Creeping Discharge Developing on Vegetable-Based Oil / Pressboard Interface under AC Voltage

Fri Murdiya, Ryoichi Hanaoka, Hideki Akiyama, Katsunori Miyagi,
Kanazawa Institute of Technology, Department of Electrical and Electronic Engineering,
7-1 Ohgigaoka, Nonoichi, Ishikawa 921-8501, Japan

Kiyoshi Takamoto
Kanden Engineering Corporation,
3-1-176 Fukuzaki, Minato-ku, Osaka 552-0013, Japan

and **Takaaki Kano**
Lion Corporation,
3-7 Honjo 1-Chome Sumida-ku, Tokyo 130-8644, Japan

ABSTRACT

The behavior of creeping discharges developing on the pressboard surface was investigated experimentally in palm fatty acid ester oil, natural rapeseed oil and commercial mineral oil under variable ac voltages with 60 Hz, respectively. The oil-impregnated pressboard was used as the solid dielectric and it was immersed completely into the same oil. The tungsten needle electrode was installed in the one side of pressboard surface without the counter electrode as a high voltage electrode and a grounded fine copper rod was adhered tightly in the other side of pressboard as a back side electrode. The discharge shape, streamer extension, streamer velocity and tracking at the oil/pressboard interface were observed as a function of the time and voltage by using a still camera equipped with a night viewer. Simultaneously, the discharge current and dissipated energy were measured. The gas components dissolved in oils by the creeping discharge were also examined by the dissolved gas-in-oil analysis (DGA). In this paper, it is presented that there are distinctive events due to the occurrence of creeping discharges.

Index Terms - **AC high voltage, creeping discharge, streamer extension, vegetable-based oils, mineral oil, tracking, dissolved gas-in-oil analysis (DGA).**

1 INTRODUCTION

ELECTRICAL insulation is essentially one of the most important parts in high-voltage equipment such as power and distribution transformers. Conventionally, compound insulation systems which are composed of insulating oil and oil-impregnated cellulose products (pressboard, kraft paper, wood etc.) have widely been employed to insure the inside electrical insulation of power transformers for more than a century. To obtain excellent dielectric and cooling characteristics, petroleum-based mineral oil (the so-called transformer oil) with their high performances has been most often used as the dielectric fluid in these insulation systems. The use of mineral oil, however, has a considerable risk to the environment due to its poor biodegradability and slight toxicity, and also has some problems such as exhaustion of mineral resources in the near future, copper sulfide-induced corrosion, environmental pollution caused by oil leakage, atmospheric pollution due to burning, etc. Thus recently the environmentally inoffensive vegetable-based oils have been considered for a substitute of mineral oil [1-5] and the comparison between mineral oil and vegetable-based oils on the partial discharge, creeping discharge and electrical breakdown phenomena has been investigated by many researchers for the last ten years [6-11]. Vegetable-based oils such as PFAE (palm fatty acid ester) oil and rapeseed oil are expected for insulation design of an environmentally fitted power transformer, because they have many advantages on the environmental compatibility and electrical insulation, e.g. excellent biodegradability, non-toxic, high flash point, high relative permittivity, non-copper sulfide, better dielectric strength of insulation at low moisture level, as compared with mineral oil. However, vegetable-based oils have a high moisture saturation limit (~2500 ppm at 20 °C), since it is prone to take up water in chemically bonded form or in dissolved form. This leads to the increase of dissipation factor and the reduction in volume resistivity or dielectric strength.

Manuscript received on 20 January 2014, in final form 12 March 2014, accepted 12 March 2014.

DOI 10.1109/TDEI.2014.004569

On the other hand, an oil/solid interface of compound insulation systems in oil-filled power transformers will be of concern as an electrical weak point due to a creeping discharge has easier progress under electric stress, because of the difference in permittivity between adjacent materials. The irreversible tree-like damage (tracking) is left on the solid surface as a result of these creeping discharges, and it results in a permanent electrically conductive path that deteriorates the insulation system. These events are regarded as one of the failure modes for the insulation system in power transformers [12, 13]. To guarantee a level of electrical insulation under high electrical stresses, the understanding of creeping discharge phenomena is most important for a designer who is expert in oil insulated power apparatus.

The purpose of this research is to make clearly the behavior of ac creeping discharges in vegetable-based insulating oils and mineral oil. This paper presents the obvious results on the discharge shape, streamer extension, streamer velocity and tracking on pressboard surface examined as a function of the time and voltage under variable ac 60 Hz voltages up to 45 kV in rms (root-mean-square) values. It is shown that the creeping discharge glows slowly in the distinctive shape under a fixed applied voltage. The surface tracking is thought to be associated with a drying process due to the micro bubbles formed on the pressboard surface during the progression of a creeping streamer.

2 EXPERIMENTS

2.1 OIL SAMPLES, PRESSBOARD TREATMENT AND ELECTRODE ARRANGEMENT

PFAE oil, natural rapeseed oil and mineral oil (transformer oil: JIS-C2320) were used as insulating oil samples in this research. PFAE oil and rapeseed oil were provided from Lion Corporation and Kanden Engineering Corporation in Japan, respectively. The main properties of oil samples are shown in Table 1. PFAE oil and rapeseed oil are better than mineral oil for environmental safety, because of an excellent biodegradability and non-toxicity. The flash points of PFAE oil and rapeseed oil are higher than mineral oil, and mineral oil does not only slightly generate dioxins but also toxic products under fire condition, while there is no toxicity in the vegetable-based oils. The kinetic viscosity is lower in PFAE oil, but much higher in natural rapeseed oil as compared with mineral oil. PFAE oil and rapeseed oil also 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 level conditions, which is advantageous for electrical insulation in the oil/pressboard compound insulating system. In this research, oil samples were dried for 24 hours at 60 °C under vacuum conditions. As a result, moisture levels in PFAE oil, rapeseed oil and mineral oil measured by a Karl Fisher titration were 77.4 ppm, 65.1 ppm and 36.8 ppm, respectively.

Table 1. Main properties of oil samples.

Physical and electrical properties	PFAE oil	Rapeseed oil	Mineral oil
Density (20°C) g/cm³	0.86	0.92	0.88
Kinetic viscosity (40°C) mm²/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}

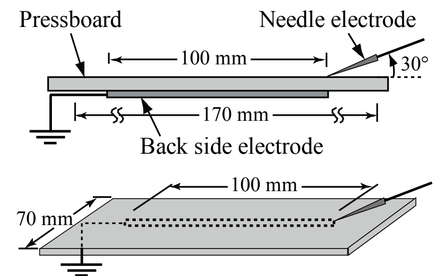


Figure 1. Schematic of electrode system.

A high density pressboard with three dimensions; 70 mm width, 170 mm length and 3 mm thickness was used as the solid dielectric. The surface of this pressboard has small elliptical dimples (~0.29 mm width, ~0.82 mm length and ~0.013 mm depth in size), which is arrayed uniformly by the compression within the manufacturing process. Pressboard was first dried for 24 hours at 60 °C and then impregnated with the oil sample under vacuum conditions to remove moisture and gasses from the fibrous structure as much as possible. Subsequently, it was immersed completely into 10.5 liters of the same oil in a transparent acrylic test vessel. A tungsten needle with a tip radius ~30 µm was installed as the point electrode on one side of the pressboard surface as shown in Figure 1. The needle was placed at an angle of ~30° to the pressboard surface and was used as a high voltage electrode. The acute angle of the needle electrode will lead the streamer in one direction rather than the radial direction. In this research, the counter electrode was not installed on the pressboard to avoid the surface flashover between the needle tip and the counter electrode. The other side of pressboard has a grounded copper rod (2 mm diameter and 100 mm length) which has been adhered tightly by an epoxy resin as a back side electrode (BSE). The needle tip on the pressboard surface was positioned just above one end of the BSE.

2.2 EXPERIMENTAL SETUP AND PROCEDURE

Figure 2 shows the schematic of the experimental setup employed to observe the behavior of creeping discharges. An acrylic test vessel equipped with the electrode system in Figure 1 was put into the stainless steel vessel filled with gaseous

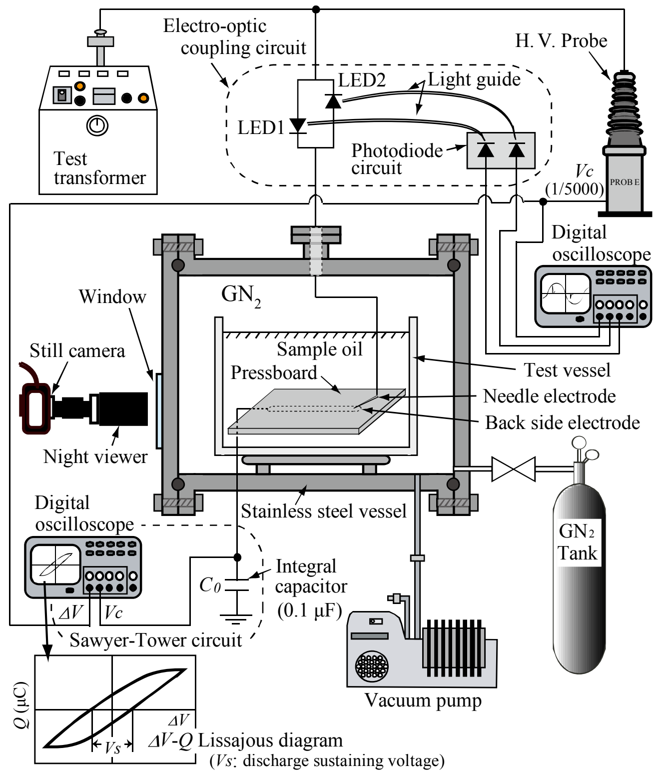
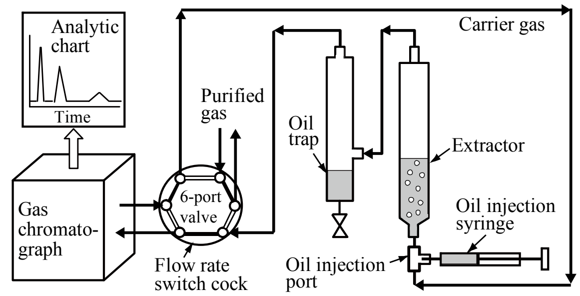


Figure 2. Schematic of experimental setup.



Measurement conditions of dissolved gases

Subject of components	Carrier gas	Analytic colmn	Detector	Injection rate (mL)	Extraction time (s)
Hydrocarbon (C_1 - C_2)	Nitrogen	Porapak+ Activated alumina	FID	1.0	120
Hydrocarbon (C_1 - C_2), CO, CO_2	Nitrogen	Activated carbon	FID	1.0	120
Hydrogen	Nitrogen	Molecular sieve	TCD	1.0	120
Oxygen, Nitrogen	Helium	Molecular sieve	TCD	1.0	120

*The separated CO and CO_2 were measured via a methanation reaction using restoration colmn (methanizer). *FID: Flame ionization detector, *TCD: Thermal conductivity detection

Figure 3. Schematic of gas analysis system.

nitrogen (GN_2: 99.999 % purity) by using a vacuum pump and GN_2 high-pressure tank to avoid the oxidation of oil and invasion of moisture. Variable ac 60 Hz voltages V_{rms} in the range of 0 to 45 kV were applied to the needle electrode by a test transformer with maximal output voltage of 100 kV (AG-100K50, Nissin Pulse Electronics Inc.). The voltage waveform was monitored by an oscilloscope through the high-voltage probe with 1/5000 output (EP-100K, Nissin Pulse Electronics Inc.). At a certain value of applied voltage, after the inception of the partial discharge at the needle tip, the creeping streamer progressed gradually over the pressboard surface to parallel and normal directions to the BSE. The discharge shapes were photographed using a still camera equipped with a night viewer (C5100, Hamamatsu Photonics Inc.). These photographic data were taken as a function of the time and voltage to obtain the features of streamer growth. In this paper, the parallel and normal streamer extensions to the BSE were estimated by measuring the maximal length L_m from needle tip to streamer head and maximal width W_m of the streamer over both sides of the BSE, respectively. The L_m and W_m were plotted as the average of five trials under identical applied voltage. The distinct feature on the pressboard surface occurred in the middle of the streamer growth was observed photographically. The pressboard puncture event and the marks on pressboard surface appeared after the creeping discharge development were also observed.

Electrical current and dissipated energy based on the creeping discharge were examined by using an electro-optic coupling circuit and a Sawyer-Tower circuit, respectively, as shown in Figure 2. The discharge currents were detected by two light emitting diodes (LED1 and LED2 in a reversed parallel connection) which were connected to the needle electrode (high voltage side). The light emitted from the LED was transmitted to a photodiode through a light guide. Thus the current flowing through the needle electrode at a half cycle in positive and negative polarities of the alternating voltage might be detected by LED1 and LED2, respectively. The light of discharge was also observed by the naked eye with the aid of a night viewer. The energy dissipated by the creeping discharge was measured by the ΔV-Q Lissajous diagram monitored from the low voltage ΔV divided by a high voltage probe and the electric charge Q of a capacitor C_0 (0.1 μF) connected between the BSE and the ground. The dissipated energy J_i can be calculated as $J_i=V_sQf=mSfC_0$ joule/second, where V_s denotes the discharge sustaining voltage, f the frequency of applied voltage (60 Hz), m the voltage dividing ratio (5000) and S the area of the Lissajous diagram.

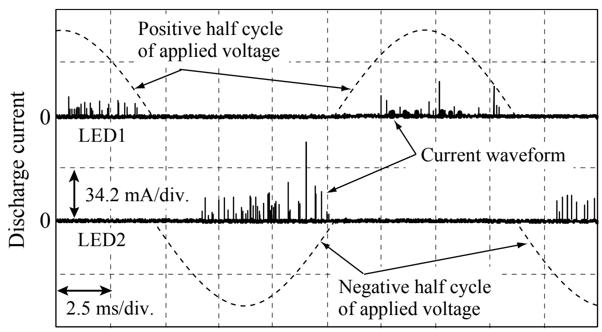
On the other hand, the gas components dissolved in oils by the creeping discharge were examined by means of gas chromatography (GC). Generally, the dissolved gas-in-oil analysis (DGA) has widely been used to estimate a feature of faults in oil-filled transformers [14-16]. The schematic of the gas analysis system used in this research and the measurement conditions of dissolved gases are shown in Figure 3. The gas components were detected by introducing directly the gases dissolved in sample oil to the GC using the stripping extraction method which was done by the carrier gas itself bubbling through a small volume of the oil sample. The extraction was controlled by turning the six port valves [17].

All experiments were performed at room temperature in the atmospheric pressure.

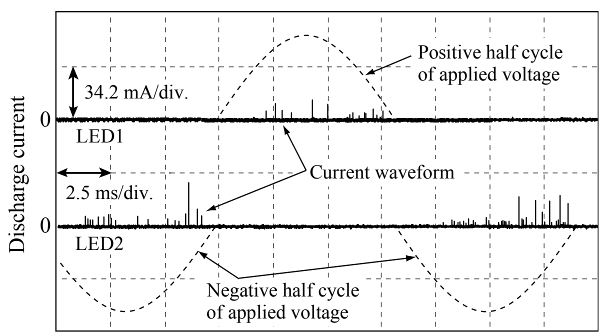
3 RESULTS AND DISCUSSION

3.1 DISCHARGE CURRENT, CREEPING DISCHARGE FEATURE AND DISSIPATED ENERGY

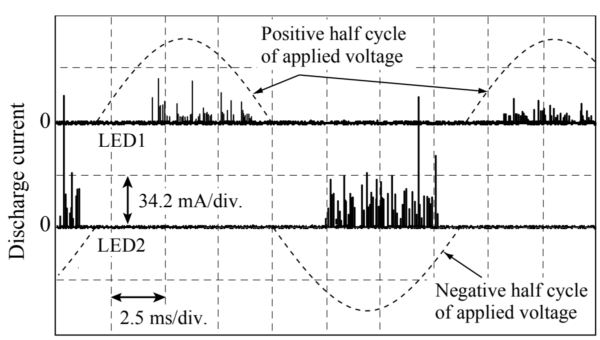
Figure 4 shows typical examples of the current waveform taken as a function of the time t_m under a fixed voltage. First, the partial discharge (PD) was initiated at the needle tip when the applied voltage exceeded the critical value withstand of the bulk oil. The discharge current at this time was observed in the form of many pulses as shown in Figure 4a. The local breakdown at the needle tip was attributed to an ionization process in the oil at the high electric field level of more than approximately 2 MV/cm. The number of pulses was numerous in the negative half cycle as compared with the positive half cycle of the applied voltage. This suggests that the impact ionization process due to the electrons emitted from the needle tip takes precedence over the field ionization process. The PD pattern was changed to the shape of a creeping streamer which



(a) t_m=2 min: Inception of partial discharge

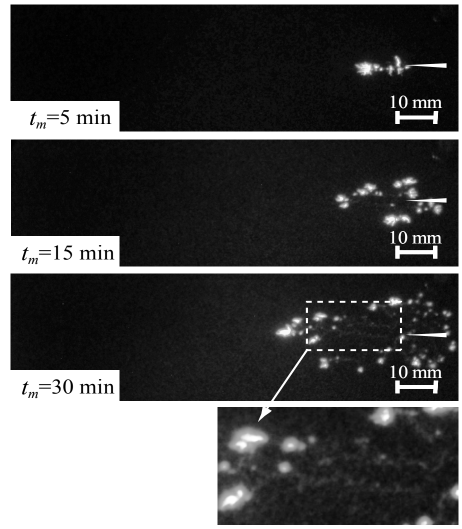


(b) t_m=15 min: Development of creeping streamer

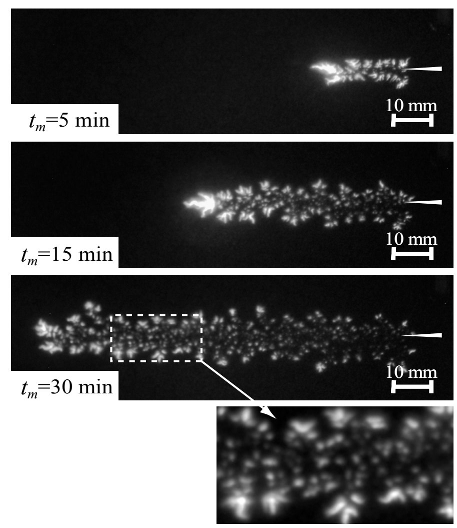


(c) t_m=25 min: Approach to pressboard puncture breakdown

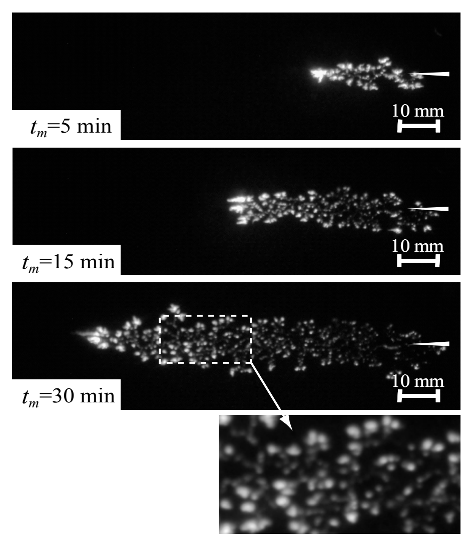
Figure 4. Typical examples of current waveform. (V_{rms}=35 kV, oil sample: Rapeseed oil)



(a) PFAE oil



(b) Rapeseed oil



(c) Mineral oil

Figure 5. Typical photographic profiles of creeping streamers as a function of time (V_{rms}=35 kV).

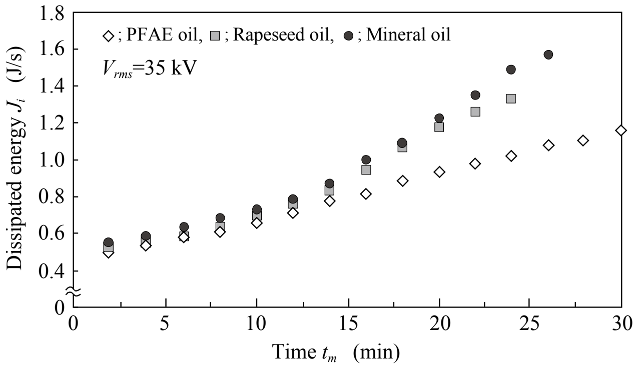


Figure 6. Energy dissipated by creeping discharges.

grew slowly in parallel and normal directions to the BSE after a short duration (roughly 1 to 2 minutes) of the voltage application. The amplitude and number of current pulses during the streamer growth became smaller than those observed for PD as shown in Figure 4b. The streamer growth will be associated with the ionization at a low energy in gaseous layer or low density region of oil on or near the oil/pressboard interface rather than the bulk oil. The current pulses, however, increased greatly when the pressboard was approaching to the punch-though breakdown event, as shown in Figure 4c. These features on the current waveform were observed similarly for all oil samples used here.

Typical photographic profiles of creeping streamers taken as a function of the time t_m imposing the voltage for PFAE oil, rapeseed oil and mineral oil are shown in Figure 5, respectively. The following features were found from these observations on growth of creeping streamers. The streamers were characterized by many formations of a fine branching and flashing spot. The flashing spots were clearly located in the head of streamer branches which indicated an ionization zone. It could be observed through a night viewer that the flash in rapeseed oil and mineral oil emitted a light brighter than that in PFAE oil. The streamers were easy to develop in the parallel direction rather than normal direction to the BSE. The streamer velocity in rapeseed oil and mineral oil was faster than that in PFAE oil, and the length L_m and width W_m of the streamer channel were longer than those in PFAE oil at the same discharge duration. The streamers in rapeseed oil and mineral oil had a lot of fine branches with many small flashing spots, while the streamer in PFAE oil was of a few thick branches.

The energy J_i dissipated by the occurrence of creeping discharges was measured as a function of the time t_m under a fixed voltage and the typical result is shown in Figure 6. The energy J_i increased with the time, which revealed that the creeping discharge gradually spreads its area over the pressboard surface. The J_i in rapeseed oil and mineral oil was larger than that in PFAE oil. This reflects that the creeping streamer in both rapeseed oil and mineral oil has an extension larger than that in PFAE oil at the same discharge duration, as shown in photographic profiles of Figure 5. The J_i-values dissipated during the creeping discharge will be able to produce a high temperature which is enough to decompose the cellulose or oil in a local area nearest to the streamer channels.

3.2 GAS COMPONENTS DISSOLVED IN OILS BY CREEPING DISCHARGE

Table 2. Gases generated in oils. (V_{rms}=30 kV)

Dissolved gases		H_2	CH_4	C_2H_6	C_2H_4	C_2H_2	CO	CO_2	N_2
Limit of quantitation		5	1	1	1	0.2	2	2	50
Rapeseed oil	t_m= 5 min	6	1	1	1	5	8	117	63601
	t_m=20 min	12	3	3	3	15	17	263	61536
Mineral oil	t_m= 5 min	5	2	1	2	8.4	3	178	65823
	t_m=20 min	22	11	3	4	29	4	212	67690

*t_m: Discharge duration unit: (ppm)

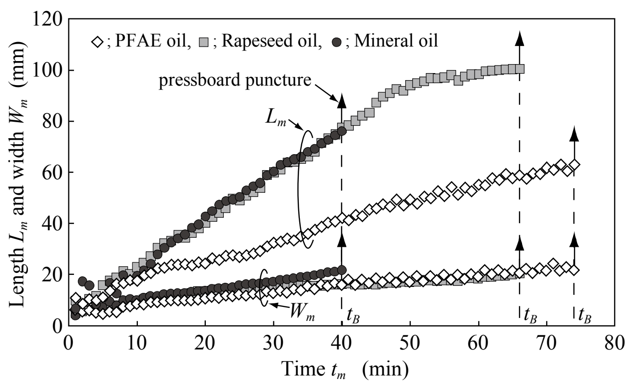
The gas components dissolved in oil samples (typically rapeseed oil and mineral oil) after the creeping discharge treatment were examined by using the gas analysis system in Figure 3. Seven gas components; hydrogen (H_2), methane (CH_4), ethane (C_2H_6), ethylene (C_2H_4), acetylene (C_2H_2), carbon monoxide (CO) and carbon dioxide (CO_2) were chosen as a target of gas analysis in this research. The ppm value of gases generated in oils is shown in Table 2 which indicates the following features. The relatively small amount of CH_4, C_2H_6 and C_2H_4 was detected in both rapeseed oil and mineral oil at the discharge duration of 20 minutes, and the amount of H_2 and C_2H_2 was much larger than ppm values of above gases. CO and CO_2 were also detected in both oils. The amount of CO in rapeseed oil was more than that in mineral oil and CO_2 was included much more than CO. The amount of nitrogen (N_2) gas given for reference was normally much greater than other gases, because of gaseous nitrogen filled in the test vessel with the oil sample.

It is well known that when the dielectric oils such as mineral oil are subjected to high thermal and electrical stresses, various gases generate due to the decomposition of the oil. Generally, the C-H molecular bonds are produced or decomposed at lower temperatures or energy, and higher temperatures or energy are necessary to produce or decompose the C-C single bonds, C=C double bonds and C≡C triple bonds. The creation of gases depends on the temperature, and the fault gases are generated in the order of $H_2 \rightarrow CH_4 \rightarrow C_2H_6 \rightarrow C_2H_4 \rightarrow C_2H_2$ with an increase of temperature. H_2 gas appears at the temperature in the range of 100 to 150 °C. CH_4 and C_2H_6 gases with the C-H and C-C single bonds respectively can be formed at the temperature in the range of 250 to 350 °C. C_2H_4 gas with C=C double bond can also be formed at higher temperature in the range of 200 to 500 °C. The formation of C_2H_2 with C≡C triple bond starts at the temperature exceeding 500 °C (usually 500 to 700 °C) [16, 18]. Meanwhile, if an oil-impregnated cellulose is involved in the oil, CO and CO_2 gases can be generated due to cellulosic thermal decomposition at lower temperature than that for oil decomposition (above a threshold temperature of approximately 150 °C). CO_2 gas increases much more rapidly than CO with an increase of temperature.

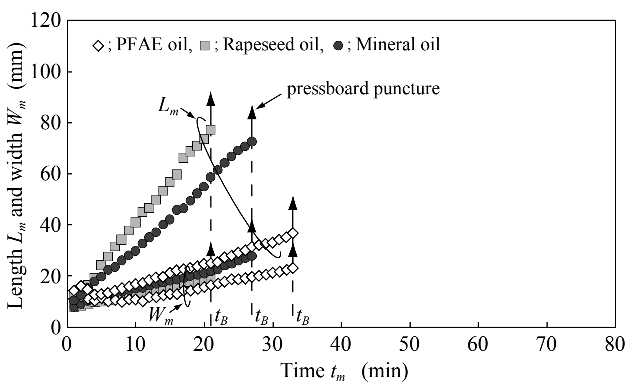
Conventionally, the DGA fault diagnostic can be estimated by the Duval triangle method which has been standardized by the International Electro-technical Commission (IEC) [19, 20]. The Duval triangle plots of the DGA data obtained in the present research belong to "low energy discharges" in both rapeseed oil and mineral oil. However, the discharge energy leads to the rise of temperature similar to or exceed 500 °C at the local region on or nearby the creeping streamer channels, because of the fact that C_2H_2 gas is detected by the occurrence of creeping discharges as shown in Table 2.

3.3 STREAMER EXTENSIONS AND PRESSBOARD PUNCTURE EVENT

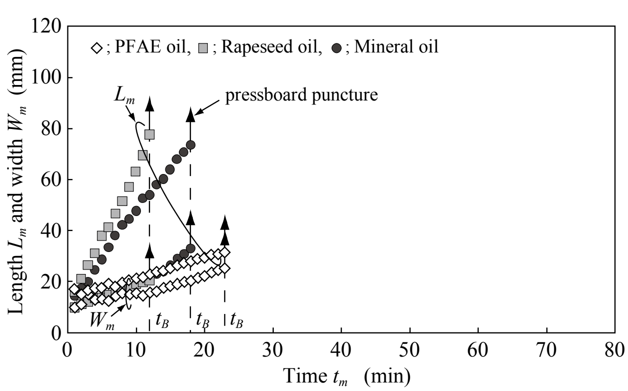
The mean length L_m and width W_m of streamer channels in PFAE oil, rapeseed oil and mineral oil were plotted as a function of the time and voltage from the photographic data for five trials, respectively. Figure 7 shows the L_m and W_m as a function of the time t_m for different voltages. The streamer growth exhibits roughly a linear dependence on the time t_m' where the slope of curves represents the mean velocity of



(a) V_{rms}=30 kV



(b) V_{rms}=35 kV



(c) V_{rms}=40 kV

Figure 7. L_m and W_m as a function of time t_m for different voltages.

Table 3. Mean streamer velocities u_L and u_W in parallel and normal directions to BSE.

Oil samples	Applied voltage V_{rms} (kV)					
	30		35		40	
	u_L (mm/min)	u_W	u_L (mm/min)	u_W	u_L (mm/min)	u_W
PFAE oil	0.8	0.19	0.8	0.3	0.8	0.5
Rapeseed oil	1.7	0.2	3.2	0.4	5.6	0.9
Mineral oil	1.7	0.4	2.5	0.6	3.3	1.2

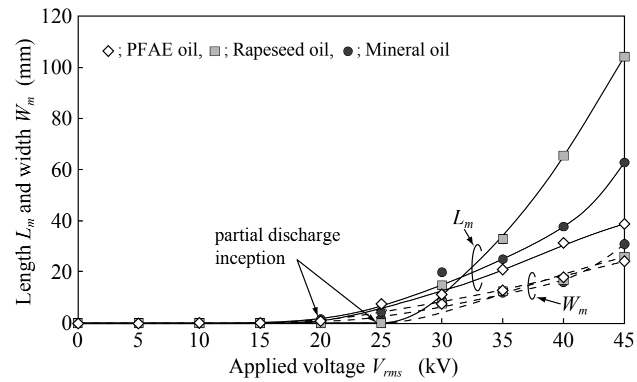


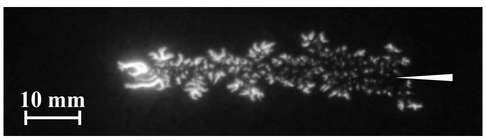
Figure 8. L_m and W_m as a function of applied voltage V_m.

streamers. The mean streamer velocities u_L and u_W in parallel and normal directions to the BSE are shown in Table 3. The u_L was much faster than u_W under identical applied voltage. This indicates clearly the effect of the BSE on the streamer growth. Although rapeseed oil and mineral oil were significantly different in a kinetic viscosity, the u_L-value was faster than that in PFAE oil with a low viscosity. This indicates that the streamer growth is independent from the kinetic viscosity of oils for ac creeping discharges. However, rapeseed oil will be disadvantageous to the cooling effect for applying to practical power equipment, because of its high kinetic viscosity in spite of slightly large thermal conductivity (Table 1) as compared with PFAE oil and mineral oil. It is seemed that there is need to modify a cooling system to applying rapeseed oil to a large capacity transformer. Figure 8 shows the L_m and W_m as a function of the voltage V_{rms} for three oil samples. The V_{rms} was elevated gradually in 3-minute intervals. The partial discharge inception was similarly at 20 kV in both PFAE oil and mineral oil, while this initiated at 25 kV in rapeseed oil. The electric fields at the needle tip for these inception voltages are estimated as ~2.2 MV/cm in both PFAE oil and mineral oil and ~2.8 MV/cm in rapeseed oil. The L_m and W_m increased clearly with the increase of V_{rms}, and L_m in rapeseed oil was much longer than that in PFAE oil and mineral oil at V_{rms}>35 kV.

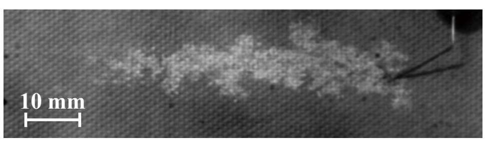
A sudden puncture breakdown of the pressboard occurred in the middle of the streamer progression. The time t_B from the voltage application to the puncture is shown in Figure 7 which is marked by an arrow as a minimal time for five trials. The t_B decreased when the V_{rms} was increased, although it had a large standard deviation. The pressboard puncture occurred at the position separated approximately 2 to 5 mm from the needle tip. This may be caused by the relaxation of the electric field near the needle tip due to the accumulation of space charge [21, 22].

3.4 FORMATION OF SURFACE TRACKING

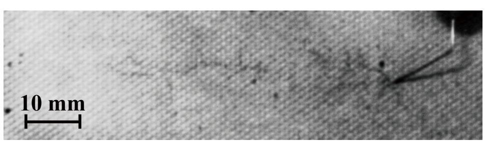
When the creeping discharge developed on the pressboard surface as shown in Figure 9a, a white mark which resembled a discharge shape appeared on the pressboard surface as shown in Figure 9b [12, 23]. The white mark grew simultaneously with the streamer growth from initial discharge at the needle tip. Then many tiny bubbles floating in the oil were observed at the surrounding area of streamer branches. The formation of this white mark is thought to be associated with gas generated into the pressboard or bulk oil during the streamer progression. As predicted from the dissipated energy and DGA data (Figure 6 and Table 2), a higher temperature more than ~500 °C can locally be produced on or nearby the streamer channels. The oil or moisture inside the pressboard will be decomposed or evaporated by the local overheating near the pressboard surface. Consequently, the created gases are put out from the fibrous structure of cellulose because of the gas expansion. Maxwell's stress also will promote this effect. In this case, Maxwell's stress is forced toward the pressboard side from the oil side, because the permittivity in cellulosic area near the pressboard surface including a lot of gases will become smaller than that in the oil area. Then, the oil is pulled into the pressboard and it acts so as to put out gases from the cellulosic structure. The gases generated by heating, however, will be captured in the small pores at the pressboard surface due to the surface tension of the oil and cellulose fibers. This results in a drying process on the pressboard surface and appears as the white mark which is covered by a thin gaseous layer or low density region of oil. The formative process of the white mark is illustrated in Figure 10. Overheating nearby the streamer channels will also decompose the oil molecules and produce the fault gases which may partially be captured in the pores of the pressboard surface. When the gases captured in the pores were expanded to the size exceeding the surface tension, tiny gas bubbles will be visualized in the bulk oil as observed in this research. As a result, the head of streamer branches can be developed by an active ionization due to the presence of the white mark, even if the lower energy than that in bulk oil. When a test vessel was evacuated by a vacuum pump after the creeping discharge development, the white mark disappeared from the pressboard surface at a short time. This is evidence of the presence of a drying area containing micro-bubbles at the oil/pressboard interface.



(a) Example of creeping discharge (V_m=35 kV, t_m=15 min)



(b) White mark on pressboard surface after creeping discharge



(c) Tracking pattern with dark marks on pressboard surface

Figure 9. Typical patterns of creeping discharge, white mark and tracking on pressboard surface. (oil sample: rapeseed oil)

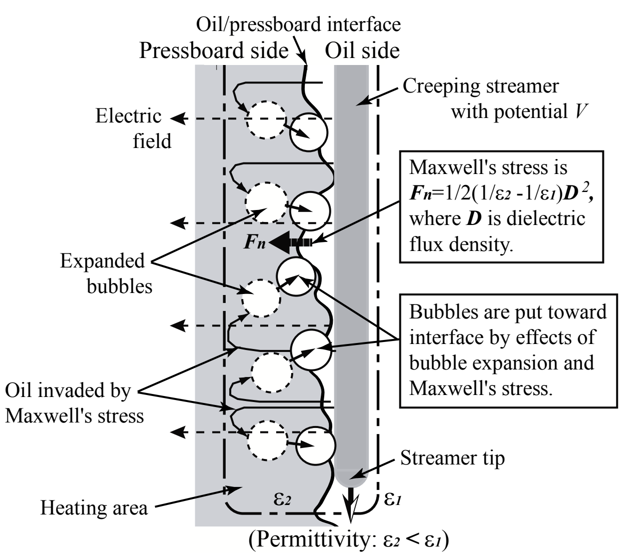


Figure 10. Formative process of white mark.

The creeping discharge left the irreversible tracking pattern with dark marks on the pressboard surface as shown in Figure 9c. A considerable high temperature is produced at a local area nearest to the streamer channels by the discharge energy as mentioned above. The heat energy is transmitted directly to the dried area of the pressboard surface through the oil with high thermal conductivity (typically 0.13 to 0.18 W/m·K). Then the cellulose fibers are carbonized by the overheating, because the temperature for the carbonization of cellulose is more than approximately 400 °C. Consequently, the tree-like tracking damage is formed on the pressboard surface. Once tracking was formed on the pressboard surface, the streamer

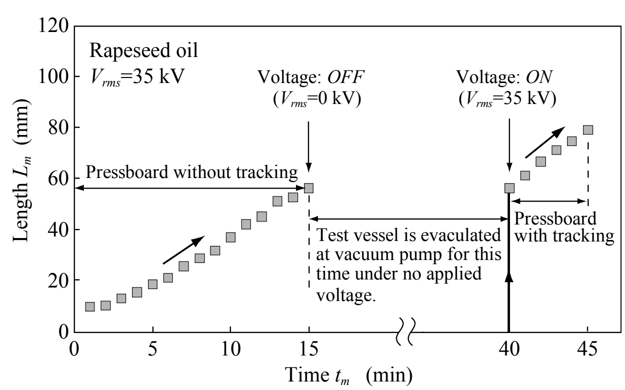


Figure 11. Typical relation between L_m and t_m for pressboard with and without tracking damage.

progressed through the tracking path as soon as the voltage was applied to the needle electrode and the discharge with similar pattern as Figure 9a occurred at a tracking area on the pressboard. Subsequently, the streamer started to grow gradually at its head again. Figure 11 shows the relation between L_m and t_m for the pressboard with and without the tracking under a fixed applied voltage. It is evident that the development of ac creeping discharges is promoted greatly by the tracking damages on the pressboard surface, because of an electrically conductive property of carbonic paths.

4 CONCLUSIONS

The creeping discharges in PFAE oil, rapeseed oil and mineral oil were investigated using the oil/pressboard system with the needle electrode and grounded rod type BSE under ac 60 Hz voltages up to 45 kV in rms.

The creeping streamer developed slowly on the pressboard surface in the shape with many branches under a fixed voltage. Then, the phenomena with the flashing spots indicating an ionization zone at the head of streamer branches were also observed in this experiment. The flashes in rapeseed oil and mineral oil emitted a light more luminous than in PFAE oil. The streamer expanded to the parallel direction rather than normal direction to the BSE. The streamer velocity in rapeseed oil and mineral oil was faster than that in PFAE oil, and the streamers grew longer than PFAE oil under the same discharge duration. The streamers in rapeseed oil and mineral oil had a lot of fine branches with many small flashing spots, while the streamer in PFAE oil was of a few thick branches. A puncture breakdown of the pressboard occurred suddenly in the middle of the streamer growth. The time up to the puncture event decreased when the imposed voltage was increased.

Furthermore, the creation of C_2H_2 gas obtained from the DGA suggested that the temperature at a local region on or nearby the creeping streamer channels was risen up to more than at least 500 °C by the discharge energy. A white mark on the pressboard surface resembled to a discharge shape appeared synchronously with streamer growth. This was attributed to a drying process due to the electrical and thermal effects. The creeping discharge left a dark tree-like tracking damage indicating a carbonized conductive path on the pressboard surface. Such the tracking damage promoted greatly the development of ac creeping discharges.

ACKNOWLEDGMENT

We thank the Ministry of Education, Culture, Sports, Science and Technology (MEXT) for the financial support through the Program for the Strategic Research Foundation at Private University, 2011-2016. The authors also thank the Ministry of Education of Japan for the financial support by a Grant-in-Aid for scientific research.

REFERENCES

[1] T. V. Oommen, "Vegetable Oils for Liquid-Filled Transformers", IEEE Electr. Insul. Mag., Vol. 18, No. 1, pp. 6-11, 2002.

[2] E. Gockenbach and H. Borsi, "Performance and New Application of Ester Liquid", IEEE 14th Int'l. Conf. Dielectr. Liquids, pp. 203-2006, 2002.

[3] B. Dolata, H. Borsi, and E. Gockenbach, "Comparison of Electric and Dielectric Properties of Ester Fluids with Mineral Based Transformer Oil", 15th Int'l. Sympos. High Voltage Eng., T8-484, pp. 1-5, 2007.

[4] T. Kano, H. Iwabuchi, Y. Hashida, J. Yamada, T. Hikosaka, A. Yamazaki, Y. Hatta, and H. Koide, "Analysis of Electro-Chemical Characteristics of Palm Fatty Acid Esters as Insulating Oil", IEEE 16th Int'l. Conf. on Dielectric Liquids, S4-01, pp. 307-310, 2008.

[5] M. A. G. Martins, "Vegetable Oils, an Alternative to Mineral Oil for Power Transformers – Experimental Study of Paper Aging in Vegetable Oil Versus Mineral Oil", IEEE Electr. Insul. Mag., Vol. 26, No. 6, pp. 7-13, 2010.

[6] M. Shinke, K. Miyazato, T. Tada, Y. Takeuchi, Y. Nakagami, R. Shimizu, M. Kosaka, and M. Wada, "Fundamental Studies on Development of Environment Friendly Vegetable Oil Filled Transformer", IEEJ Trans. PE, Vol. 123, No. 2, pp. 187-193, 2003. (in Japanese)

[7] C. T. Duy, O. Lesaint, M. N. Ngoc, A. Denat, Y. Bertrand, W. Daoud and M. Hassanzadeh, "Streamer Initiation and Breakdown in Vegetable-Based Biodegradable Oil", 16th Int'l. Sympos. High Voltage Eng., C-47, pp. 1-5, 2009.

[8] D. Vukovic and S. Tenbohlen, "Comparative Evaluation of Breakdown Strength of Natural Esters and Mineral Oil", 16th Int'l. Sympos. High Voltage Eng., C-14, pp. 1-6, 2009.

[9] H. Yamamoto, S. Otsuka, R. Hanaoka, S. Takata, N. Osawa, Y. Kanamaru and H. Koide, "Creeping Discharge in PFAE Oil Traveling over Pressboard Surface with Small Alien Substances", IEEJ Trans. Fundamentals Materials (FM), Vol. 130, No. 11, pp. 1019-1024, 2010.

[10] N. A. Muhamad, B. T. Phung and T. R. Blackburn, "Application of Common Transformers Faults Diagnosis Methodes on Biodegradable Oil-filled Transformers", Electr. Eng. pp. 207-216, 2012.

[11] Y. Kasahara, M. Kato, S. Watanabe, M. Iwahashi, R. Wakamatsu, T. Suzuki, A. Kanetani, K. Kano and T. Tamura, "Consideration on the Relationship Between Dielectric Breakdown Voltage and Water Content in Fatty Acid Esters", J. Amer. Oil Chem., pp. 1223-1229, 2012.

[12] J, Dai, Z. D. Wang and P. Jarman, "Creepage Discharge on Insulation Barriers in Aged Power Transformers", IEEE Trans. Dielectr. Electr. Insul., Vol. 17, No. 4, pp. 1327-1335, 2010.

[13] Q. Liw and Z. D. Wang, "Streamer Characteristic and Breakdown in Synthetic and Natural Ester Transformer Liquids with Pressboard Interface under Lightning Impulse Voltage", IEEE Trans. Dielectr. Electr. Insul., Vol. 18, No. 6, pp. 1908-1917, 2011

[14] M. Duval, "New Techniques for Dissolved Gas-in-Oil Analysis", IEEE Electr. Insul. Mag., Vol. 19, No. 2, pp. 6-15, 2003.

[15] IEC Publication 60567, "Oil-Filled Electrical Equipment – Sampling of Gases and Analysis of Free and Dissolved Gases - Guidance", Ed. 4, 2011

[16] S. Singh, D. Joshi and M.N. Bandyopadhyay, "Software Implementation of Duval Triangle Technique for DGA in Power Transformers", Int'l. J. Elect. Eng., Vol. 4, No. 5, pp. 529-540, 2011.

[17] R. Hashi, R. Hanaoka, H. Yamamoto, K. Takamoto, S. Nishikawa, H. Kaneda and K. Miyagi, "Analysis of Gases Dissolved by AC Creeping Discharge in Rapeseed Oil", 32rd Technical Meeting on Insulating Oil Section JPI, No.6 pp. 28-32. 2012, (in Japanese)

[18] M. Gutten, J. Jurcik and D. Korenciak, "The Monitoring of Oil Transformer 22/0.4 kV in Laboratory Conditions", J. Electr. Control Eng. (JECE), Vol. 3, No. 3, pp. 1-5, 2013

[19] IEC Publication 60599, "Mineral Oil–Impregnated Equipments in Service-Guide to the Interpretation of Dissolved and Free Gases Analysis", 1999

[20] M. Duval, "A Review of Faults Detectable by Gas-in Oil Analysis in Transformers", IEEE Electr. Insul. Mag., Vol. 18, No. 3, pp. 8-17, 2002.

[21] E. Kuffel and W. S. Zaengl, *High Voltage Engineering -Fundamentals-*, 1st ed., Pergamon Press: Tokyo, pp. 381-382, 1984.

[22] M. Zahn and R. Hanaoka, "Kerr Electro-Optic Field Mapping Measurements using Point-Plane Electrodes, Supplement à la Revue "Le Vide": Science, Technique et Applications", No. 275, pp. 360-372, 1995.

[23] P. M. Mitchinson, P. L. Lewin and B. D. Strawbridge, "Tracking and Surface Discharge at the Oil-Pressboard Interface", IEEE Electr. Insul. Mag., Vol. 26, No. 2, pp. 35-41, 2010.

Fri Murdiya was born in Jambi, Indonesia in 1980. He is currently a Ph.D. Student at Kanazawa Institute of Technology, Ishikawa, Japan and also a lecturer at electrical engineering at Riau University, Pekanbaru, Indonesia. He received his B.Sc. degree in electrical engineering from North Sumatera University Medan, Indonesia in 2003 and the M.Sc. degree in lightning protection system from the School of Electrical, Electronics and Informatics at Bandung Institute of Technology, Indonesia in 2009. His research interests include lightning protection system, creeping discharges on insulating cable and liquid insulation.

Ryoichi Hanaoka (M'94) was born in Kanazawa, Ishikawa, Japan in 1950. He received the M.Eng. degree in electrical engineering from Kanazawa University, Ishikawa, Japan in 1981 and the Dr. Eng. degree in electrical engineering from Tokyo Institute of Technology, Tokyo, Japan in 1987, respectively. Since 1996, he has been a Professor of electrical engineering at Kanazawa Institute of Technology (KIT), Ishikawa, Japan and at present, he is the head of the Center for Electric, Optic and Energy (EOE) Applications at KIT. He has been engaged in studies on electrical conduction, breakdown and creeping discharge phenomena in dielectric liquids, electric field calculation in high voltage engineering, EHD phenomena in dielectric liquids and development of ER/MR fluids. He was a Visiting Scientist at the Massachusetts Institute of Technology (MIT), Cambridge, USA from 1993 to 1994. Dr. Hanaoka is a member of the IEE Japan and the Institute of Electrostatics, Japan.

Hideki Akiyama was born in Kurume, Kyushu, Japan in 1989. He received the B.Eng. degree in electrical engineering from Kanazawa Institute of Technology, Ishikawa, Japan in 2012. Currently, he is a Master course student in Kanazawa Institute of Technology. He has been engaged in the study on creeping discharges in gases and dielectric liquids. Mr. Akiyama is a student member of the IEE Japan.

Katsunori Miyagi was born in Asahikawa, Hokkaido, Japan in 1957. He received the B.Eng., M.Eng. and Dr. Eng. degrees from Muroran Institute of Technology in Japan in 1980, 1982 and 2000, respectively. He worked for 20 Technology in Japan in 1980, 1982 and 2000, respectively. He worked for 20 years in Transformer Factory at Meidensha Corporation, Japan since 1982. In 2002, he joined Japan AE Power Systems Corporation, Japan, as a manager of Research & Development Department. Since 2012, he has been a Professor of electrical engineering at Kanazawa Institute of Technology, Ishikawa, Japan. Dr. Miyagi is a member of the IEE Japan.

Kiyoshi Takamoto was born in Osaka, Japan in 1953. He received the M.Eng. degree in chemical engineering from Kansai University, Osaka, Japan in 1978. He is a Factory Manager at Kanden Engineering Corporation, Osaka, Japan. He has been engaged in the studies on automatic analysis of dissolved gases in oils, diagnostic techniques of oil-filled transformers and quality guarantee of insulating oils. Mr. Takamoto is a member of the IEE Japan.

Takaaki Kano was born in Kanagawa, Japan in 1971. He received the M.Eng. degree in applied chemistry from Keio University, Kanagawa, Japan in 1996. He worked for 17 years in chemicals research laboratories at Lion Corporation, Japan since 1996 and joined as a research manager of Chemicals research laboratories since 2008. He has been engaged in studies on natural esters as electrical insulating liquids. Now he is a manager of sales development department in chemical division at Lion Corporation.