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EARLY DETERIORATION OF PALM FATTY ACID ESTERS (PFAE) OIL

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Abstract This paper deals with the early deterioration of PFAE oil. Partial discharge (PD) behaviors of the PFAE oil under dry and moist conditions are investigated. Gases generated by the PFAE oil under PD and low thermal faults are analyzed. The suitability of Duval Triangle 3 method to interpret PD fault in the PFAE oil is evaluated. A CO/CH_4 ratio to expect the temperature of low thermal fault in PFAE oil is proposed.

Keywords: insulating oil; moisture content; natural ester; partial discharge; PFAE; thermal fault.

1. INTRODUCTION

The natural ester of triglyceride type-based insulating liquid has been proven to be a good alternative for mineral oil. Under triglyceride structure, the viscosity of natural ester is very high. The typical viscosity values of triglyceride form natural ester-based insulating oils that have been commercially available, and mineral oils at 40 °C, measured based on ASTM D445 standard, are 33 and 9.2 mm^2/s, respectively [1]. In order to obtain the low viscous natural ester-based insulating oil, thus higher fluidity, natural monoesters are introduced. The viscosity of a commercially available natural monoester, PFAE, is 5.1 mm^2/s at 40 °C, which is lower than the typical viscosity value of mineral oils [2].

PFAE oil has been implemented in oil filled-distribution transformer [3]. It is a common field practice in Japan that moisture content of an oil is not strictly controlled before being used in a distribution transformer. Moisture content increases during the operation of the transformer due to the oxidation of oil molecules, as well as that of paper insulation [4]. Moisture ingression could also happen when insufficient dry air entering the transformer's tank, or when there was a leakage on the gasket [5]. PD properties of PFAE oil under different moisture content are then investigated and reported in this paper.

The application of the PFAE oil is intended to be extended to the higher voltage of power transformer. The need for diagnosis method to assess their performance is important. For this reason, the research on generated gases by thermal and electrical stresses in PFAE are conducted and also reported in this paper. Particular attention is paid to the early stage of deterioration of the oil molecules, i.e. the deteriorations due to the low temperature overheating, the low thermal faults having temperatures range up to 300 °C, and due to the partial discharge. Detection at the early stage of deterioration will help preventing insulation from being damage which could lead to the early end of equipment's life.

2. PD PROPERTIES OF PFAE UNDER DIFFERENT MOISTURE CONTENT

2.1 SAMPLES The oil samples used for investigation of PD properties are PFAE having different moisture contents. Dry sample represented by an as received oil, the oil without pretreatment before being used as experimental specimen. Another sample was moist sample which was prepared by adding about 0.5 ml of water into the PFAE oil having a volume of 1000 ml. The sample was stirred at 500 rpm at 40 °C for about 12 hours using magnetic stirrer.

2.2 EXPERIMENTAL ARRANGEMENT AND PROCEDURE The oil chamber used for PD measurement was made of acrylic in which electrode pairs of needle-plane configuration was immersed, as depicted in Fig. 1. The tip radius of the needle electrode is 10 μm. The diameter and thickness of plane electrode are 68 mm and 5 mm, respectively. An acrylic with the thickness of 5 mm was put on the surface of the plane electrode, the gap between the needle and acrylic was 5 mm.

The schematic diagram of the PD measurement is shown in Fig. 2. R detector was used to discriminate the polarity of PD pulses, whereas combined DI and CD6 detectors were used to measure the integrated apparent charge of PD pulses. The partial discharge was generated in each oil sample by applying AC high voltage on the needle electrode. Application of voltage was set at a given value, and it was being kept for about 2 minutes for conducting measurement.

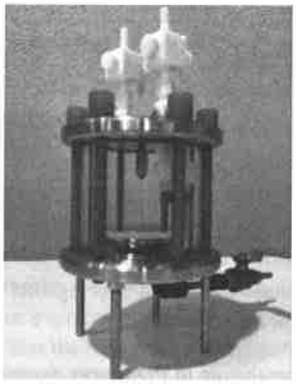


Fig. 1. Chamber used for PD measurement.

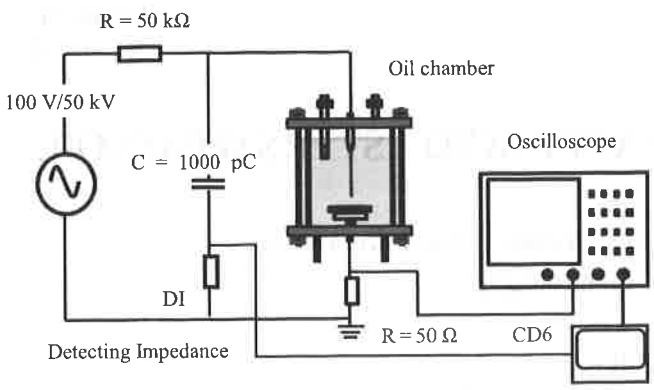
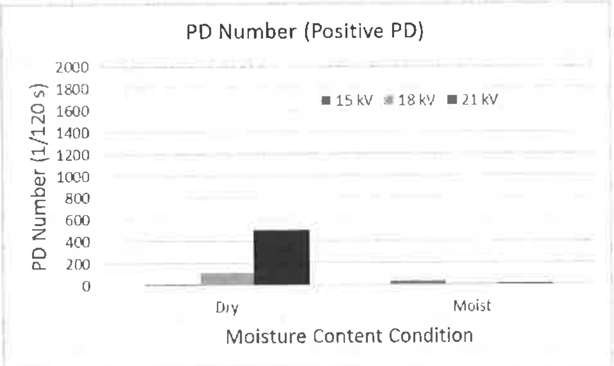
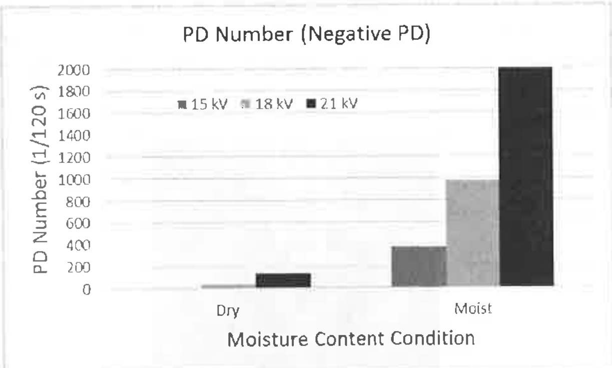


Fig. 2. Experimental set up for PD measurement

2.3 RESULTS AND DISCUSSION Fig. 3 shows the change in PD number against applied voltage of dry and moist samples of PFAE. For positive PD, the number of PD in dry sample tends to increase with applied voltage, while that in the moist sample remains constant. At a higher level of applied voltage, the PD number of moist sample is much less than that of dry sample. For negative PD, the number of PD in both dry and moist samples increase with the applied voltage. A slight increase was observed in the dry sample, but a drastic increase was found in the moist sample. The number of PD in moisture sample is remarkably higher than in dry sample at all levels of applied voltages.



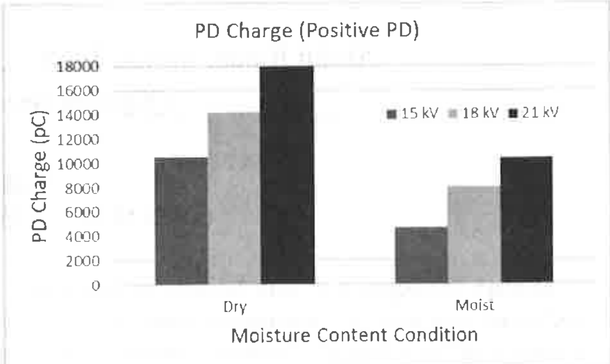
(a)



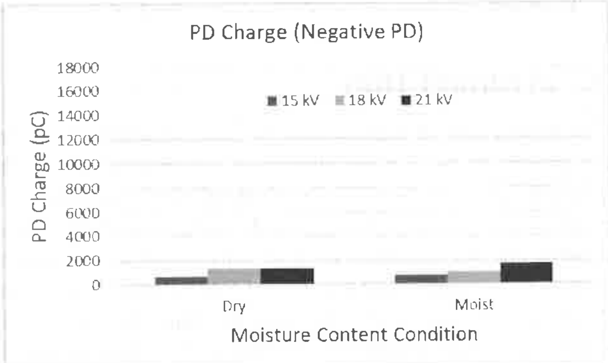
(b)

Fig. 3. The change in PD number against applied voltage; (a) Positive PD, (b) Negative PD.

Fig. 4 shows the change in PD charge against applied voltage of dry and moist samples of PFAE. For positive PD, PD charges of both dry and moist samples increase with applied voltage, and the PD charge of dry sample is always higher than that of moist samples whatever the applied voltage is. For negative PD, no significant different in the PD charges of both dry and moist samples was found, and the change in applied voltage does not make a significant difference in PD charge of both samples.



(a)



(b)

Fig. 4. The change in PD charge against applied voltage; (a) Positive PD, (b) Negative PD.

The addition of moisture intensifies PD activities in PFAE oil which is indicated by the drastic increase in PD number. This intense PD mostly took place at the negative polarity of applied voltage, but small in PD charge. The PD number of positive PD decrease, but its decrease is not as drastic as the increase in that of negative PD. The addition of moisture also decreases the PD charge of positive PD.

The change in PD behavior of PFAE sample by addition of moisture can be attributed to the electronic affinity of water molecule. It should be noted that water molecule contains oxygen atom which is highly electronegative (electronegativity = 3.44). The existence of fluorine atom having high electron affinity (electronegativity = 3.98) in Galden D-40 fluid was suspected to be the main reason of the different discharge behavior of Galden D-40 from Ugilec C 101 and Baylectrol 4900 liquids. Unlike two other fluids, PDIV and SIV of Galden D-40 are lower and took place at the negative polarity of applied voltage [6]. It is also mentioned in [7] that molecular structure has a significant effect on the streamer propagation. The main parameter affecting streamer propagation is the electronic affinity of the liquid molecules.

3. GAS GENERATION OF PFAE OIL

3.1 CAUSED BY PD FAULTS To investigate gases generated by PD in the PFAE oil, the same experimental setup as that in section 2 was used. The PFAE oil sample was stressed by applying an AC high voltage of 20 kV, and the voltage application was being kept until PD number of 5000, 8000 and 12000 took place. Two kinds of gas samples were prepared for each oil sample; gases from oil-free space at the upper part of the oil inside the chamber, and gases from the oil. Gas in oil was extracted using headspace method. Gas samples were then analyzed using a gas chromatograph (GC-2014 model, Shimazu Corp. Japan).

The types of combustible gases generated by PD in PFAE samples stressed at 20 kV under the needle plane electrode configuration, are methane, ethylene, acetylene, and carbon monoxide, as depicted in Fig. 5. It is interesting that hydrogen is produced by PFAE oil in not significant amount, and this behavior applies for all tested samples stressed with different numbers of PD. This result differs from that usually found in the literature. It has been a consensus that hydrogen is the key gas used for interpreting PD fault in mineral oil. Hydrogen was also found to be the main gas in a triglyceride type vegetable oil-based insulating liquid, FR3, under PD stresses [8].

Another interesting result is the low generation amount of carbon monoxide. It was unexpected result since PFAE contains –COO- link in its structure. It also can be seen from the Fig. 5 that the main combustible gas produced by the oil was methane.

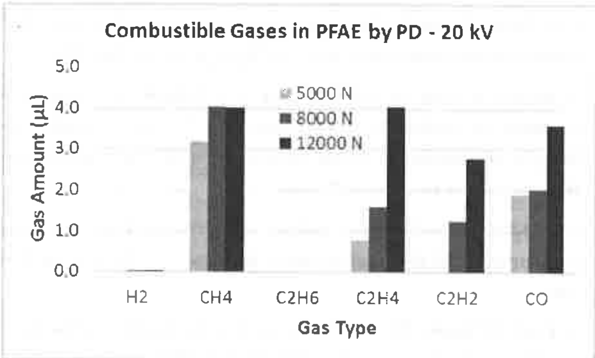


Fig. 5. Gasses generated by PFAE under PD faults.

3.2 CAUSED BY LOW THERMAL FAULTS

Gases generated by PFAE oil under low temperature overheating were investigated for five different temperature levels; 200, 225, 250, 275 and 300 °C. The experimental arrangement and procedure can be found in [9]. The results are depicted in Fig. 6. The types of combustible gases produced in significant amount are only carbon monoxide and methane. The amount of carbon monoxide is much larger than that of methane. Hydrogen is sometimes obtained in not significant amount.

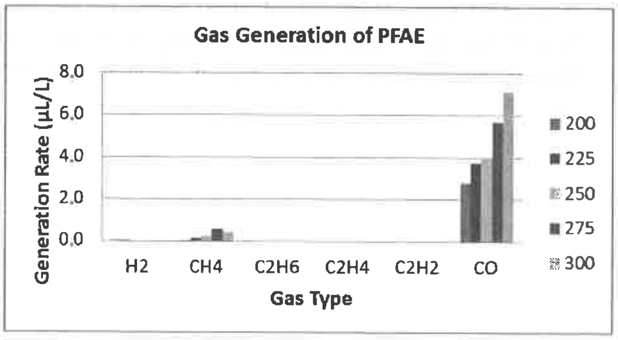


Fig. 6. Gasses generated by PFAE under Low Thermal faults.

This result differs from that usually produced by the natural ester of triglyceride type which under low temperature overheating produce ethane in a significant amount. The ethane is even suggested to be the key gas for the thermal fault of the natural ester of triglyceride type [10] [11]. The difference in ethane generation is due to the existence of C-C double bond in triglyceride type natural ester, which is absent in PFAE structure [9].

4. FAULT INTERPRETATION

4.1 DUVAL TRIANGLE FOR PD FAULT

Duval Triangle (DT) 1, which is also called classical Duval Triangle, is a well-established method used to interpret electrical and thermal faults in mineral oil filled transformer. The increase in the usage of non-mineral oils motivates the appearance of Duval Triangle (DT) 3. Two types of DT3 were developed to accommodate two natural ester-based insulating liquids, Envirotemp and Biotemp [12], but only the DT3 for Envirotemp is used to evaluate its applicability for PFAE oil in this paper.

Three kinds of gases are required in implementing DT3 method; CH_4, C_2H_4, and C_2H_2 [12]. All of these gases are found in the PD stressed PFAE samples and the plots of each case are depicted in Fig. 7. It can be seen that DT3 incorrectly interprets all PD fault cases. The samples stressed with 8000 and 12000 number of PDs are diagnosed to be the discharge of high energy type (D2), whereas the sample stressed with 5000 number of PDs is mistakenly put into the low thermal fault region in T1. The absence of C_2H_2 in the sample stressed with 5000 number of PDs is attributed to a low total energy dissipated by discharge, and it is indicated by its total PD charge which is much lower than other cases. The total and average PD charge produced by the oils is shown in Fig. 8.

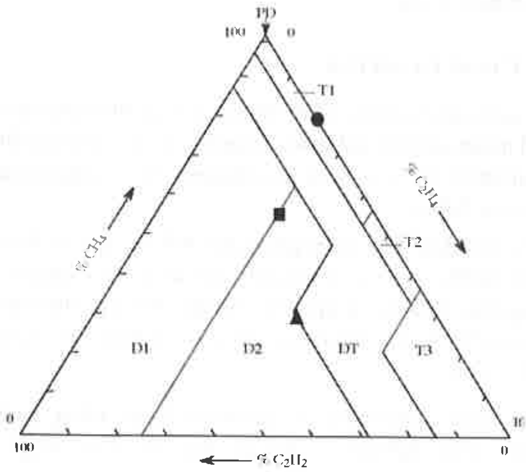


Fig. 7. Fault interpretation of PFAE samples using Duval Triangle 3 (DT3) method. ● : 5000 N; ■ : 8000 N; ▲ : 12000 N.

4.2 CO/CH4 RATIO

DT3 method cannot be used for low thermal faults because under these faults the PFAE samples produce only methane and carbon monoxide. However, an alternative gas ratio is sometimes used to expect the heating temperatures. For instance, the ratio of C_2H_6/CH_4 was used in [13] to estimate the overheating temperature within the range of 100 to 200 °C. Based on our experimental result (Fig. 9), in spite of some deviations, it seems that the ratio of CO/CH_4 could possibly be used to estimate the temperature within the range of 200 to 300 °C. For instance, the ratio less than 10, indicates the temperatures of greater than 300 °C.

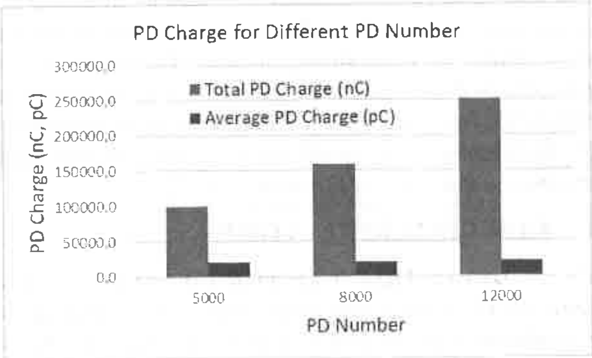


Fig. 8. The total and the average PD charge produced by discharge in PFAE samples stressed with different number of PD.

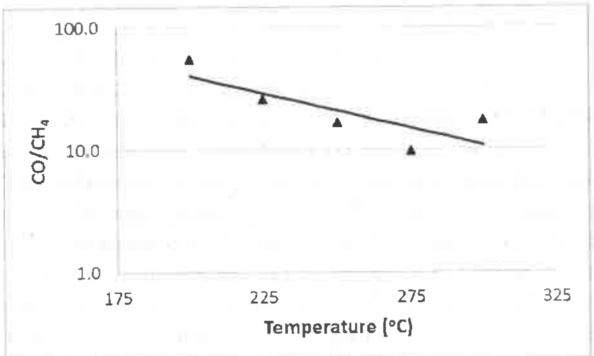


Fig. 9. The variation of CO/CH_4 ratio of PFAE oil against temperature change.

5. CONCLUSIONS

The early deterioration of PFAE oil include PD behavior under dry and moist samples and gases generated by the oil under PD and low thermal faults have been investigated. Some conclusions can be drawn as follows:

1. The addition of moisture intensifies PD activities in PFAE oil. PD number increase drastically and took place mainly at the negative polarity of applied voltage. Positive PD still took place, but with a significant decrease in both PD charge and PD number.
2. The main combustible gas produced by the PFAE under PD fault was methane, whereas that by low temperature overheating fault was carbon monoxide.
3. Hydrogen and ethane, which are considered as the main gases for triglyceride type natural ester under PD and low thermal faults, respectively, are not observed in PFAE oil.
4. DT3 method overestimates PD fault with 8000 and 12000 PD numbers by put them into the discharge of high energy (D2) area. For sample stressed with 5000 PD number, DT3 mistakenly interprets it as a low thermal fault (T1).
5. DT3 cannot be used to interpret low temperature overheating faults. Instead, the ratio of CO/CH_4 is proposed.

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