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Impulse Creeping Streamer and Propagation Velocity in Vegetable and Mineral Oils with Pressboard Interface

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Abstract: This paper presents an experimental study on the creeping discharge propagating over the pressboard surface in two vegetable oils (PFAE (palm fatty acid ester) oil and CRS (crude rapeseed) oil) and commercial mineral oil under the quasi-square impulse voltage with any pulse width. The pressboard impregnated with the sample oil is immersed completely into the same oil. The tungsten needle electrode is installed in the pressboard surface with and without the counter electrode to generate a creeping discharge. The other side of pressboard has the thin copper rod as a back side electrode. A comparison of the shape and stopping length of positive and negative streamers, discharge current, emitted light signal, and temporal variation and velocity of streamer propagation is reported for all different oil-pressboard interfaces. It has been shown that the behavior of creeping streamers has unique characteristics and polarity effects, and the traveling mode and propagation velocity of streamers are greatly different depending on the type of oil.

Key words: Creeping streamer, stopping length, propagation velocity, quasi-square impulse voltage, PFAE oil, CRS oil, mineral oil.

1. Introduction

An electrical insulation system in high-voltage power equipment such as transformers and cables is constituted by a composite of insulating oil and oil-impregnated cellulose products as a traditional technique over many decades. However, the oil-solid interface will be considered as an insulating weakness which the creeping streamer is easy to progress under a high electric stress such as lightning surge, because of the difference in permittivity between adjacent materials. The creeping discharge is one of the major inducements to insulation failures since the creeping streamers can lead to a flashover accident [1-3]. The better understanding of creeping discharge is beneficial to guarantee a level of electrical insulation for a designer and manufacturer who is expert in oil-insulated power apparatuses.

Corresponding author: Ryoichi Hanaoka, professor, research fields: pre-breakdown, breakdown and creeping discharge phenomena in insulating liquids, electric field calculation, EHD phenomena in liquids and development of ER/MR fluids.

A petroleum-based mineral oil with a high ability as an electrical insulation and cooling medium has most been used so far as practical insulating oil. Recently, some problems relating to the protection of the environment; a poor biodegradation, scarcity of petroleum resources, environmental pollution due to the oil leakage and burning, sulfide-induced corrosion of copper etc., are pointed out to the mineral oil. Therefore, the environmentally inoffensive insulating oils are required as alternatives of mineral oil. Currently, vegetable-based oils such as PFAE (palm fatty acid ester) oil and CRS (crude rapeseed) oil are considered as a prospective candidate [4-8]. A distribution transformer of 20,000 kVA class using rapeseed oil has already been developed in Japan [9]. The electrical performance of vegetable oils has been studied by many researchers under various test conditions for the last twenty years [10-16]. However, the phenomena with respect to the creeping discharges over the oil-solid interface are not yet deeply known. We pursue further the previous work [17].

This paper presents the experimental results on the behavior of positive and negative streamers propagating over the pressboard surface in insulating oils observed under the quasi-square impulse voltage. The needle electrode is used to generate a streamer, since a strong electric field of 10^8 V/m or more is required for the initiation of a streamer in oils. The oil-impregnated high density pressboard with a back side electrode (thin copper rod) is selected as a solid insulator. The shape and stopping length of streamers are obtained from photographic images taken at a still camera at the same time as the oscilloscope measurement of the discharge current and light signal. The temporal variation of streamer propagation is observed by using a high-speed streak camera system and the propagation velocity of streamers is analyzed from streak images. The streamer shape and stopping length have a specific polarity effect at a vegetable or mineral oil-pressboard interface, which depends on the voltage and pulse width. There is a remarkable difference in the traveling mode and propagation velocity of streamers depending on the type of oil.

2. Experiments

2.1 Test Insulating Oils and Electrode Arrangement

Three insulating oils: PFAE oil, CRS oil and mineral oil (JIS-C2320) were used as test oils. PFAE oil was provided from Lion Specialty Chemicals Co., Ltd., in Japan and CRS oil and mineral oil were provided from Kanden Engineering Corporation in Japan. PFAE oil has a saturated fatty acid chemical structure without a double bond between atoms and it is derived by the synthesized process involved with transesterification of fatty acid methyl ester and alkyl alcohol through molecular design technique. CRS oil consists of an unsaturated fatty acid chemical structure with a carbon double bond, which contains high percentage of oleic acid (more than 60%). Table 1 shows the main physical and electrical properties of the test oils. PFAE oil and CRS oil are better than mineral oil for environmental safety due to an excellent biodegradability and non-toxicity, and the flash points are higher than mineral oil. Mineral oil produces a slight dioxin and hazardous gases by combustion. The kinetic viscosity is lower in PFAE oil and much higher in CRS oil as compared with mineral oil. PFAE oil and CRS oil are possible to improve the insulation coordination in permittivity between adjacent materials, because of their high relative permittivity. The electrical breakdown voltage is higher than mineral oil at low moisture levels. This is advantageous for electrical insulation in the oil-pressboard composite system. However, vegetable oils usually have a high moisture saturation limit (~2,500 ppm at 20 °C), because their oils are prone to take in the moisture in chemically bonded form or dissolved form. This results in the increase of dissipation factor (tanδ) and the reduction of breakdown voltage. In this work, all test oils were dried for 24 hours at 60 °C under vacuum conditions. As a result, the moisture content in PFAE, CRS and mineral oils obtained by a Karl Fisher titration was 134.0, 126.0 and 33.5 ppm, respectively.

The schematic of the electrode arrangement used in the experiment is shown in Fig. 1. A high density pressboard (70 mm width, 170 mm length and 3 mm thickness) with and without the brass counter electrode (CE: same length as the width of pressboard) was prepared in advance. A thin copper rod with 2 mm diameter and 100 mm length was attached to the back

Table 1 Main physical and electrical properties of test oils.

Physical and electrical properties		PFAE oil	CRS oil	Mineral oil
Density (20°C)	g/cm^3	0.86	0.92	0.88
Kinetic viscosity (40°C)	mm^2/s	5.06	36.0	8.13
Pour point	°C	-32.5	-27.5	-45.0
Flash point	°C	176	334	152
Thermal conductivity (25°C)	W/m·K	0.13	0.18	0.13
Toxicity		non-toxic	non-toxic	slightly toxic
Ability to biodegradability		high	high	low
Breakdown voltage (Moisture level: 10 ppm or less)	kV/2.5mm	81	74	70-75
Relative permittivity (80°C)		2.95	2.86	2.2
Dissipation factor:tan δ (80°C)		3.1×10^{-3}	8.3×10^{-2}	1.0×10^{-3}
Volume resistivity (80°C)	Ω·cm	7.1×10^{12}	4.4×10^{12}	7.6×10^{15}

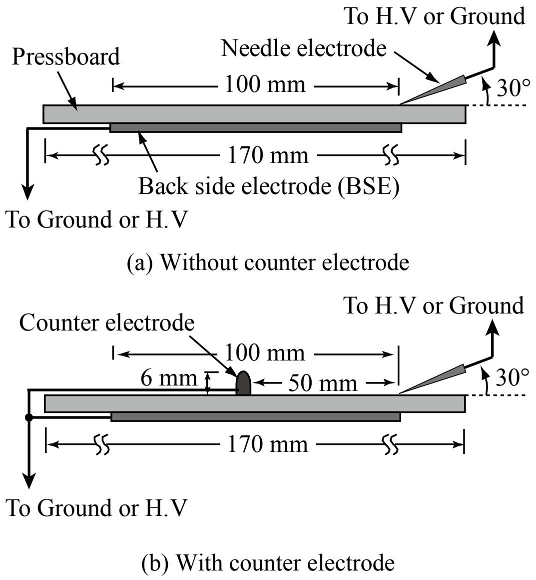


Fig. 1 Schematic of electrode arrangement.

side of all pressboards as a BSE (back side electrode). The counter electrode was connected to the BSE. The pressboard was impregnated with the test oil under vacuum conditions to remove a moisture and air from the fibrous structure as much as possible after drying by the thermostatic oven for 24 hours at 60 °C, and was immersed completely into a transparent acrylic vessel with the same test oil of 0.7 liters. The tungsten needle electrode with a tip radius of ~30 μm was placed on the pressboard surface with an inclination of ~30° from the surface. The needle tip was positioned just above the one end of BSE.

2.2 Experimental Setup and Procedures

Fig. 2 shows the schematic of the experimental setup employed to observe the creeping discharge. The oil- filled acrylic vessel with the electrode system of Fig. 1 was put into the stainless steel vessel filled with gaseous nitrogen (GN_2: 99.999% purity) by a vacuum pump and GN_2 high-pressure tank to avoid the contact with oxygen and moisture. The high voltage generator (PE-100L, Nissin Pulse Electronics Inc.) which can supply the negative quasi-square impulse voltage (peak value of voltage V_p: 0-80 kV and pulse width T_w: 1.5-10 μs) was used in this study. The wave front time was 1.5 μs and time to half value of wave tail was ~14 μs as shown in Fig. 3. The voltage waveform was monitored by an oscilloscope using the high-voltage probe with 1/5,000 (EP-100K, Nissin Pulse Electronics Inc.). The negative streamer was observed by applying the voltage to the needle electrode and grounding the BSE as shown in Fig. 2. The positive streamer was observed by applying the voltage to the BSE (or CE) and grounding the needle electrode. Therefore, the current signal of positive and negative streamers was always detected as a negative polarity. The discharge current was measured with a digital oscilloscope by the combined use of 50 ohm non-inductive resistor connected to the ground electrode (needle or BSE) and an attenuator. The light signal emitted by the discharge was detected by a photo-sensor module (H10721-20, Hamamatsu Photonics K. K.) at the same time as the current signal. The shape and stopping length of streamers were measured photographically as a function of the V_p and T_w by the digital SLR (single-lens reflex) camera (D-750, Nikon Co.). The shooting condition of the camera was set to the exposure time of 0.5 seconds at an iris opened state. On the other hand, the temporal variation of streamer propagations was observed by using the high-speed digital streak camera system (Optoscope-SC, Nac Image Technology Inc.) to analyze the propagation velocity of streamers. All the experiments were carried out at room temperature and atmospheric pressure.

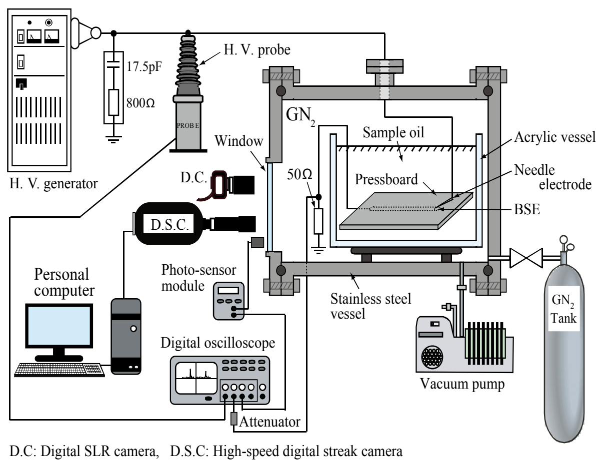


Fig. 2 Schematic of experimental setup.

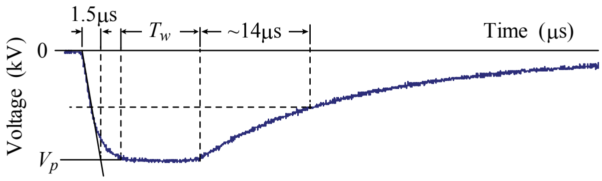


Fig. 3 Schematic of quasi-square impulse voltage.

3. Experimental Results and Discussion

3.1 Streamer Shape, Discharge Current and Light Signal

Fig. 4 shows typical photographic images of a positive and negative streamer obtained at the voltage V_p with different T_w for the pressboard without CE in Fig. 1a. In all test oils, the streamer is characterized by a many branching, but there is a difference in the shape of positive and negative streamers. Positive streamers display a tree-like shape with a slim branch compared to negative streamers with a thickish stem. The streamer shape is also different depending on the type of oil even if the streamer polarity is the same. The streamers in CRS oil and mineral oil are of a standard shape that has many branches in a different type. Positive streamers have many tree-like channels in both oils. Negative streamers display a tree-like shape for CRS oil and a bush-like shape for mineral oil. While in PFAE oil, two different modes with a tree-like shape are observed in the positive streamer. One is luminous streamer starting from the needle tip which is regarded as primary streamer, and many flashing spots that suggest an active ionization zone compared to other oils are observed in the head of streamer branches. The other is slim streamer with a poor brightness starting from flashing spots of the primary streamer. This streamer is regarded as secondary streamer. An appearance of such two modes is remarkable when the V_p is larger than 65 kV. Negative streamer appears in a tree-like shape with a thick stem, but streamer growth has been suppressed as compared to other oils under the identical voltage.

Fig. 5 shows typical discharge current and light signal for positive and negative streamers. The discharge current has many intermittent pulses and the light signal is synchronized with the current pulse. The first large variation in the current waveforms is due to a charging process just after the voltage application. Each pulse in the current and light signal seems to correspond to the individual branch of streamer. The current pulses in the positive streamer

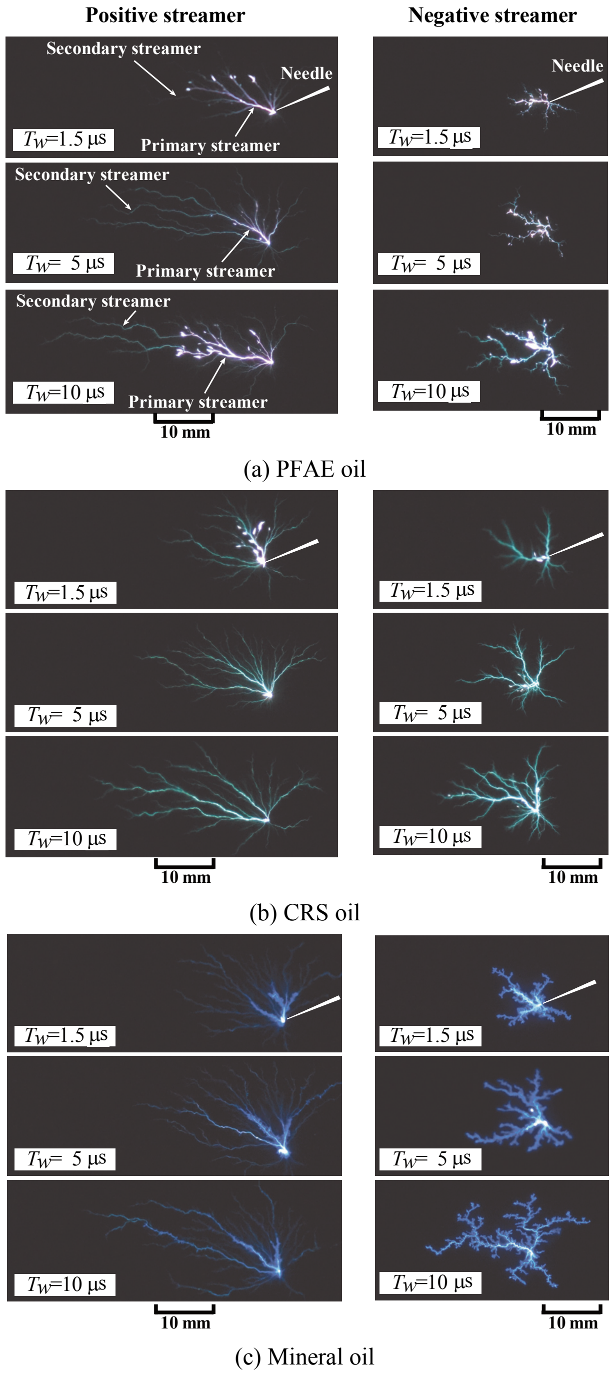


Fig. 4 Typical images of creeping streamers for pressboard without CE. V_p = 70 kV.

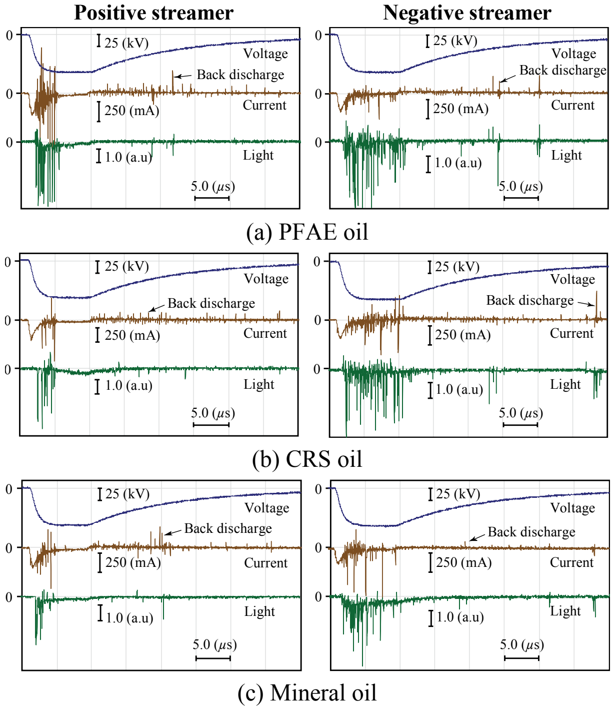


Fig. 5 Typical examples of discharge current and light signal. Pressboard without CE. V_p = 70 kV, T_w = 5 μs.

are concentrated in the vicinity of the front time of the voltage irrespective of the T_w, but the pulses in the negative streamer occur in all duration of T_w. By the way, in these current waveforms, the positive small current pulses have appeared in the wave tail of the voltage. It seems that these current pulses which are opposite polarity to the streamer current pulses are due to a back discharge occurring with a fast drop of the voltage. The back discharge phenomenon can be observed on the solid surface in contact with the electrode whatever the polarity of impulse voltage [18]. The charges trapped on the solid surface near the electrode by the occurrence of creeping discharge can induce the strong reverse electric field during the falling period of the impulse voltage and then the current results in the opposite polarity.

3.2 Stopping Length of Steamers

A positive and negative streamer travels in both the parallel and normal to the BSE as shown in Fig. 4. The extension of streamer in a parallel and normal direction is estimated by measuring the stopping lengths; maximal length L_m from needle tip to streamer head and maximal width W_m of the streamer over both sides of the BSE. Figs. 6 to 8 show typical relationships between L_m, W_m and V_p obtained using the pressboard without CE. The L_m and W_m were plotted as the average of five trials under the identical voltage applied at intervals of about 30 minutes. Each datum has a standard deviation of ±10-15%. In all test oils, the L_m and W_m of positive streamers are longer than those of negative ones under the identical V_p and T_w. The polarity effect on the stopping length of streamers will be caused by an ionization mechanism on the streamer propagation, namely the field ionization process for positive streamers and electron impact ionization process for negative ones. The positive and negative streamer extension increases with increasing T_w under the identical V_p. The growth

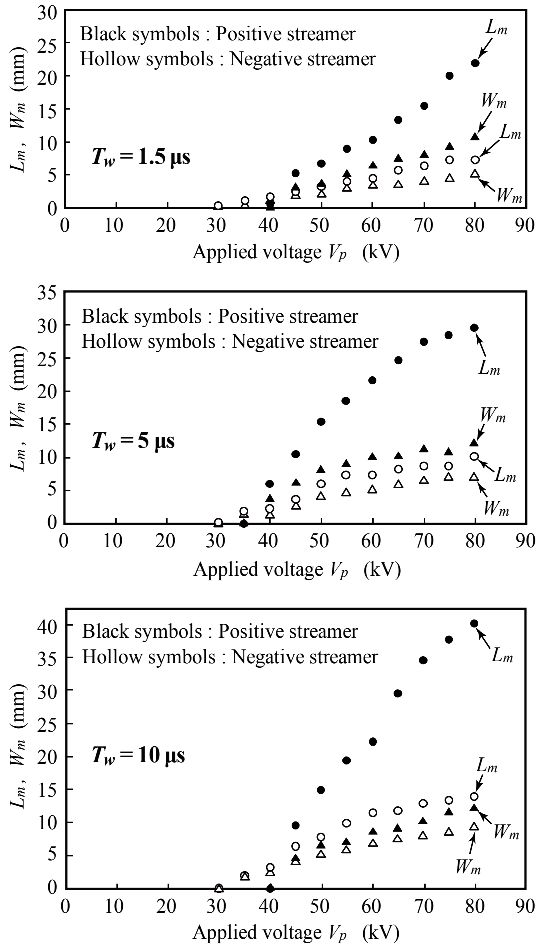


Fig. 6 Relationships between L_m, W_m and V_p in PFAE oil.

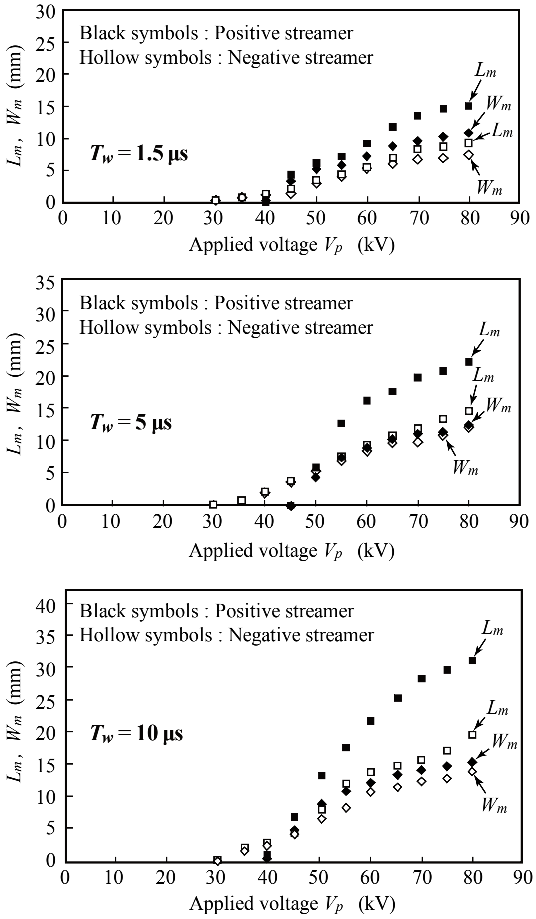


Fig. 7 Relationships between L_m, W_m and V_p in CRS oil.

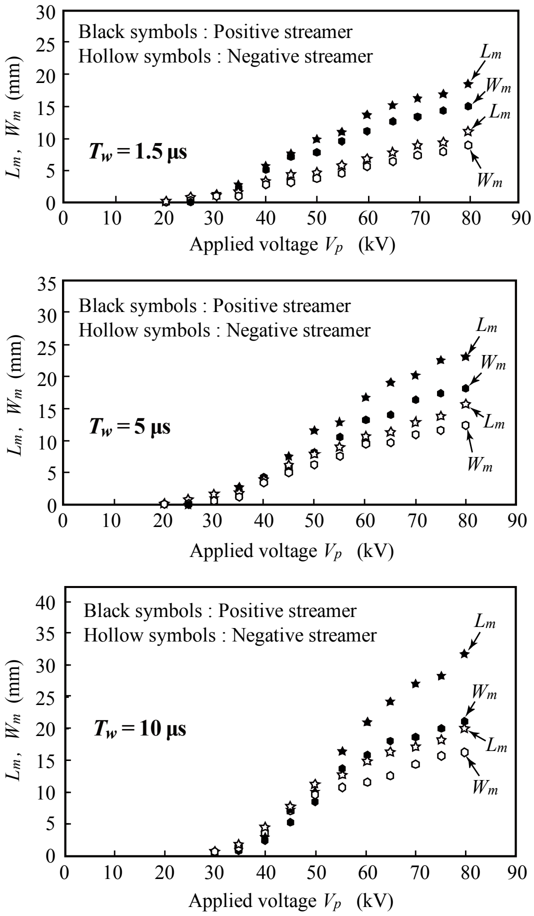


Fig. 8 Relationships between L_m, W_m and V_p in mineral oil.

of streamer has different features depending on the type of oil. The characteristic of L_m and W_m in CRS oil is roughly the same as that in mineral oil. While the L_m of positive streamers in PFAE oil is longer than that in other oils due to the presence of secondary streamers, but the L_m of negative streamers is the same or less compared to other oils under the identical V_p and T_w. The growth of streamer can also be promoted by the presence of the CE (counter electrode) on the pressboard surface. Fig. 9 shows an example of the effect of CE on the stopping length of negative streamer. The growth of streamer is remarkable at the voltage greater than ~50 kV.

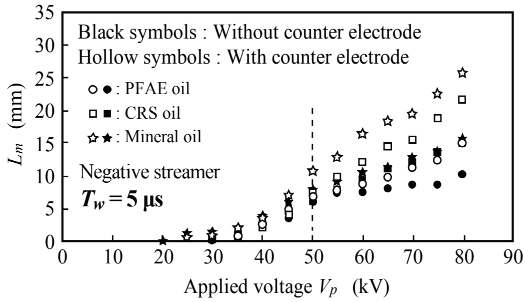
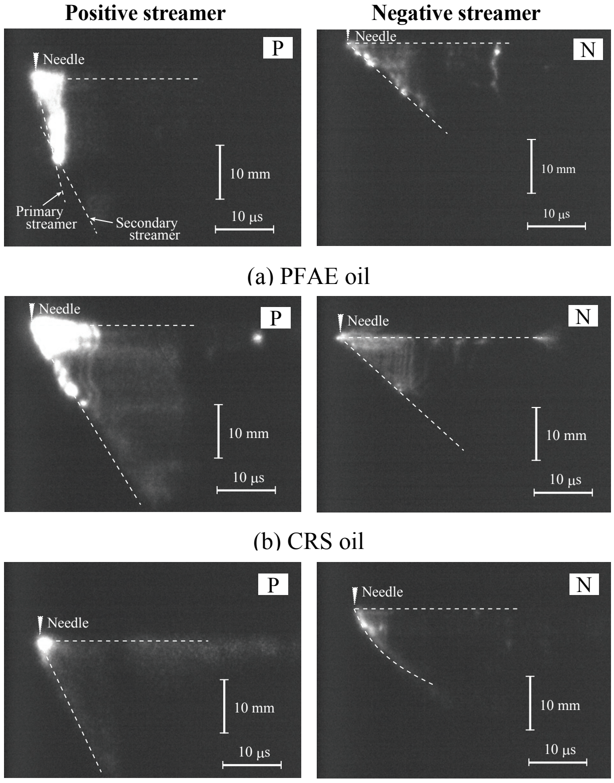


Fig. 9 Effect of CE on stopping length of negative streamer.

3.3 Traveling Mode and Velocity of Streamers

Generally, the propagation velocity of streamers in liquids or along liquids-solid interfaces is quantified by the average or instantaneous value. The average velocity is determined by the stopping length and propagation time of streamers. The instantaneous velocity can be found from continuous framing images of streamer propagation [19-21]. In this study, the streak images were captured by the streak camera system under the voltage conditions of V_p = 65-75 kV and T_w = 1.5-10 µs. These images give us the temporal variation to analyze the velocity of streamer. Fig. 10 shows typical streak images taken for positive and



(a) PFAE oil

(b) CRS oil

(c) Mineral oil

Fig. 10 Typical streak images of streamer propagation. Pressboard without CE. V_p = 70 kV, T_w = 10 μs.

negative streamers in the three different oils. The traveling mode and propagation velocity of streamers depend on the shape and polarity of the streamer.

The positive streamer in PFAE oil with the tree shape grows almost linearly with time which means a constant velocity as shown in Fig. 10a-P, but there are two modes; primary and secondary streamers as previously mentioned. The primary streamer has a strong brightness and the secondary streamer is very weak. Flashing spots at the head of primary streamer with a thick stem suggest an active ionization zone, and the electric field in these spots will be greatly enhanced due to the charge accumulation. Consequently, a slim secondary streamer starts newly from flashing spots. On the other hand, the negative streamer grows linearly with time (see Fig. 10a-N) at a unitary mode with the tree shape. The propagation velocity is determined from the slope of linear line in the streak image. Table 2 shows the propagation velocity of positive and negative streamers. In the positive streamer, the primary streamer propagates at a high velocity of 4.6-7.8 km/s although having a large variation. The velocity of secondary streamer is 2.4-3.7 km/s which are ~2 times lower than primary streamer. While the velocity of negative streamer is 0.9-1.6 km/s and is much lower than that of positive streamers (primary and secondary streamers). Linear variation of the positive and negative streamer propagation representing a constant velocity appears to be attributed to the tree-like pattern of the streamer.

In CRS oil, both positive and negative streamers appear in the tree shape (Fig. 4b). In this case, the streamer grows linearly with time regardless to the polarity as shown in Fig. 10b and has a certain constant velocity. Table 3 shows the propagation velocity of positive and negative streamers. The streamer velocities are 1.6-2.0 km/s and 1.0-1.5 km/s for positive and negative polarities, respectively. The velocity of positive streamer is ~1.4 times higher than of negative one. The significant dependence of the applied voltage is not observed on these velocities.

The positive streamer in mineral oil is the tree shape (Fig. 4c). The streamer grows linearly with time as shown in Fig. 10c-P. The propagation velocities are shown in Table 4. The positive streamer propagates at a constant velocity of 2.4-2.6 km/s. On the other hand, the growth of negative streamers is different from that of positive streamers. The negative streamer appears in the bushy shape (Fig. 4c). In this case, the streamer grows at a quadratic curve which indicates that the

Table 2 Propagation velocity of streamers in PFAE oil.

V_p (kV)	Streamer mode	T_w=1.5 (μs)	T_w=5 (μs)	T_w=10 (μs)
		Positive streamer velocity $u(+)$ (km/s)		
+65	Primary streamer	4.66	7.20	6.39
	Secondary streamer	2.70	2.78	2.72
+70	Primary streamer	7.50	7.80	6.55
	Secondary streamer	3.72	3.22	3.10
+75	Primary streamer	7.50	6.39	7.83
	Secondary streamer	2.39	2.94	3.11
		Negative streamer velocity $u(-)$ (km/s)		
-65	Unitary streamer	0.94	0.86	0.95
-70	Unitary streamer	1.08	1.02	1.00
-75	Unitary streamer	1.56	1.58	1.56

Table 3 Propagation velocity of streamers in CRS oil.

V_p (kV)	Streamer mode	T_w=1.5 (μs)	T_w=5 (μs)	T_w=10 (μs)
		Positive streamer velocity *u(+)* (km/s)		
+65	Unitary streamer	1.83	1.78	1.80
+70	Unitary streamer	1.67	1.56	1.70
+75	Unitary streamer	2.00	1.82	1.89
		Negative streamer velocity *u(-)* (km/s)		
-65	Unitary streamer	1.22	1.22	1.26
-70	Unitary streamer	1.22	1.06	1.04
-75	Unitary streamer	1.39	1.44	1.37

Table 4 Propagation velocity of streamer in mineral oil. (positive streamer).

V_p (kV)	Streamer mode	T_w=1.5 (μs)	T_w=5 (μs)	T_w=10 (μs)
		Positive streamer velocity *u(+)* (km/s)		
+65	Unitary streamer	2.49	2.56	2.41
+70	Unitary streamer	2.56	2.40	2.47
+75	Unitary streamer	2.58	2.44	2.49

velocity decreases with time as shown in Fig. 10c-N. For instance, the velocities after 5 μs and 10 μs from the application of voltage with T_w = 10 μs were ~0.83 km/s and ~0.52 km/s, respectively. These velocities are ~3-5 times lower than the velocity of the positive streamer. A nonlinear mode of the negative streamer growth appears only in mineral oil. This appears to be attributed to the bush-like pattern of the streamer.

4. Conclusions

The creeping discharge over the pressboard surface in vegetable-based oils (PFAE oil and CRS oil) and mineral oil was studied under the quasi-square impulse voltage with V_p = 0-80 kV and T_w = 1.5-10 μs. The characteristics on the streamer shape and stopping length, discharge current and light signal, and traveling mode and propagation velocity of streamers were compared for all different oil-pressboard interfaces.

The creeping streamers are typified by channels with a lot of branching in all test oils. The positive streamer has a slim branch compared to the negative streamer with a thickish stem. Positive streamers in both CRS and mineral oils have many tree-like channels. Negative streamer appears in a tree-like shape for CRS oil and in a bush-like shape for mineral oil. While in PFAE oil, two different modes with a tree-like shape; luminous primary streamer and secondary streamer with poor brightness are observed in the positive streamer. Primary streamer starting from the needle tip has many flashing spots in the streamer head. Secondary streamer progresses from flashing spots of the primary streamer. Negative streamer in PFAE oil is the tree shape with a thick stem, and its growth is suppressed as compared to other oils under the identical voltage.

The discharge current appears in many intermittent pulses which are synchronized with the light signal of the discharge. The current pulses in the positive streamer are concentrated in the vicinity of the front time of the voltage irrespective of the T_w, but the pulses in the negative streamer appear in all duration of T_w. While in the wave tail of impulse voltage, the small current pulses with opposite polarity to the streamer current pulses are observed by a back discharge phenomenon.

The streamer extension is estimated by the stopping lengths; L_m and W_m. In all test oils, the stopping lengths of positive streamer are longer than those of negative one under the identical V_p and T_w. The growth of streamer is promoted by increasing T_w under the identical V_p. The L_m and W_m in both CRS and mineral oils are of roughly the same characteristic. While in PFAE oil, the L_m of positive streamers is longer than in other oils due to the presence of secondary streamers, but the L_m of negative streamers is the same or less compared to other oils under the identical V_p and T_w. The CE on the pressboard surface promotes the streamer growth.

The traveling mode and velocity of streamers depend on the shape and polarity of streamer. The streamer with a tree-like shape grows linearly with time and the streamer with a bush-like shape grows at a quadratic curve. The velocity of positive streamers is always faster than that of negative ones in all test oils. Positive and negative streamers in PFAE oil appear in the tree shape. In the positive streamer, primary streamer propagates at very high velocity: 4.6-7.8 km/s, but secondary streamer reduces its velocity: 2.4-3.7 km/s. The negative streamer propagates at very low velocity: 0.9-1.6 km/s. Positive and negative streamers in CRS oil appear in the tree shape. The streamer velocities are 1.6-2.0 km/s and 1.0-1.5 km/s for positive and negative polarities, respectively. In mineral oil, the positive streamer appears in the tree shape and propagates at a constant velocity of 2.4-2.6 km/s. The negative streamer displays the bushy shape. In this case, the streamer grows quadratically and the velocity decreases with time. For the voltage with T_w = 10 μs, the velocities after 5 μs and 10 μs from the voltage application are ~0.83 km/s and ~0.52 km/s, respectively.

The risk of the flashover accident in oil-filled power equipment will increase by the occurrence of positive streamers with a long extension. The high velocity of streamer also may cause a flashover even an overvoltage of short intervals.

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