Charge Behavior in Palm Fatty Acid Ester Oil (PFAE) / Pressboard Composite Insulation System under Voltage Application

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***Abstract*—Palm Fatty Acid Ester Oil (PFAE) is one of the most promising environment-friendly biodegradable insulating oils for transformers. PFAE has significant advantages compared to other vegetable origin insulating oils and mineral oil, e.g. not only good insulation performance, high permittivity and high moisture tolerance, but also excellent cooling ability due to low kinematic viscosity, high thermal and chemical stability and high productivity. However, since the molecular content of PFAE is quite different from mineral oil, the fundamental charge behavior in PFAE has not been clarified yet. To clarify the temporal and spatial charge behavior in PFAE, we directly measured the electric field in oil duct model with PFAE / pressboard (PB) composite insulation system under dc voltage application and charged flow condition by using Kerr electro-optic field measurement technique. By the comparison of electric field and charge behavior characteristics with fresh and degraded mineral oil, we revealed that the essential mechanism of charge behavior is similar, but the difference in temporal and spatial characteristics is attributed to the higher intrinsic ion density and higher permittivity of PFAE than that of mineral oil.**

Keywords-transformer; insulating oil; palm fatty acid ester; electric field; Kerr electro-optic measurement; space charge

I. INTRODUCTION

Since the mineral oil is low-priced and has excellent insulation performance, the mineral oil has been widely used for oil-immersed transformers. However, biodegradability of the mineral oil is low, and the flash point is rather low. Recently, on the issues of environmental impact, a demand of environment-friendly insulating oil is increasing. Various candidates of environment-friendly insulating oil have been investigated [1–4]; especially, Palm Fatty Acid Ester oil (PFAE) [5] has advantages of good biodegradability, excellent insulating performance, lower viscosity, high cooling ability, good oxidation stability, and high productivity.

From the above many advantages, the transformers using PFAE will become more compact and have higher reliability than the conventional transformers. However, because the molecular content of PFAE is quite different from the mineral oil, the fundamental charge behavior in PFAE has not been clarified enough. Moreover, PFAE has low volume resistivity [5, 6], then it is considered that PFAE has rather high ion density. For the practical insulation design of transformer adopting PFAE, it is necessary to clarify the charge behavior.

To clarify the temporal and spatial charge behavior in PFAE, we directly measured the electric field in oil duct model with PFAE / pressboard (PB) composite insulation system under dc voltage application and charged flow condition by using Kerr electro-optic field measurement technique. Then, by the comparison of electric field and charge behavior characteristics between PFAE and mineral oil, we revealed the similarity and the difference in the essential mechanism of charge behavior.

II. PROPERTIES AND FUNDAMENTAL CHARACTERISTICS OF PFAE

Palm oil is a triglyceride of C16 and C18 fatty acid. Oil palm shows high productivity and its crop yield per unit area is 7 to 10 times higher than that of other vegetable seeds. PFAE is supplied by following reactions [7]:

$$
\begin{array}{lcccccc}
CH_2OCOR & & & & & & CH_2OH \\
| & & & & & & | \\
CHOCOR & + & 3CH_3OH & \longrightarrow & 3RCOOCH_3 & + & CHOH \\
| & & & & & & | \\
CH_2OCOR & & & & & & CH_2OH \\
\text{Fat and oil} & & \text{Methanol} & & \text{Fatty acid methyl ester} & & \text{Glycerin}
\end{array}
\quad (1)
$$

$$\underset{\text{Fatty acid methyl ester}}{R^1COOCH_3} + \underset{\text{Alkyl alcohol}}{R^2OH} \longrightarrow \underset{\text{Fatty acid alkyl ester}}{R^1COOR^2} + \underset{\text{Methanol}}{CH_3OH} \quad (2)$$

PFAE is fatty acid alkyl esters (R^1COOR^2) made from Palm oil. The properties of PFAE and mineral oil are shown in Table I. PFAE has advantages of lower kinetic viscosity, higher flash point, and higher relative permittivity than mineral oil [8]. In addition, partial discharge inception voltage measured by turn-to-turn models and section models in PFAE has also shown a better insulation performance than mineral oil [5]. It means that the transformer using PFAE has both better cooling efficiency and insulation performance. Therefore, we expect to realize a more compact with environment friendly transformer by using PFAE.

According to oxidation stability experiments based on Japanese Industrial Standard (JIS) C2101: "Testing method of electrical insulating oils", both of the breakdown voltage and the total acid value of PFAE changed a little. However, the breakdown voltage of mineral oil decreased by less than half, and the total acid value of mineral oil increased over 100 times compared with initial sample [5]. Therefore, the oxidation stability of PFAE is expected to be better than that of mineral oil.

III. Electric Field Measurement Setup

The molecular content of ester oil such as PFAE is quite different from mineral oil [7, 9], and the fundamental charge behavior in PFAE will be different especially under a composite insulation system. To clarify the temporal and spatial charge behavior in PFAE, we directly measured the electric field in oil duct model with PFAE / pressboard (PB) composite insulation system under dc voltage application and charged flow condition by using Kerr electro-optic field measurement technique.

Fig. 1 shows an experimental setup for field measurement

TABLE I. Properties of PFAE and Mineral Oil

	PFAE	Mineral Oil (fresh oil)	Mineral Oil [a] (degraded oil)
Mass density (g/cm^3) at 15°C	0.86	0.87	—
Kinematic viscosity (mm^2/s) at 40°C	5.06	8.36	—
Relative permittivity	2.95	2.2	2.2
Volume resistivity (Ω·cm) at 25°C	$> 10\times10^{12}$	4.6×10^{14}	4.4×10^{12}
tanδ (%) at 80°C	0.31	0.001	0.77
Flash point (°C)	186	145	—
Breakdown voltage (kV) at 2.5 mm gap	81	70–75	—
Charge relaxation time (s) at 25°C	> 2.61	85.7	0.84
Kerr constant (m/V^2)	9.1×10^{-17}	2.0×10^{-15}	2.0×10^{-15}

a. Sample data.

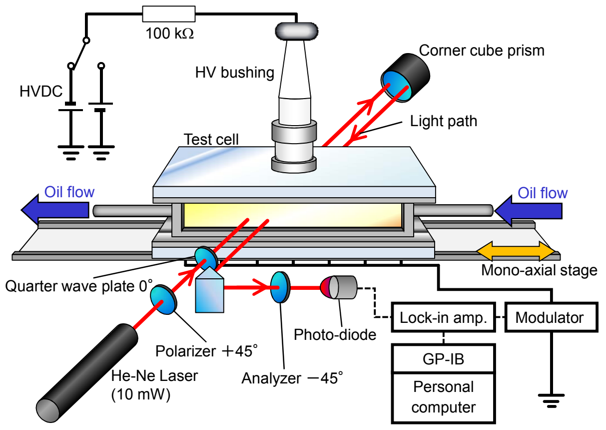


Figure 1. Experimental setup for electric field measurment in oil using Kerr electro-optic technique.

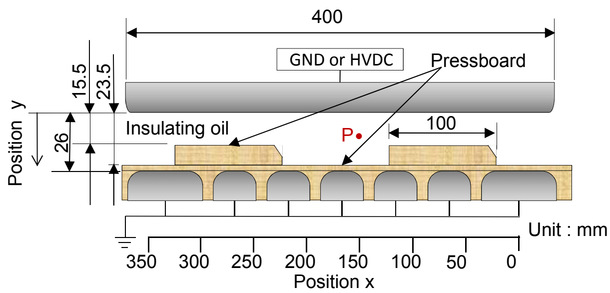


Figure 2. Electrode model of oil duct in transformer.

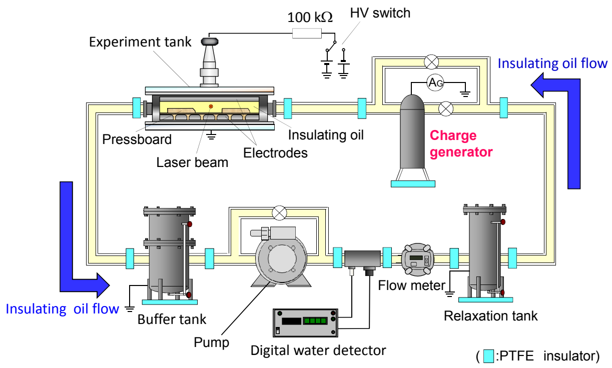


Figure 3. Oil circulation system.

in oil using Kerr electro-optic effect [6, 10]. A He-Ne laser beam is polarized by the polarizer and passed through the electrically stressed oil gap of the electrode system. The passed laser beam is detected by the photo-diode whose signal is analyzed with a lock-in amplifier. By using this setup, we can directly measure the electric field strength and its time transition in oil. The measured Kerr constant of PFAE is about 1/20 of that in mineral oil as shown in Table I. The highest sensitivity of field measurement is proportional to the Kerr constant, and it is 0.1 kV/mm in PFAE and 0.01 kV/mm in mineral oil.

Fig. 2 shows the electrode configuration placed in the test cell in Fig. 1. An uneven PB was placed on the grounded lower electrode of the parallel-plane electrodes. This PB form simulates a typical oil duct in actual transformer. The upper electrode was connected to a high voltage generator or ground.

Fig. 3 shows an oil circulation system. The system includes the measurement tank (Fig. 1), an oil pump, a charge generator and two tanks (a charge relaxation tank and flow buffer tank). This system was filled with insulating oil (PFAE or mineral oil). The insulating oil could be forced to flow by the pump at the rate of 14 ℓ/min. The insulating oil could be charged in the charge generator by using an oil filter. As the filter selectively absorbs negative charges in the oil, the oil was charged with positive polarity. We measured the generated charge density by using the high resistance ampere meter. All experiments were carried out at room temperature.

IV. Electric Field and Charge Behavior in PFAE/Pressboard Composite Insulation System

A. *Temporal Change of Electric Field in Static Oil*

Fig. 4 shows temporal variation of electric field strength at measurement point P (x = 150 mm) in Fig. 2 with dc voltage of +30 kV in static PFAE. The electric field strength was generated at the moment of voltage application (t = 0 s) and decreased with time because it relaxed by the accumulating positive charge on PB.

Fig. 5 shows the comparison of electric field distribution and temporal variation between PFAE and mineral oil with positive dc voltage application (PFAE: +30 kV, mineral oil (fresh and degraded): +10 kV). The electric field strength in Fig. 5 is normalized with average applied electric field. The average field is calculated from the applied voltage divided by the gap length between the upper and lower electrodes.

The share of voltage in PFAE at t = 0 s was lower than those in both of fresh and degraded in mineral oil. This can be explained from the equivalent circuit as shown in Fig. 6. Electric field strength E_i in oil at immediately after voltage application can be obtained by

$$E_i \approx \frac{V}{\frac{\varepsilon_{oil}}{\varepsilon_{PB}} d_{PB} + d_{oil}} . \quad (3)$$

ε_{oil} and ε_{PB} are permittivity of oil and PB, respectively. d_{oil} and d_{PB} are the gap length in oil and the thickness of PB, and V is the applied voltage. From (3), the electric field strength is determined by the permittivity ratio between oil and PB under ac field. Since relative permittivity of PFAE is higher than mineral oil, the share of voltage in PFAE was lower than that in mineral oil.

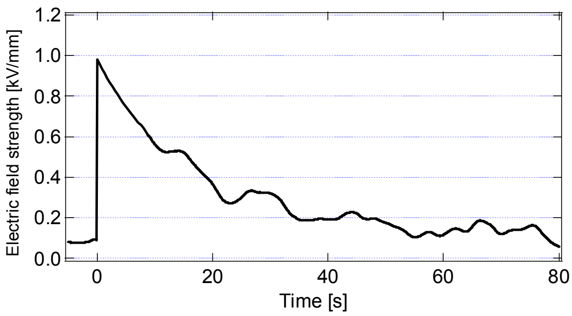
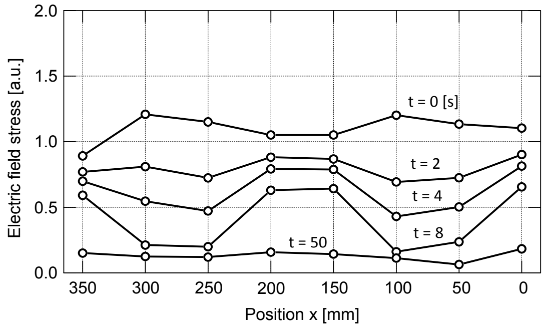
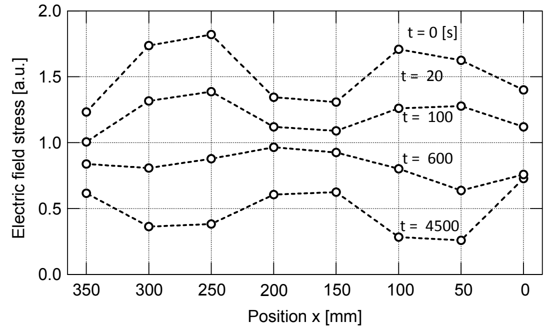


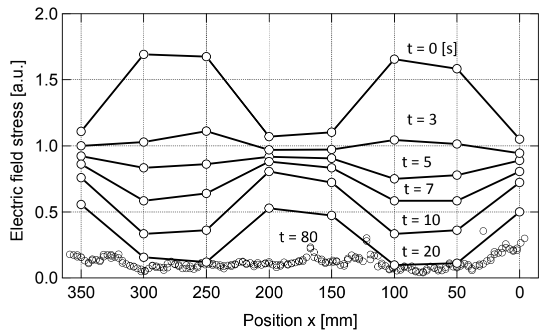
Figure 4. Temporal variation of electric field strength in static PFAE with dc voltage of +30 kV at x = 150 mm.



(a) PFAE (+30 kV).



(b) Mineral oil (fresh oil) (+10 kV).



(c) Mineral oil (degraded oil) (+10 kV).

Figure 5. Distribution and temporal transition of normarized electric field strength.

Compared with Figs. 5a and 5b, attenuation speed of electric field strength in PFAE was much faster than that in mineral oil (fresh). This phenomenon can be explained with the charge behavior [11]. In oils, positive and negative charges exist. The positive charges drifted towards the lower electrode due to the applied electric field and accumulated on PB. On the other hand, negative charges drifted and disappeared at the upper electrode. As a result, electric field in oil gap was weakened by the accumulated positive charges on PB. The

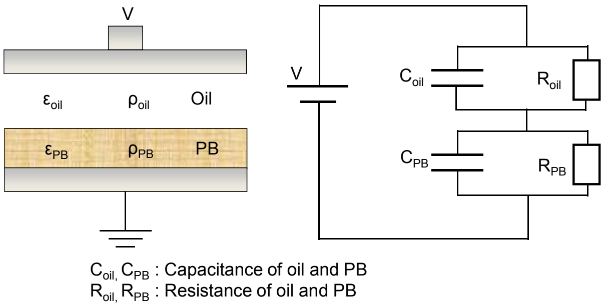


Figure 6. Equivalent circuit of oil / pressbord insulating system.

attenuation speed of electric filed depended upon PB thickness. From the equivalent circuit of Fig. 6, attenuation time constant (τ) of electric field strength in oil can be obtained by

$$\tau \approx \left(\varepsilon_{\text{oil}} + \varepsilon_{\text{PB}} \frac{d_{\text{oil}}}{d_{\text{PB}}} \right) \rho_{\text{oil}} \, . \tag{4}$$

τ depends on volume resistivity ρ_{oil} and permittivity ε_{oil} of each oil. Permittivities of two oils are same order. On the other hand, the volume resistivity of PFAE is lower than mineral oil (fresh). Thus, the attenuation speed of electric field strength in PFAE was much faster than that in mineral oil (fresh).

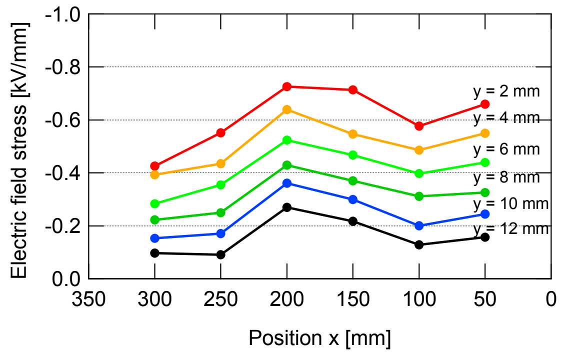
B. *Electric Field Distribution under Charged Oil Flow*

In a charged oil flow condition without voltage application, the electric field was generated and increased with time. Fig. 7 shows electric field distribution in oil duct model of Fig. 2 in PFAE and mineral oil (degraded) [12] at steady state under positive charged oil flow when the upper and lower electrodes were connected to ground. This phenomenon can be explained with space charge behavior in oil gap, taking account of Poisson's law. The positive space charges accumulate on PB due to the self electric field by the space charges, and the opposite electric field is generated by the accumulated charges. Then, the electric field due to the accumulated charges is superimposed on the electric field generated by the space charges. Assuming uniformity of space charge in oil gap along y direction at steady state, the electric field E_{oil} in oil can be expressed as

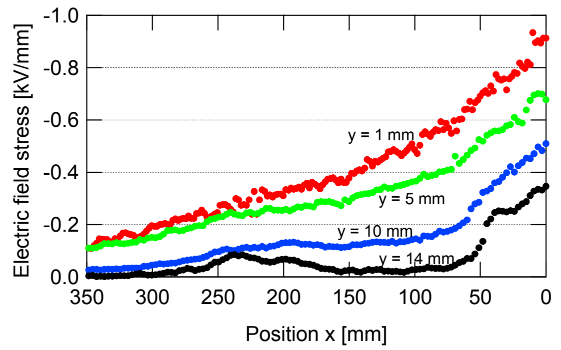
$$E_{\text{oil}} = -\frac{q_s}{\varepsilon_{\text{oil}}}\left(d_{\text{oil}} - y\right) - \frac{q_a - \varepsilon_{\text{PB}} E_{\text{PB}}}{\varepsilon_{\text{oil}}} \, . \tag{5}$$

q_s and q_a are space charge density in oil and accumulated charge density on PB. y is distance from the upper electrode. E_{PB} is electric field in PB. Fig. 8 shows the decaying characteristics of space charge density evaluated from Fig. 7 by using (5).

In both oils, the field strength E_{oil} and charge density q_s decreased as a function of the distance x from the inlet of oil flow, because the generated space charges drifted toward the upper electrode and gradually disappeared into the upper electrode. In PFAE, charge decay due to this mechanism was



(a) PFAE.



(b) Mineral oil (degraded oil).

Figure 7. Electric field distribution of oil duct model in PFAE and mineral oil under charged oil flow.

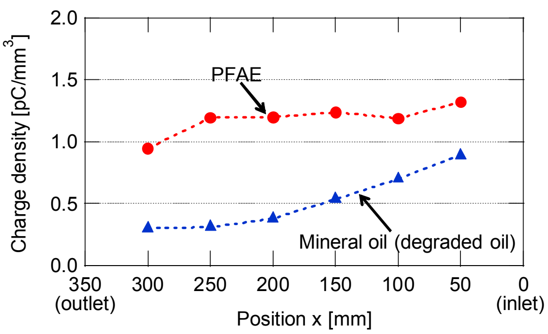


Figure 8. Space charge density distribution in PFAE and mineral oil.

smaller than the degraded mineral oil. This is because the charge relaxing time of the degraded mineral oil was much shorter than PFAE as shown in Table I.

C. *Transient Electric Field at Voltage Application under Charged Flow*

Fig. 9 shows the electric field in uncharged PFAE flow at y = 2 mm and in charged PFAE flow at y = 2, 6, 12 mm after dc voltage application of −20 kV at x = 50 mm. In both conditions, the negative high electric field was generated immediately after the voltage application and decreased with time, as is the case of static oil condition. Fig. 9 shows that, in all measuring points and conditions, the electric field behaviors corresponded with each other. From this result, it seems that the charge accumulation process on PB is independent of the charging of

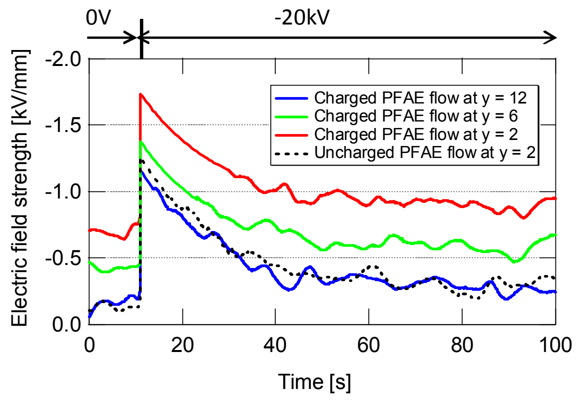
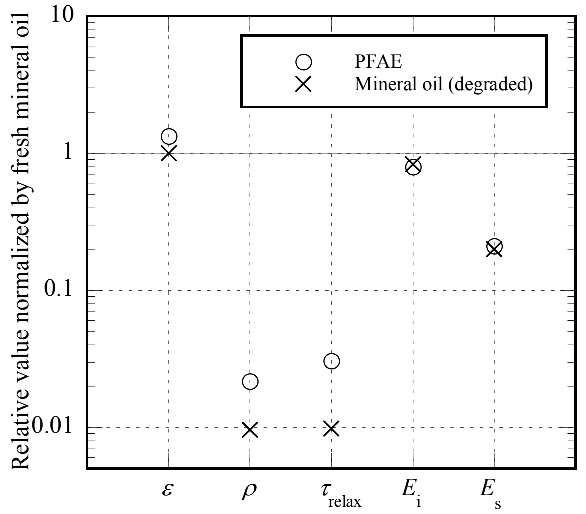


Figure 9. Temporal change of electric field in PFAE with dc −20 kV at x = 50 mm.



ε : permittivity, ρ : volume resistivity, τ_{relax}: charge relaxation time, E_i: initial electric field stress, E_s: steady state field stress

Figure 10. Comparison of various characteristics of PFAE and degraded mineral oil for fresh mineral oil .

PFAE. The accumulated charge density on PB generated by voltage application was calculated as 53 pC/mm^2. On the other hand, the initial ion density in PFAE was estimated above 1,400 pC/mm^3 [13]. Therefore, necessary charges for the accumulation on PB were much smaller than the initial ions and could be supplied from only near the PB. Namely, the charge balance in whole oil gap was almost unaffected by the voltage application. This phenomenon was also observed in the degraded mineral oil, which also has high ion density [12].

Fig. 10 summarizes the comparison of characteristics about electric field and charge behavior in oils. The values in Fig. 10 are normalized by that of fresh mineral oil. The electric field strength (E_i) in oil immediately after voltage application and that (E_s) at steady state under dc voltage application are the values at x = 150 mm, namely the oil gap length d_{oil} is 23.5 mm and the PB thickness d_{PB} is 2.5 mm. The charge relaxation time τ_{relax} is much smaller in PFAE and degraded mineral oil than in fresh mineral oil. Moreover, E_s is also smaller in PFAE and degraded oil than in fresh mineral oil. These are derived mainly from the lower resistivity. PFAE and degraded mineral oil has similar low resistivity and high ion density, therefore, the charge and electric field behavior in PFAE and degraded oil are similar.

V. Conclusions

PFAE (Palm Fatty Acid Ester Oil) has advantages of lower kinetic viscosity, higher flash point, and higher electric permittivity comparing with mineral oil. By the comparison of electric field and charge behavior characteristics with mineral oil, we revealed that the essential mechanism of charge behavior is similar, but the charge relaxation time is much lower than that of mineral oil. Therefore, we can expect PFAE as superior insulating oil for more compact and environment-friendly transformers.

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