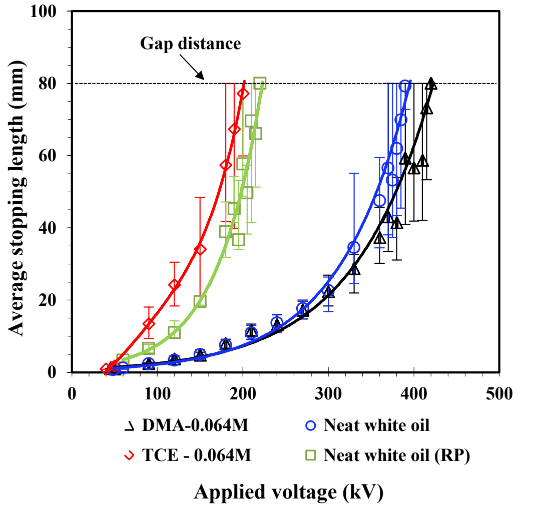

Figure 19. Stopping length of negative streamers versus applied voltage. Streamers touching the plane electrode usually cause breakdown.

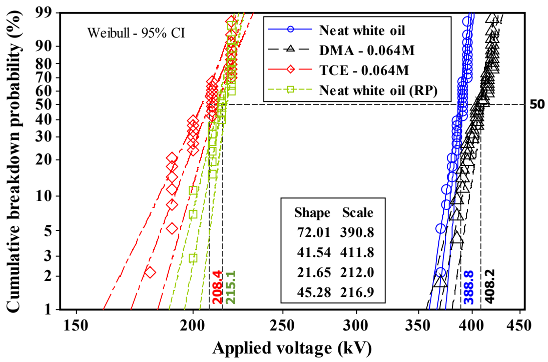

Figure 20. Weibull plots of breakdown voltages for negative streamers.

3.2.3. Average time and velocity. Figure 21 shows the average stopping time, t_s, and the average time to breakdown, t_{BD}, versus applied voltage. Time plots of reduced pressure and TCE cases have similar shapes. However, reduced pressure increases t_s about tenfold while TCE slightly reduces it. Both reduced pressure and TCE significantly decrease t_{BD}. However, while reduced pressure increases the maximum value of t_{BD} threefold, TCE also reduces it by a factor of three. On the other hand, DMA has no influence on t_s but raises t_{BD} a little. Similarly as for positive streamers, at a threshold voltage (V_{th}), t_{BD} of negative streamers falls from some hundreds of µs to some µs. RSD of t_{BD} shows a similar tendency when applied voltage is increased for all cases. Below V_{th}, RSD is about 17% and increases to 80% around V_{th} except for the DMA case. With DMA presence, RSD can reach a value of 240%.

Above V_{th}, RSD drastically reduces to about 20% for the DMA case and 11% for the other cases.

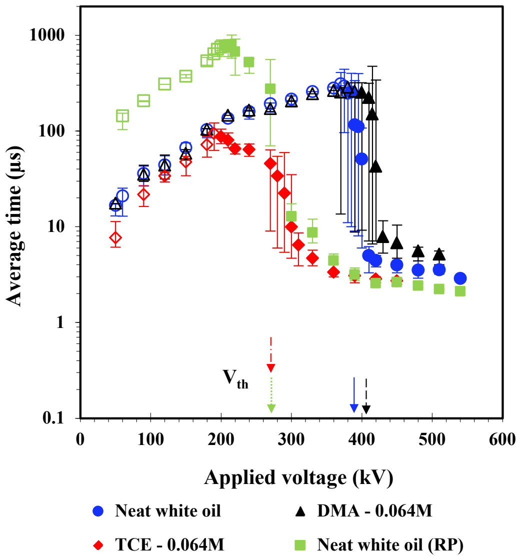

Figure 21. Average times to stop and breakdown for negative streamers versus applied voltage. Empty symbols for stopping time. Filled symbols for time to breakdown.

As for positive streamers, the velocity of negative streamers increases in step when raising the applied voltage (Figure 22). However, the velocity of negative streamers is only about one tenth of that of positive streamers. Below V_a, the velocity of 50-200 m/s was found for the neat white oil. This velocity is gradually increased with the rate of 0.3 (m/s)/kV. Although reduced pressure starts streamer propagation as slow as 20 m/s, the velocity increases with increasing voltage at a rate of 1.3 (m/s)/kV. Thus, reduced pressure reduces both V_b and V_a.

DMA does not influence the velocity. Nevertheless, TCE increases not only the velocity about tenfold but also the rate of velocity increase with voltage to 6.3 (m/s)/kV. This may be used to explain why TCE significantly reduces V_b and V_a. Similar as for positive streamers; at V_a, negative streamers appear either in slow or fast modes. Just above V_a, a steep rise in velocity is observed because streamers shift from slow to fast modes. For TCE and reduced pressure cases, when V_a is reduced, at the same time we observe an increase in velocity of fast mode streamers about 50%. On the other hand, DMA slightly raises V_a and reduces the velocity of fast mode streamers by around 35%.

Below V_a, RSD of the velocity shows a value of about 15%. Around V_a, it increases to 80% for reduced pressure and TCE cases and 150% for the other cases. Above V_a, RSD drops to approximately 11% except for the DMA case. DMA doubles RSD.

Table 2 shows the influence of reduced pressure, DMA, and TCE on V_b, V_a, and V_a/V_b for negative streamers. In neat white oil and with DMA, the ratio V_a/V_b is approximately 1. It means that in these cases, streamers accelerate around V_b, and DMA does not significantly change the ratio V_a/V_b. Nevertheless, both reduced pressure and TCE increase the ratio V_a/V_b to a value of about 1.3 because they reduced V_b more than V_a. Different from positive streamers; reduced pressure significantly reduces V_a of negative streamers, i.e. reduced pressure strongly affects the transition process from slow to fast modes. Similarly, TCE also markedly reduced V_a, thus significantly impacting this transition process to the 4th mode.

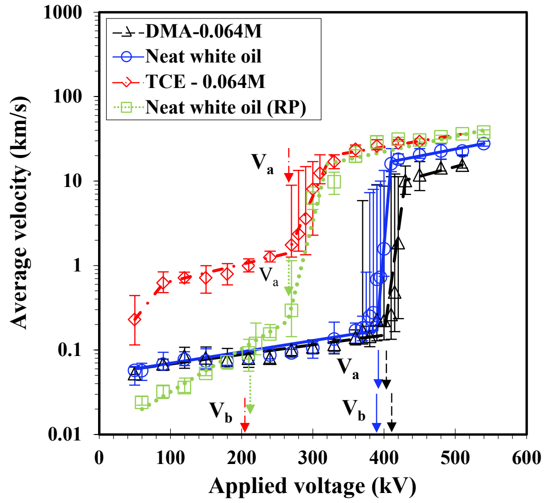

Figure 22. Average velocity of negative streamers versus applied voltage.

Table 2. The ratio V_a/V_b of negative streamers versus types of oil.

Types of oil	V_b (kV)	V_a (kV)	V_a/V_b
Neat white oil	388.8	390	1.00
DMA-0.064M	408.2	400	0.98
TCE-0.064M	208.4	270	1.29
Neat white oil (RP)	215.1	270	1.26

3.2.4. Streamer modes, shape and propagation. The four distinct negative streamers modes, also based on measured propagation velocity, were reported in [20]. However, these modes were observed in small gaps. Therefore, a more detailed description of negative streamer modes in a long gap is called for.

The 1st mode streamers were recorded when applied voltage was below V_a. This mode streamer can cross the electrode gap with very low velocity of 20-300 m/s and result in breakdown. Streamers have bush-like shape constituted of multiple channels emerging from the needle tip. The number of channels increases with voltage. These channels are further branched as seen in Figure 23 (a) and (b). Similar shapes of streamers were observed with DMA. This streamer mode cannot be seen in the TCE case because when TCE is added into white oil, streamer velocity is increased approximately tenfold (Figure 22), i.e. streamers switch from the 1st to the 2nd mode.

A typical streak image, correlated to light emission and current pulses, of streamers in neat white oil is shown in Figure 24. At first, luminous channels trigger the propagation with velocity of approximately 7 km/s, and then streamers develop with much lower velocity of 200-400 m/s. Some reilluminations and numerous diffuse flashes occur during propagation. A similar image was obtained with DMA. However, under reduced pressure, the background light, coming from both streamer stems and tips, is more visible and many weak reilluminations were recorded.

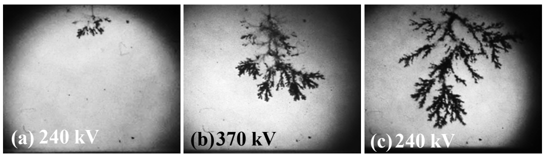

Figure 23. Typical shapes of the negative 1st mode streamers; (a)-Neat white oil; (b)-Neat white oil; (c)-Neat white oil at reduced pressure.

The 2nd mode streamers were observed around V_a except in the TCE case, which shows this mode streamers at values below V_a. In this mode, streamers are more filamentary than those of the 1st mode (Figure 25). Streamers have tree-like shape except in the TCE case. TCE makes streamers more filamentary and branched, resulting in a spherical overall shape (Figure 25 (c)).

Streamer velocity varies from 0.6 to 2 km/s. This 2nd mode cannot be seen in the DMA case. Figure 26 shows a typical streak image of streamers in neat white oil at reduced pressure. Similar to the 1st mode streamers, they still begin with bright channels. Nevertheless, in this mode, streamers not only have a higher starting velocity (24.4 km/s) but also propagate faster (1 km/s). Both background light and weakly continuous light, emitted from streamer heads, are observed. No current was recorded except for a small current pulse correlated to a light emission pulse. In the TCE case, a similar image to neat white oil at reduced pressure was recorded except that numerous weak reilluminations superimposed on the background light were captured. In this case, properties of the streak photograph are quite similar to those of the 2nd mode of positive streamers (Figure 13).

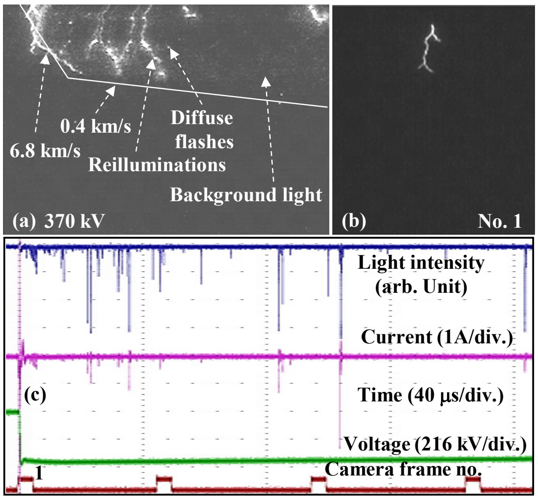

Figure 24. (a) A typical streak image of the negative 1st mode streamers in neat white oil; (b)-Frame image of (a); (c)-corresponding signals of (a).

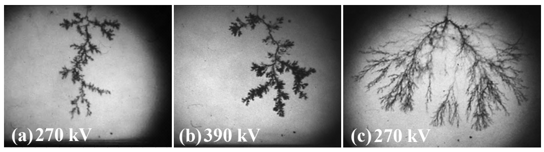

Figure 25. Typical shapes of the negative 2nd mode streamers; (a)-Neat white oil at reduced pressure; (b)-Neat white oil; (c)-TCE.

Similarly as for positive streamers; the 3rd mode of negative streamers, appearing around V_a, was also defined as a transition mode. However, this streamer mode was only observed in some rare cases. Then streamers comprise of one main stem enclosed by lateral branches as exhibited in Figure 27. Numerous small "knobs" appear along the main and lateral stems except for the TCE case. It was observed that DMA does not significantly change the shape of this streamer mode. As compared to the 2nd mode streamers, the 3rd mode streamers seem to be thinner, and they cross the electrode gap with higher velocity (5-8 km/s). Streamer propagation is composed of two successive stages (Figure 28). Luminous channels of 40 km/s are seen at the beginning of propagation and streamer propagates with velocity of 3.3 km/s. An increase in velocity to 9.5 km/s is measured in the later stage. Reilluminations seem to repeat quite periodically during propagation.

The 4th mode streamers are easily observed as the applied voltage is above V_a. Streamers are composed of some main channels surrounded by numerous lateral branches as shown in Figure 29. It seems that small "knobs" seen in the 3rd mode streamers develop into the lateral branches for this mode streamers. Streamers are as fast as 10-40 km/s. In comparison with neat white oil, the 4th mode streamers seen with DMA added have similar shapes. When further increasing the applied voltage, streamers will branch more. Figure 30 presents the typical streak image of this streamer mode. Streamers start with high velocity of 38 km/s during 1 μs, and then velocity falls to less than one third (11 km/s) before increasing again to 44 km/s during the final stage. A steep rise in this final stage may result from bright channels, occurring when streamers approach the plane electrode (Figure 29). Similar characteristics can be seen for streak images of the streamers in the neat white oil, DMA and TCE cases. Well above V_a, only continuous luminosity can be seen in the streak image (Figure 31), and streamers propagate with quite constant velocity of 28 km/s. Correlated to this, a continuous light emission is seen (Figure 31 (c)). Although streamer current cannot be recorded in this case due to the high capacitive current at a rising edge of the impulse, it is believed to have similar shape to the light pulse, i.e. streamer current steadily increases. As compared to positive streamers (Figure 17), the continuous luminosity of the 4th mode negative streamers seems to be less visible.

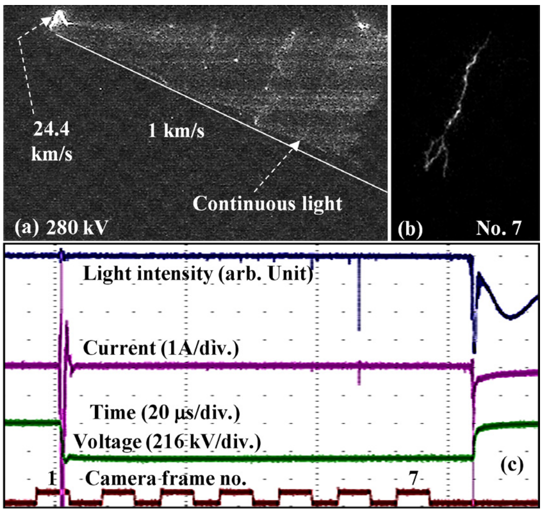

Figure 26. (a)-A typical streak image of the negative 2nd mode streamers in neat white oil at reduced pressure; (b)-Frame image of (a); (c)-Corresponding signals of (a).

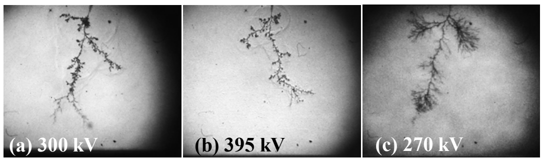

Figure 27. Typical shapes of the 3rd mode streamers. (a)-Neat white oil at reduced pressure; (b)-Neat white oil; (c)-TCE.

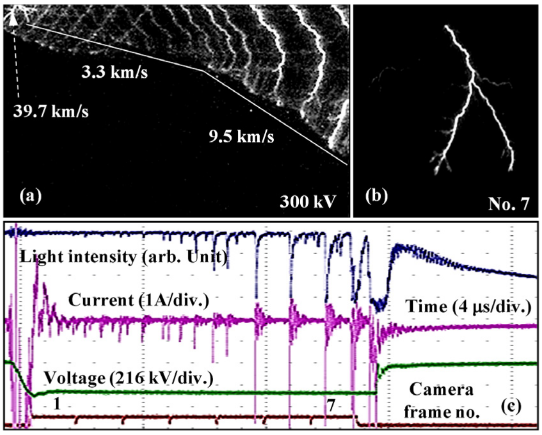

Figure 28. (a)-Typical streak image of the 3rd mode streamers at 300 kV in neat white oil at reduced pressure; (b)-Frame image; (c)-Corresponding signals.

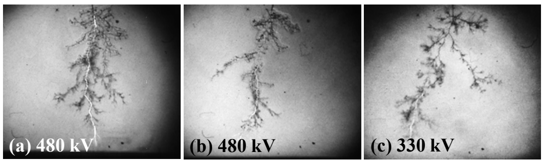

Figure 29. Typical shapes of the negative 4th mode streamers; (a)-Neat white oil at reduced pressure; (b)-Neat white oil; (c)-TCE. All images taken just before breakdown.

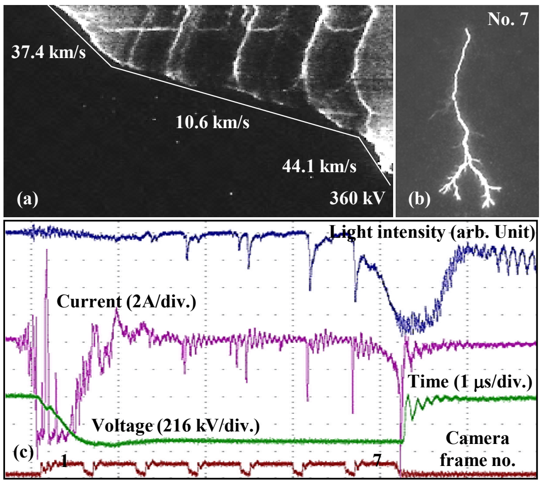

Figure 30. (a)-Typical streak image of the negative 4th mode streamers in neat white oil at reduced pressure; (b)-Frame image of (a); (c)-Corresponding signals of (a).

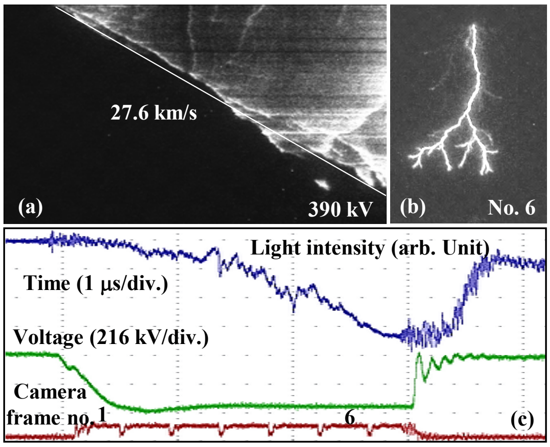

Figure 31. (a)-Typical streak image of the negative 4th mode streamers at 390 kV in neat white oil at reduced pressure; (b)-Frame image; (c)-Corresponding signals.

4. Discussion

4.1. Comparison between polarities

Positive streamers are more filamentary than negative streamers (Figure 9 and Figure 25) and about ten times faster than negative streamers (Figure 8 and Figure 22). The breakdown voltage of positive streamers is less than half that of negative streamers (Figure 6 and Figure 20). Three types of modes were seen for positive streamers while four distinct modes were observed in negative streamers. Just above V_a, the branches of both positive and negative streamers are drastically reduced and streamers switch from slow to fast modes (Figure 8, Figure 14, Figure 22, and Figure 27).

Although reduced pressure makes both polarity streamers much more branched, it still increases the velocity of breakdown streamers and reduces V_a (Figure 8, Figure 9, Figure 22, and Figure 23). It seems that reduced pressure have a stronger effect on streamer velocity than branching. Reduced pressure decreases V_a about 5% and 31% for positive and negative polarities respectively. It means that the transition from slow to fast modes in negative streamer is more sensitive to reduced pressure.

For positive streamers, DMA accelerates non-breakdown streamers, and decelerates breakdown streamers, thus reducing V_b and increasing V_a (Figure 6 and Figure 8). On the other hand, negative streamers are only insignificantly influenced by DMA (Figure 20 and Figure 22). This is similar to what has been reported for Marcol 70 in small gaps [1] and in cyclohexane in a long gap [12]. It is suggested that the reason is as follows: The kinetic energy of seed electrons emitted from streamer tips drastically reduces with increased travel distance since the electric field quickly decreases with the distance from the tip. Moreover, the number of DMA molecules is low for a volume closer to the tip. Thus, the probability of the seed electrons to collide with and ionize the molecules of DMA is low. In addition, at negative polarity, an abundance of seed electrons is emitted from the tips so a few extra electrons from ionization of DMA molecules can only make little change to number of and size of electron avalanches. This suggests why the influence of DMA on streamer propagation of negative polarity is insignificant.

Because TCE makes positive streamers less branched and negative streamers more filamentary, it slightly increases the velocity of positive polarity and markedly raises that of negative polarity. Consequently, V_b and V_a of both kinds of streamers are reduced (Figure 8, Figure 9, Figure 22, and Figure 25).

4.2. Comparison with other liquids

4.2.1. Positive streamers. Because of similar experimental conditions, a comparison of positive streamers in white oil in this study with those in mineral transformer oil in [5, 25] is performed. Although, the general characteristics of positive streamers are quite similar between the two types of oils, their streamers still show some different behaviors as follows. First, the ratio V_a/V_b is about 1.3 for white oil and reaches approximately 2.2 for mineral transformer oil. This is because V_a is much higher for mineral transformer oil though both oils possess similar V_b (V_b = 162.1 kV for 8 cm gap in white oil; V_b ~130 kV and 180 kV for 7.5 cm and 10 cm gaps in mineral transformer oil [5]; V_b ~135 kV for 6 cm gap in mineral transformer oil [25]). The special characteristic of very high V_a of mineral transformer oil is attributed to the presence of a certain amount of polyaromatics. This is evidenced by adding a low ionization potential additive, e.g. pyrene, into cyclohexane [10]. This result was reproduced with another low ionization potential additive (DMA) in long gap studies in cyclohexane [12], in Exxsol oil [23], and in white oil here. From Table 1, adding DMA into white oil will increase the ratio V_a/V_b from 1.3 to 2.1. Second, the voltage range of the transition from the slow 2nd mode to the fast 4th mode streamers, which was first mentioned in [4], is different for these oils. In mineral transformer oil, this transition voltage range is around 100 kV [8], whereas it is much smaller and around 30 kV in white oil here. However, with small amount of

DMA, the transition voltage range is raised from 30 to 50 kV (Figure 8). Thus, from above data, one can state that for positive streamers, mixing a small amount of a low ionization potential additive, e.g. DMA, into white oil behaves more like mineral transformer oil. Third, in mineral transformer oil, well above V_a, the 4th mode streamers, preceded by the 3rd mode streamers, only occurred at the end of propagation. On the other hand, in white oil, streamers start and cross the electrode gap in the 4th mode (Figure 17).

4.2.2. Negative streamers. Negative streamers in white oil are compared with those in mineral transformer oil from [7, 25]. The general tendency of streamer velocity with increasing applied voltage is similar in both oils. However, streamer velocity is considerably lower for white oil. Below V_a, velocity of streamers in white oil is one tenth that in mineral transformer oil (0.06 km/s - 0.2 km/s for white oil; 0.6 km/s - 2 km/s for mineral transformer oil). Above V_a, streamer velocity of white oil is approximately 25% slower than that of mineral transformer oil (30 km/s for white oil; 40 km/s for mineral transformer oil). Reasonably, V_b of white oil is about 1.7 times higher than that of mineral transformer oil, although the electrode gap is smaller for the test in white oil (8 cm for white oil and 10 cm for mineral transformer oil [7]). In contrast, compared to another mineral oil in [25], V_b is only slightly higher for white oil (275 kV for 6 cm gap in mineral oil and 388.8 kV for 8 cm gap in white oil). This may be because of the different aromatic content between these mineral oils. When adding an electron scavenger, e.g. TCE, into white oil, the streamer velocity increases about tenfold to approximately 1-2 km/s, which is similar to that of mineral transformer oil [7], and V_b is reduced about a factor of two as shown in Figure 22. It means that for negative streamers, a mixture of TCE and white oil resembles mineral transformer oil very much.

4.2.3. Effect of hydrostatic pressure. In small gaps, in white oil, a reduction in pressure only facilitates the streamer propagation at low voltages [1]. This is quite different from our results showing that under reduced pressure, streamers propagate more easily for all voltage levels. On the other hand, increased pressure suppressed streamer propagation in n-pentane and cyclohexane [13, 29]. The possible explanation is that the reduction of pressure will either reduce the boiling point of the oil or facilitate easier bubble formation [30, 31]. It means that the probability of formation of bubbles created by either energy injection into the liquid from electronic processes or electro-mechanical stress [32] or both is increased under reduced pressure. The bubbles will expand to a larger size with a longer lifetime under reduced pressure [33]. This eases the formation of gaseous channels and then streamer propagation.

For positive polarity, although reduced pressure makes streamers more branched, it does not reduce streamer velocity (Figure 8). The increase in the shielding effect due to more branching is possibly counterbalanced by the enhancement of either oil evaporation or bubble formation processes induced by reduced pressure. V_a of positive streamers is almost unchanged by reduced pressure. This may indicate that the appearance of fast streamers possibly only depends on electronic processes in the liquid phase at channel tips.

For negative polarity, reduced pressure markedly changes streamer velocity. It decelerates non-breakdown streamers but accelerates breakdown streamers (Figure 22). This indicates that gaseous processes play an important role in all modes of these streamers. In spite of lower velocity and higher number of branches, the 1st mode streamers can propagate much further under reduced pressure. Thus, the propagation of the 1st mode streamers largely depends on the gaseous processes. Reduced pressure significantly reduces V_a of negative streamers. It means that both electronic and gaseous processes govern the occurrence of fast mode negative streamers.

In a small gap, the increase of hydrostatic pressure raised the initiation and breakdown voltages of tetra-ester even though the streamer velocity was increased [14]. In another small gap, the reduced pressure decreased the breakdown voltage of negative streamers much more than that of positive ones in mineral transformer oil [33]. However, in a long gap, the reduced pressure largely lowers the breakdown voltage of both polarities of streamers in white oil in this study, as a consequence of an increase in stopping length and velocity (Figure 4, Figure 8, Figure 19 and Figure 22). Thus, the breakdown voltage is increased with hydrostatic pressure for both small and large gaps as well as for both polarities.

Although, the present study in white oil was not particularly directed towards initiation (the point electrode could possibly be slightly different under the different conditions) it was found that the initiation voltage was not significantly different for normal and reduced pressure, indicating that initiation may be dependent on processes in the liquid phase.

4.2.4. Effects of additives. The fact that low ionization potential additives mainly affect positive streamers in hydrocarbon liquids and mineral oil was reported in [1, 11, 12]. This result is confirmed in this study. Moreover, one has seen that adding a low ionization potential additive, e.g. *N,N*-dimethylaniline (DMA) or pyrene, into pure liquids will result in either acceleration or deceleration of non-breakdown positive streamers. The reason is probably that these additives make positive streamers either more filamentary or more branched. With more filamentary channels, the additives will speed up streamers (in [12] and in this study) whereas with higher number of branches, they will slow down streamers [3, 19] due to mutual electrical shielding resulting in lower tip field. Therefore, low ionization potential additives either decrease or increase the breakdown voltage depending upon whether more filamentary channels or more branching is the dominating effect in the actual liquid. In [10, 12, 19, 23], low ionization potential additives decelerated breakdown positive streamers in cyclohexane and Exxsol oil due to the branching effect, leading to an increase in acceleration voltage. This result is identical to what was observed in white oil here.

In [1, 11, 12], electron scavengers such as Trichloroethylene (TCE) and carbon tetrachloride speed up only negative streamers in cyclohexane and white oil since these scavengers make streamers more filamentary. On the other hand, in this study, electron scavengers still accelerate positive streamers, thus decreasing both V_b and V_a of both polarity streamers. Contrary to this result, in small gaps in tetra-ester, electron scavengers raise the breakdown voltage of both polarity streamers although they increase the streamer velocity [14]. This confirms the fact that in small gaps the breakdown voltage is possibly controlled by initiation conditions, and illustrates that it is difficult to extrapolate the breakdown voltage from small gap studies to longer gaps.

4.2.5. Application to mineral transformer oil. A comparison between white oil and mineral transformer oil is shown in Figure 32.

In white oil, it is seen that positive streamers are about ten times faster than negative streamers. Moreover, the breakdown and acceleration voltages of positive streamers are about half of those of negative streamers. Therefore, positive streamers are more dangerous than negative ones in white oil.

In mineral transformer oil (Voltesso 35), positive streamers are only two times faster than negative streamers. Similar values of acceleration voltages are seen for both polarities. The breakdown voltage of positive streamers is about 80% of negative ones. It means that the hazard from positive streamers is significantly reduced for mineral transformer oil.

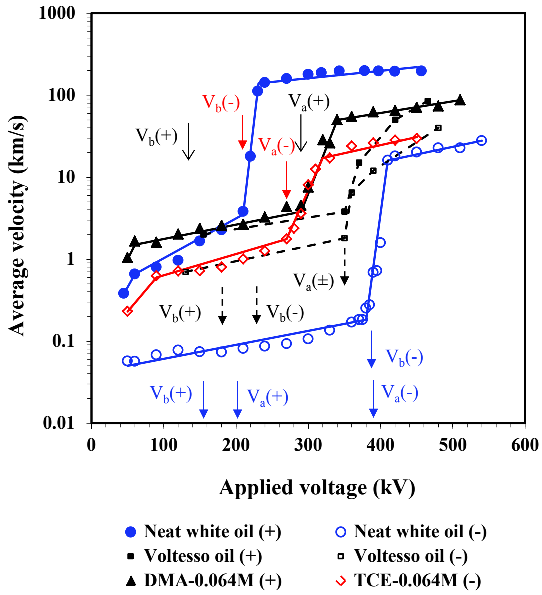

Figure 32. Average velocity versus applied voltage. Dash lines: mineral transformer oil [7].

With the presence of DMA, V_a of white oil is significantly raised to a value that is comparable to Voltesso oil. DMA also raises the ratio V_a/V_b of white oil to 2.1, which is in line with Voltesso oil (1.9-2.1) [7]. Moreover, as seen in Figure 32, the plot of velocity versus applied voltage in the case of DMA-0.064M has a tendency of approaching Voltesso oil.

When TCE is added into white oil, the three following effects are observed. First, as shown in Figure 32, TCE increases the velocity of negative streamers to a value of Voltesso oil (~1 km/s) probably related to streamers becoming more filamentary. Second, both V_b and V_a have a tendency to be reduced to a value comparable to Voltesso oil. Finally, the velocity of fast mode streamers is increased to that of Voltesso oil (Figure 32).

It is observed that the ratio $V_{b(-)(TCE\text{-}0.064M)}/V_{b(+)(DMA\text{-}0.064M)}$ is about 1.5 that is comparable to $V_{b(-)}/V_{b(+)}$ of Voltesso oil (1.3). The ratio $V_{a(-)(TCE\text{-}0.064M)}/V_{a(+)(DMA\text{-}0.064M)}$ is approximately 0.93 that is in the range of $V_{a(-)}/V_{a(+)}$ of Voltesso oil (~1.0).

From these above observations, it is proposed that the presence of aromatic/polyaromatic compounds, which have both a low IP and electron scavenging properties, in mineral transformer oil is the main reason for the similar properties of positive and negative streamers. Adding both a low IP additive and an electron scavenger to white oil may generate a type of oil similar to mineral transformer oil for both polarities.

4.3. Mechanism for streamer propagation

4.3.1. Positive streamers. The slow 2nd mode streamers begin and travel across the electrode gap with dark channels, which were defined in [27]. These channels have low conductivity, which is manifested by high voltage drop (10-20 kV/cm) and no current measured [5, 27]. This may be a sensitivity problem since it was set low so that possible reilluminations of several amperes should not be out of range. The fact that there is a gaseous phase inside streamer channels was documented in [30]. As found in [27], the channel conductivity of the 2nd mode streamer is unimportant for propagation, i.e. the processes taking place inside the channel are insignificant. Only the processes in front of streamer heads play a crucial role. As mentioned above, reduced pressure slightly increases streamer velocity and reduces V_a a little while DMA significantly affects both the velocity and V_a. It suggests that the main processes at streamer heads controlling propagation may be electronic processes. Critical charges, i.e. positive ions which produce a sufficiently high electric field to sustain new avalanches, are believed to be present at the channel tips [1, 2, 27]. Chadband and Sufian (1985) estimated a magnitude of 3-4 pC for the critical charges [2], i.e. the number of charges at the streamer head is about $1.9\text{-}2.5\times10^7$, which is lower than the critical value of charge number (10^8) in the avalanche head for the transformation from avalanche to streamer in gas discharge [34]. These critical charges were assumed to induce a tip field of 10 MV/cm [30]. An estimation of 20 MV/cm for the tip field was reported in [35]. This field was suggested to be high enough for ionization of liquid molecules [30, 35, 36]. Thus, new positive ions and electrons are created. A number of electrons may become attached and form negative ions. The movement of these negative charges, i.e. electrons and negative ions, induces thermal energy heating up and vaporizing the liquid. Thus, the streamer channel is extended. The thermal power dissipated at the channel tip was calculated to be about 10 W [30]. The idea of ionization processes taking place at the channel tip is supported by the influence of low ionization potential additives in this study or in [1, 3, 10, 11, 12]. The fact that increased pressure suppresses streamer growth [29] and reduced pressure favors its propagation in this study supports the existence of gaseous processes. Although the tip field was proven to be one of the main factors to control streamer propagation [18], a correct value of this tip field has not been determined. This is because of the presence of multiple channels, with further branching, and undefined dimensions and magnitude of space charges at the channel tips. However, we support the hypothesis that for continued propagation, the channel tip field is at least equal to the needle tip field at initiation voltage [37]. In this study, the slow bush-like streamers (1st mode) could not be observed because of the large radius of the needle electrode (diameter ϕ = 0.15 mm). Only filamentary streamers are recorded at the 50% initiation voltage (52 kV). The field at the needle tip is calculated to be 2.4 MV/cm at 52 kV by using the finite element method (FEM) [38, 39] with COMSOL Multiphysics program. The model for this calculation is shown in Figure 33a. This field value is higher than the suggested minimum field (1.3 MV/cm) for an electron multiplication process in n-hexane [40]. Numerous ramifications at the channel tip in Figure 9 and Figure 12 may be an indication of this process. Consequently, impact ionization in a small volume of liquid ahead of the channel tip is suggested to explain the formation of new charges. With simulation, discharges inside micro-bubbles formed by high electric field at the channel tips were considered origins for starting new streamer branches [36]. This may indicate that micro-bubbles act as one source of supplying seed electrons for the impact ionization.

At V = 220 kV > V_a, the fast 4th mode streamers start and propagate with bright channels (Figure 16a). The time to breakdown of this mode streamer is less than 1 μs, whereas it is 20-50 μs for the 2nd mode streamer. Although the current pulse of this streamer mode could not be recorded in this study due to the high capacitive charging current during the initial part of the impulse, it is probably continuously increasing [8]. In addition, the voltage drop of streamers in mineral transformer oil at V_a is smaller than 1 kV/cm [6]. Thus, the 4th mode streamer channel may be highly conductive, and the propagation mechanism as well as the nature of streamer channels of the 4th mode streamers is possibly different from those of the 2nd mode streamers.

Figure 16 (a) suggests that the filament diameter could be 0.15 mm or maybe less in case this image was overexposed. A model of a single growing conducting channel having a diameter D of 0.15 mm (Figure 33b) is used to calculate the channel tip field by again using the FEM calculations with COMSOL Multiphysics program. The tip field is calculated to be between 7-20 MV/cm during most of the crossing. This field is considered sufficient for avalanche processes [41]. Therefore, the collisional ionization may take place ahead of the channel tip. To maintain streamer propagation, the required seed electrons must be continuously created around the channel tip by possibly photo ionization resulting from channel tip processes [42].

As suggested above, the 4th mode streamer channel is highly conductive, i.e. there is possibly a highly or fully ionized plasma state inside the channel. Thus streamer propagation is considered the extension of the point electrode. The streamer tip field will increase continuously and become several times higher than in the 2nd mode as obtained by simulation (7-20 MV/cm compared to 2.4 MV/cm). Due to higher tip field, the collisional ionization and photo-ionization, if possible, in front of streamer heads are stronger leading to higher charge concentration and electric field. This ultimately leads to a significant increase in the velocity of the 4th mode streamers.

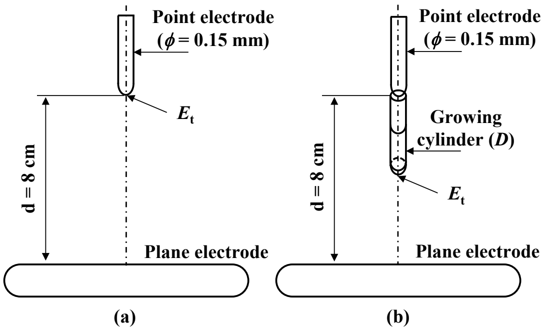

Figure 33. A model for calculating electric field at the tip. (a)-For calculation of point tip field; (b)-For calculation of channel tip field.

4.3.2. Negative streamers. Felici (1988) [43] suggested the following hypothesis to explain the propagation of the slow 1st mode streamers: Streamer channels are filled with a weakly ionized vaporized liquid wherein partial discharges occur. Hot electrons created by discharges will bombard the gas/liquid interface, thus heating and further evaporating the liquid. This extends the streamer channels. For continued propagation, the electrons at the channel tip, which soon become attached and form negative ions and are swept aside by the liquid flow, must be replaced by new hot electrons supplied by successive discharges in the vapor. The existence of a weakly ionized gaseous phase in the streamer channel is supported by two experimental results: First the strong effect of increased pressure [9] or reduced pressure as seen in this study on negative streamers and second the very large voltage drop along streamer channel; being about 330 kV/cm in the first stage of propagation as seen in the plot of stopping length versus applied voltage in case of neat white oil (Figure 19) if one takes the inverse of the streamer length to step peak voltage ratio as a measure of the internal field of the channel.

A propagation mechanism for the faster mode streamers was first introduced by Devins et al (1981) [1]. He proposed a two-step model. Firstly, electrons that are injected into liquid from plasma tip are captured, thus forming negative space charges. Then, these space charges will build up an electric field that directly ionizes the liquid when the threshold field is reached. However, the electric field required for this ionization process is suggested to be as high as 15 MV/cm [44].

Thus, we attempt to roughly determine the field at the channel tip to clarify which mechanism creates new electrons. The tip field of streamer channels at the initiation of the 2nd (390 kV) and 4th (420 kV) mode streamers was calculated with a growing cylinder model (Figure 33b) by employing the FEM calculations with COMSOL Multiphysics program.

For the 2nd mode streamers, the growing cylinder of the model is non-conductive with voltage drop of 12.5 kV/cm being taken as the inverse of the growth rate of 8×10^{-2} cm/kV (Figure 19). Because dense side branches enclose a main channel (Figure 34a), the shielding effect of the side branches on the main channel is strong. Thus the diameter *D* of the cylinder model should be equal to that of an artificial cylinder encircling all side branches. *D* is estimated from Figure 34a, as 3.2 mm. The field at the channel tip is then found to be almost constant and 1.3-2 MV/cm during most of the crossing. This tip field satisfies the minimum requirement for collisional ionization in n-hexane (1.3 MV/cm [40]) but does not meet the condition for cyclohexane and propane in [41].

For the 4th mode streamers, at 540 kV the streak image of neat white oil will be similar to that of this oil at reduced pressure (Figure 31 (a)), i.e. streamer channels are highly conductive at this voltage magnitude and the voltage drop is assumed to be negligible. The voltage drop of streamers at 390 kV is 12.5 kV/cm as determined above. On the assumption that the voltage drop decreases linearly when the applied voltage is increased, the voltage drop of the streamers at 420 kV is 10 kV/cm determined by interpolation. In this case, the side branches are sparse (Figure 34b), so the shielding effect can be neglected and the diameter *D* of the cylinder model (Figure 33b) is equal to that of the main channel. With an estimated diameter *D* of 0.3 mm (Figure 34b), the channel tip field is about ten times higher than that of the 2nd mode streamers, which may explain why the velocity of the 4th mode streamers is raised by a factor of approximately twenty. During the growth of the 4th mode streamers, a channel tip field of 11-20 MV/cm is estimated. This high tip field meets the condition of 2.5-7 MV/cm for collisional ionization [41]. It is therefore possible that collisional ionization could be responsible for generation of new electrons of faster modes of negative streamers.

Both TCE and reduced pressure decrease V_a about 31%, and when the applied voltage exceeds V_a, the streamer velocity is similar in the two cases (Figure 22). This means that both electronic and gaseous processes at streamer heads are important for propagation of the 3rd and 4th mode negative streamers.

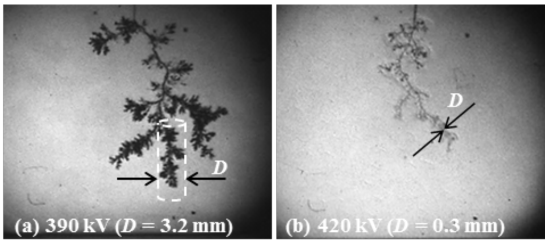

Figure 34. Diameter of cylinder models.

5. Conclusions

It is clear that in white oil, positive streamers are more dangerous than negative ones. However, the hazard of positive streamers at lightning impulse is significantly reduced for mineral transformer oil. The reason is possibly that the low IP property of aromatic/polyaromatic compounds slightly changes the streamer velocity and the breakdown voltage, and largely increases the acceleration voltage of positive streamers. For negative streamers, in contrast, the electron trapping property of such compounds increases the velocity by a factor of ten, and reduces the breakdown and acceleration voltages by 50% and 30%, respectively.

Adding DMA caused positive streamers to behave like those in mineral transformer oil while adding TCE had the same influence on negative streamers. Therefore, it is proposed that adding both a low IP additive and an electron scavenger into white oil would produce a type of liquid similar to mineral transformer oil for both polarities.

The sufficient difference in IP between aromatic/polyaromatic compounds and paraffinic/naphthenic compounds is considered as a main reason for the very high acceleration voltage of mineral transformer oil, i.e. good *V-t* characteristics. Thus aromatic/polyaromatic compounds are very important for good behaviour of mineral transformer oil.

It is evident that both electronic and gaseous processes are responsible for propagation of both low and fast mode streamers in a long gap. This may indicate that suggested impact ionization of liquid molecules followed by Joule heating and evaporation of the liquid is a dominant mechanism for propagation of streamers. Fast positive streamers depend more on electronic processes while fast negative streamers are governed by both electronic and gaseous processes.

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