Study on Streaming Electrification Properties of Palm Fatty Acid Ester (PFAE) Oil due to Aging

by Abdul Rajab

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***Abstract*— Palm fatty acid ester (PFAE) is mono ester oil which has better cooling property than mineral oil and other poly esters. Recently, natural ester has been tested on extra high voltage large power transformer. Large power transformers have a risk of streaming electrification. Many studies have been conducted to investigate streaming electrification properties of mineral oil immersed transformers and their countermeasures. However, streaming electrification properties of natural esters are rarely studied. Therefore, this paper presents a study on streaming electrification properties of PFAE due to aging. PFAE and mixed oils were prepared under several conditions. Aging test was conducted by heating the oil samples at 100 °C for 360, 720, 1080 and 1440 hours. The results show that heating causes various trends of volume resistivity and positive increases in electrostatic charging tendency (ECT) with respect to aging time. At initial state, ion dissociation on additive compound decreases volume resistivity and increases ECT. However, during the heating, the dissociation is not accelerated. Additive compound is dissociated into radicals to mitigate oxidation. In the mixture of 20% mineral oil and 80% PFAE, higher changes in volume resistivity and ECT indicate that degradation is more likely to occur in mineral oil part. In addition, air circumstance has effects on volume resistivity and ECT.**

Keywords—streaming electrification; transformer; mono ester oil; mixture of mono ester and mineral oil; electrostatic charging tendency; long term aging test

I. Introduction

High voltage large power transformers have a risk of streaming electrification. The streaming electrification occurs at the surfaces of celluloses exposed to oil flow. In 1970's, streaming electrification problem was observed at early stage of development of 500 kV class transformers. Many studies have been carried out to investigate streaming electrification properties. In 1990's, deterioration of mineral oil was known as one of the factors that contributes electrostatic charging [1]. Oxidation in sulfur and hydrocarbon molecules is responsible for the increase of electrostatic charging [2-4]. The electrostatic charging is likely changed rapidly by air exposure during maintenance. Thus one of countermeasures applied to suppress electrostatic charging in mineral oil immersed transformers is by adding 1,2,3-benzotriazol (BTA) to their insulating oil [5].

Natural ester has been investigated for application as insulating material [6]. It has been commercially used since 1999. Thereafter, the liquid was established in transformers for distribution grid and partially introduced in medium power transformers. Chemical structure of natural ester is naturally three fatty acid groups which are bonded on a glycerol. It is known as tri-ester. PFAE is modified chemically to obtain mono ester. As a result, the liquid has lower viscosity than other vegetable oils and mineral oil. It means that PFAE has better cooling property than other vegetable oils and mineral oil [7,8]. In addition, PFAE does not contain carbon-carbon double bond, so that it possesses better oxidation stability than other vegetable oils which contain unsaturated fatty acid [8,9].

Recently, polyester oil has been successfully tested on extra high voltage large power transformer [10]. Since the streaming electrification is more likely to occur in large power transformers, the streaming electrification properties of natural ester oil immersed transformers are important to be understood. However, streaming electrification properties of natural esters are rarely studied. Therefore this paper deals with a study of streaming electrification properties of PFAE due to thermal aging. Eight kinds of oil samples were prepared from three oil types, i.e. PFAE with additive, PFAE without additive and mineral oil. Some oil samples were degassed and placed under nitrogen circumstance, whereas other oil samples were not degassed and placed under air circumstance. Long term aging test was conducted by heating the oil samples at 100 °C for a given time. After heating was completed, ECT and volume resistivity were measured at room temperature. The influences of heating, additive, mineral oil and air circumstance on the streaming electrification properties were discussed.

II. Experimental Procedure

A. Oil samples

Three different oil types were used in this experiment, i.e. PFAE with additive (PFAE(A)), PFAE without additive

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(PFAE(NA)) and new mineral oil (MO). PFAE is mono ester oil which is developed by LION SPECIALTY CHEMICALS CO., LTD., Japan. Mineral oil is naphthenic based oil which is confirmed to meet Japanese Industrial Standard (JIS) C 2320. Eight kinds of oil samples were prepared from the three oil types as shown in Table I.

TABLE I. OIL SAMPLES FOR THE EXPERIMENT

Oil Samples	PFAE(A)	PFAE(NA)	MO	Cr*)
1) [PFAE(A)]N_2	100%	-	-	N_2
2) [PFAE(NA)]N_2	-	100%	-	N_2
3) [0.8PFAE(A)+0.2MO]N_2	80%	-	20%	N_2
4) [0.8PFAE(NA)+0.2MO]N_2	-	80%	20%	N_2
5) [PFAE(A)]Air	100%	-	-	Air
6) [PFAE(NA)]Air	-	100%	-	Air
7) [0.8PFAE(A)+0.2MO]Air	80%	-	20%	Air
8) [0.8PFAE(NA)+0.2MO]Air	-	80%	20%	Air

*) **Cr**: Circumstance

B. *Procedure of thermal aging test*

Tightly sealed stainless steel tanks with capacity of 8000 mℓ were used, as shown in Figure 1. Oil samples 1-4 were degassed and placed in the tanks under nitrogen circumstance, while oil samples 5-8 were not degassed and placed in the tanks under air circumstance. Long term aging test was conducted by heating the oil samples at 100 ^{0}C for 360, 720, 1080 and 1440 hours. After the heating was completed, ECT and volume resistivity (ρ) were measured at room temperature.

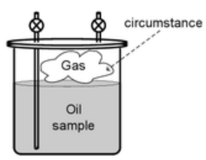


Fig. 1. Stainless steel tank

C. *Electrostatic Charging Tendency (ECT)*

ECT was measured by using Mini Static Tester. This method is standardized by Electrical Technology Research Association (ETRA) Japan and recommended by transformer working group of CIGRE. The structure of mini static tester is given in Figure 2.

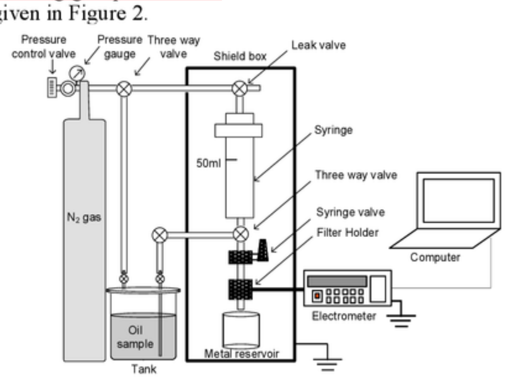


Fig. 2. Mini Static Tester

50 mℓ oil inside syringe was flown through a paper filter placed in a filter holder. Generated charges on the paper filter were measured using an electrometer (ADVANTEST, R8240) with a minimum detection level of 10 fA. Commercial paper filter was used as a static generation part. The paper filter was dried for about 24 hours at 100 ^{0}C and was kept in a closed container with silica gel before being applied for the measurement.

Midpoint value *i*[pA] of measured current and oil velocity *v*[mℓ/s] were used to calculate ECT at t ^{0}C (room temperature) as in (1). Then ECT was corrected to a reference temperature 20 ^{0}C as in (2).

$$ECT_{t^{o}C}\ [pC/m\ell] = -\,i\ [pA] \,/\, v\ [m\ell/s] \quad (1)$$

$$ECT_{20^{o}C}\ [pC/m\ell] = ECT_{t^{o}C} \times 3.18 \exp(-0.0589t) \quad (2)$$

D. *Volume Resistivity*

Volume resistivity (ρ) was measured based on JIS C 2101. Test circuit for the measurement is given in Figure 3. DC 10 V was applied to the tested oil at room temperature for about 5 minutes. Adsorption current was measured using the electrometer (ADVANTEST, R8240) with a minimum detection level of 10 fA. 0 minute value extrapolated from the measured current was used to calculate the volume resistivity as in (3) and (4).

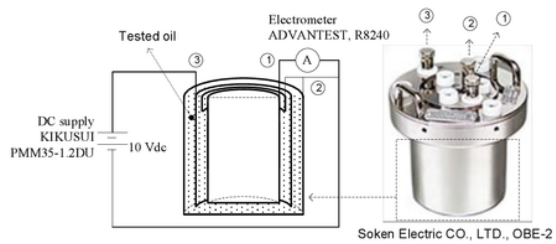


Fig. 3. Test circuit of volume resistivity measurement

$$R_x = V / I_0 \quad (3)$$

$$\rho = K R_x \quad (4)$$

where R_x is resistance in Ω, V is applied DC voltage in volt, I_0 is current at 0 minute in ampere, ρ is volume resistivity in Ω.cm and K is a constant of electrode in cm. In this experiment, a coaxial cylinder system electrode (Soken Electric CO., LTD., OBE-2) with K=1000 was used.

III. RESULTS

Figure 4 shows the trends of ECT of the oil samples under nitrogen circumstance. As can be seen, at initial state, oil samples with additive have higher ECT than oil samples without the additive. The presence of 20% mineral oil in PFAE decreases ECT. Heating causes positive increases in ECT with respect to aging time. In PFAE(A), negligible change in ECT is observed at final stage of heating, whereas other oil samples exhibit increasing tendencies.

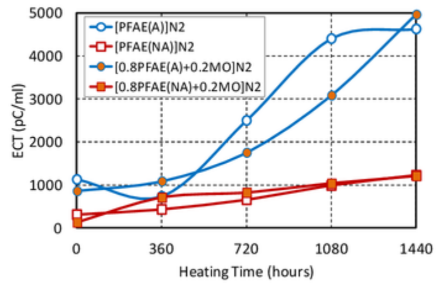


Fig. 4. Trends of ECT of oil samples under nitrogen circumstance

Figure 5 shows the trends of the ρ of oil samples under nitrogen circumstance. Volume resistivity of oil samples without additive decrease gradually with aging time. However, in oil samples with the additive, negligible change is observed in pure PFAE, while mixed oil exhibits slight increase.

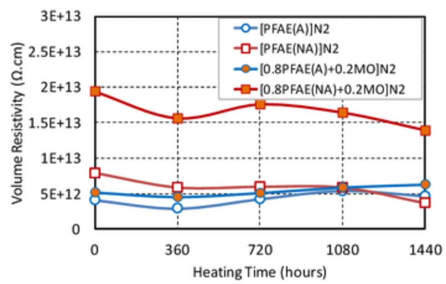


Fig. 5. Trends of volume resistivity of oil samples under nitrogen circumstance

Figure 6 shows the trends of ECT of oil samples under air circumstance. Note that different lot number of oil samples was selected for the experiment. The lot number implicitly indicates time storage of oil. At initial state, negative ECT is observed in PFAE(A). However, all the oil samples show positive increases in ECT with aging time. Significant increases are observed in the mixtures of MO and both of PFAE(A) and PFAE(NA).

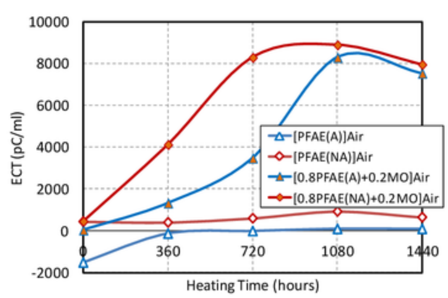


Fig. 6. Trends of ECT of oil samples under air circumstance

Figure 7 shows the trends of volume resistivity (ρ) of oil samples under air circumstance. In oil samples without additive, ρ decreases significantly. And higher decrease in ρ is observed in the mixture of PFAE(NA) and MO. Moreover, the increase of ρ is observed in PFAE(A), whereas slight decrease is observed in the mixture of PFAE(A) and MO.

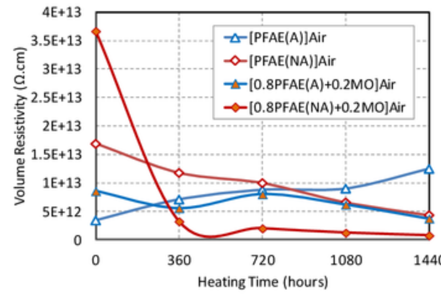


Fig. 7. Trends of volume resistivity of oil samples under air circumstance

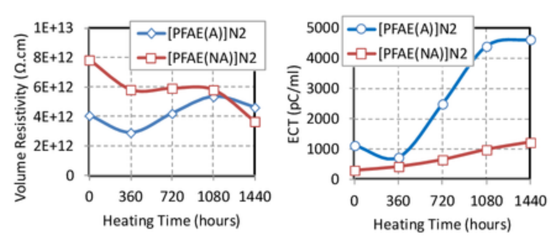
IV. DISSCUSION

A. *The effect of aging on ρ and ECT*

As shown, various trends of ρ with aging time were observed. Oil samples without additive exhibited decreases in ρ with aging time. On the other hand, [0.8PFAE(A)+0.2MO]Air and [PFAE(A)]N2 exhibited slight decrease and negligible change in ρ, respectively, whereas [0.8PFAE(A)+0.2MO]N2 and [0.8PFAE(A)]Air exhibited increases in ρ. Slight changes of ρ with the aging time observed in the oil samples with the additive are considered to reflect oxidation stability. It was also found that negative ECT was observed in PFAE(A) under air circumstance. The oil sample which had negative ECT was taken from PFAE storage with different lot number. On the other hand, all the oil samples showed positive increases in ECT with aging time.

B. *The effect of additive on ρ and ECT*

Figure 8 shows the effects of additive on ρ and ECT for oil samples under nitrogen circumstance. At initial state, PFAE(A) has lower ρ and higher ECT than PFAE(NA). PFAE(NA) exhibits decease in ρ with aging time, while negligible change in ρ is observed in PFAE(A). The results can be interpreted as follows: At initial state, additive compound is dissociated into ions. Additional charges generated from the dissociation decrease ρ and increase ECT. During the heating, the additive dissociation is not accelerated. Additive compound is dissociated into radicals to mitigate oxidation process. As results, slight change in ρ and negligible change in ECT at final stage of heating are observed. The slight increase in ρ as seen in the oil with additive is considered as the effect of ion recombination.

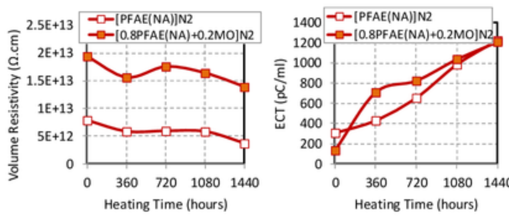


a) Volume resistivity b) ECT

Fig. 8. The effect of additive on ρ and ECT

C. *Influence of mineral oil on ρ and ECT*

Figures 9(a) and 9(b) show the influences of mineral oil (MO) on ρ and ECT, respectively. At initial state, the mixed oil has higher ρ and lower ECT than pure PFAE. It is considered that mineral oil has lower polarity than PFAE. Hence, mineral oil contains lower number of charges than PFAE. Addition of 20% MO into PFAE reduces total charges in the oil sample. As results, ρ increases and ECT decreases. However, during the heating, slightly higher decrease in ρ is observed in the mixed oil. ECT of the mixed oil also exhibits higher increase. Higher degradation is likely to occur in mineral oil part. This result indicates that mineral oil is more susceptible to oxidation than PFAE. PFAE is mono ester which does not contain carbon-carbon double bond in its fatty acid chain side. In natural ester, the higher number of carbon - carbon double bonds in its molecules makes the oil more susceptible to oxidation.

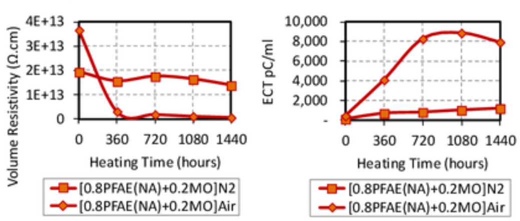


a) Volume resistivity b) ECT

Fig. 9. The influence of 20% mineral oil on ρ and ECT

D. *Influence of Air on ρ and ECT*

Figures 10(a) and 10(b) show the effect of air circumstance on ρ and ECT, respectively. Higher changes in ρ and ECT in oil sample under air circumstance are observed. Existence of oxygen is considered to contribute to oxidation of hydrocarbon part in both of PFAE and mineral oil. The oxidation process is activated first by dissociation of hydrocarbon component RH into hydrocarbon radical $R^{\bullet}$ due to heating. Hydrogen radical quickly reacts with the oxygen to form a peroxy radical $ROO^{\bullet}$. Further reaction of oxidation can be seen in Figure 11. It is considered that oxidation process produces carboxylic acid as one of by-products. Carboxylic acid is polar compound which is easily dissociated into ions. Then the ions affect volume resistivity and ECT.



a) Volume resistivity b) ECT

Fig. 10. The effect of air circumstance on ρ and ECT

Initiation of oxidation: $RH \rightarrow R^{\bullet} + H^{\bullet}$

Chain propagation: $R^{\bullet} + O_2 \rightarrow ROO^{\bullet}$

$ROO^{\bullet} + RH \rightarrow ROOH + R^{\bullet}$

Chain divergence: $ROOH \rightarrow RO^{\bullet} + OH^{\bullet}$

$RO^{\bullet} + RH \rightarrow ROH + R^{\bullet}$

$OH^{\bullet} + RH \rightarrow H_2O + R^{\bullet}$

Chain suspension: $2ROO^{\bullet}$, $2R^{\bullet}$, and $R^{\bullet} + ROO^{\bullet}$

Generation of acid: $R'COH + ½\,O_2 \rightarrow R'COOH$

Dissociation of acid: $R'COOH \rightarrow R'COO^{-} + H^{+}$

R, R': alkyl group

$R^{\bullet}$: alkyl radical

Fig. 11. The role of oxygen in oxidation process

V. CONCLUSION

Aging test was performed on the oil samples under nitrogen and air circumstances to understand streaming electrification properties of PFAE. The results are summarized as follows.

1. The heating caused various trends of the volume resistivity (ρ) and positive increases in ECT.
2. The additive had some effects on the streaming electrification properties. At initial state, the additive compound is dissociated into ions. The dissociation decreases ρ and increases ECT. It was found that, during the heating, slight changes in ρ and negligible changes in ECT were exhibited at the final stage of heating. These results are considered as mitigation of oxidation.
3. The presence of 20% MO in PFAE caused higher decease in ρ and increase in ECT with aging time. It is considered that MO is more susceptible to oxidation than PFAE.
4. Under air circumstance, oil samples exhibited significant decrease in ρ and increase in ECT.

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