Experimental Investigation on Palm-Based Oil as Alternative for Biodegradable Power Transformer Oil Application in Malaysia

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***Abstract*—Most power transformers used petroleum-based oil or so-called mineral oil as insulation. Power transformer oil functions not only as electrical insulation and cooling medium but also to suppress corona and arcing. Over the years, power transformer oil has been widely used because of its high dielectric field strength, low dielectric losses, and long-term performance. However, petroleum-based power transformer oil is non-biodegradable and non-renewable. A serious spill could contaminate soil and water. As a non-renewable source, depletion of the source will further increase the price. These have encouraged researchers to look for alternative power transformer oil for better sustainability. Palm-based oil has been seen as a potential substitute, because, it is environmentally friendly, biodegradable and renewable. However, a lot of studies need to be carried out before it can be used as alternative power transformer oil commercially. Thus, this work has been carried out to investigate several electrical and physical properties of palm-based transformer oil, such as breakdown voltage, partial discharge characteristics, kinetic viscosity, and flash point. The effect of ageing on electrical properties of the palm-based oil has also been investigated. Two types of palm-based oil, namely Palm Fatty Acid Ester (PFAE) and Refined, Bleached, Deodorized Palm Oil (RBDPO) have been selected in this work. As a comparison, the commercially available soy-based biodegradable oil is also investigated for assessment and further analysis purpose. The results revealed that PFAE and RBDPO have great potential as power transformer insulation because of their good insulating characteristics as commercially available biodegradable oil.**

***Index Terms*—Biodegradable Oils; Breakdown Voltage; Palm-Based Oil; Power Transformer.**

I. Introduction

Power transformer is one of the main apparatus in electrical power system. The electrical power is transmitted through the transmission line in high voltage system to reduce power loss. Power transformer is used to step up voltage from generation to transmission and stepping down voltage from transmission to consumers. In addition, the transformer is also used in substations for metering and protection purposes [1].

In high voltage apparatus, insulation is one of the most important parts. The insulator is intended to support or separate electrical conductors without passing current through them. In the case of power transformers, most insulation used is a liquid-type insulation, which is known as power transformer oil. Power transformer oil functions not only as an insulator but also act as a coolant. Commercial power transformer oil that has been used for many years is petroleum-based oil, the so-called mineral oil. This oil has excellent insulating properties. The main indicators for the petroleum-based oil performance are its electrical and physical properties. These properties include breakdown voltage, dissipation factor, partial discharge characteristics, kinetic viscosity, flash point, pour point, etc. These properties boost its performance and make it the right choice for power transformer oil.

Power distribution transformers owned by Malaysia's power utility company, namely *Tenaga Nasional Berhad* (TNB) are oil insulated-type and they are petroleum-based oil. Although TNB has concerns towards green technology but currently their focus is only on generation improvement towards renewable energy consumption. However, in future TNB might have the need to change to environmentally friendly power transformer oil [3].

Power transformer oil widely used is highly refined mineral oil that is stable at high temperatures and has excellent electrical insulating properties. It was first introduced in 1892 by General Electric as a dielectric coolant. The main reason for using mineral oil was due to its high flash point characteristic and the widespread production around the world [4]. It provides two main purposes in power transformer operation. It is used as an insulator and cooling medium. There are several requirements for the transformer insulating oil to act as a coolant. The main tasks are absorbing the heat from the core and winding, and then transfer the heat to the outer surface of the transformer. At higher temperature, the viscosity of the oil decreases, thus facilitating the circulation of the oil. In addition, it's also used to insulate different parts at different electrical potentials. So that oil could penetrate into and fill the spaces between coiled insulation layers.

Petroleum-based oil is hazardous to environment especially when there are incidents during operational time, such as transformer explosion, which may cause serious spill of oil into the soil or water body. In order to reduce the effect of the environmental pollution and other related issues, researchers start to look for alternative insulating oil [4-15].

The main objective of this work is to investigate the electrical and physical properties of palm-based oil, as insulating material under high voltage stress for power transformer oil application. Two types of palm-based oil samples were used in this paper, namely refined, bleached, deodorized palm oil (RBDPO) and palm fatty acid ester (PFAE). Other soy-based biodegradable oil, the so-called FR3 was used in this work for comparison. The experimental results were analyzed and compared with standard mineral oil characteristics.

II. EXPERIMENT

Preparation of the test cell follows by the IEC 60156 standard. The cleanliness of the test cell is very important when measuring dielectric properties. Because of the extreme susceptibility of insulating liquids, that influence contamination. Therefore, the test cell must be cleaned every time before use and it is strongly recommended that test cells in continuous use for routine measurements are regularly cleaned [16]. Figure 1 shows the picture of test cell used in this research work.

When cells are to be repeatedly used for testing fluids with similar chemical type and having similar electrical properties, they may be stored fully filled with a clean sample of the fluid. The test cell should simply be flush with a volume of the next sample at least three fillings of the cell.

Figure 1: Test cell for breakdown voltage test of biodegradable oil sample.

A. *Preparation of Test Sample*

After taking sample oil from the container, the test sample was filtered to remove any impurities or contaminations as shown in Figure 2. The sample was first stirred for 10 minutes using magnetic stirrer with the setting of temperature, 50˚C in order to vaporize water content and remove air bubbles in the sample as shown in Figure 3.

The test cell and electrodes were cleaned and dried before the test sample is filled in. According to the IEC 60156 standard, the gap between electrodes should be set to 2.5 mm ± 0.05 mm. Also, and the test samples were filled with about 500 ml, leaving only 3% of the test cell empty as shown in Figure 4 [16].

Figure 2: Filtering process in test preparation of the oil sample.

Figure 3: Stirring process in test preparation of the oil sample.

Figure 4: Test cell filled with oil sample.

B. *Electrical Ageing Process*

In the electrical ageing process, applied voltage will be uniformly increased from zero at the rate of 2kV/s until 10 kV_{rms}. The voltage of 10 kV_{rms} will be applied for three several ageing time, which is 1, 3 and 5 hours, respectively. For each aging process, a new oil sample will be used. Figure 5 shows the experimental setup for the electrical ageing process.

III. RESULT AND DISCUSSION

In this section the results obtained will be presented and analyzed. The first results are comparison of physical properties (viscosity and flash point) of palm-based oil samples, namely RBDPO and PFAE. Together with the soy-based biodegradable oil namely, FR3, which is already commercially used as power transformer oil. The second results are the comparison of electrical properties (breakdown voltage, dissipation factor, and partial discharge) of PFAE, RBDPO, and FR3. The third results are the effect of electrical ageing on the electrical properties on the biodegradable oil samples.

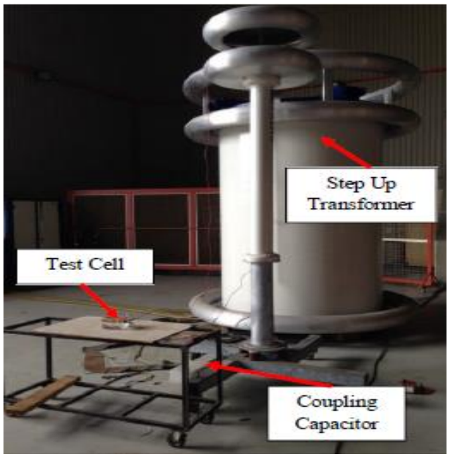


Figure 5: Experimental setup for electrical ageing test.

A. Kinetic Viscosity

Figure 6 shows kinetic viscosity result of the biodegradable oil samples at 40ºC. It can be seen clearly that PFAE has the lowest kinetic viscosity compared to RBDPO and FR3, namely 11,69 cSt. It confirmed that kinetic viscosity of PFAE meet the IEC 60156 standard (less than 12 cSt). Low kinetic viscosity enables the oil to transfer the heat evolved due to voltage stress.

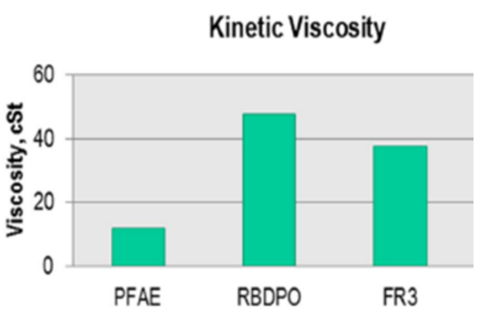


Figure 6: Kinetic viscosity results for the oil samples.

B. Flash Point

Figure 7 shows flash point result for the oil samples. It can be observed from the figure that RBDPO and FR3 have a very high flash point (above 300ºC), and even double the requirement of the standard. The PFAE also shows a quite high flash point (184ºC) and still meet the IEC standard (above 130ºC). According to American Society for Testing and Materials (ASTM) standard, the flash point for power transformer oil should be above 145ºC. With high flash point value, the transformer oil temperature becomes stable against heat effect under voltage stress.

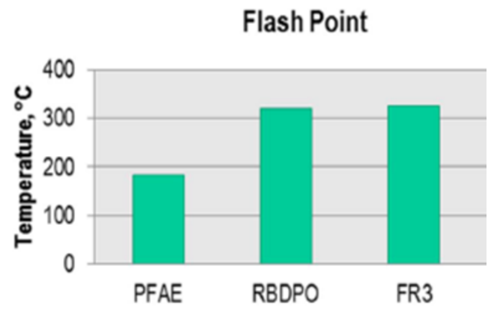


Figure 7: Flash point result for the oil samples.

C. Breakdown Voltage

Figure 8 shows the result of breakdown voltage (BDV) test for the biodegradable oil samples. It was found that the PFAE sample has the highest BDV value, which is 49.45 kV. While the RBDPO and FR3 samples recorded the values of 38.63 kV and 35.54 kV, respectively. All oil samples meet the standard for BDV value as power transformer oil application (above 30 kV). High BDV give the oil ability to prevent electrical breakdown due to overload.

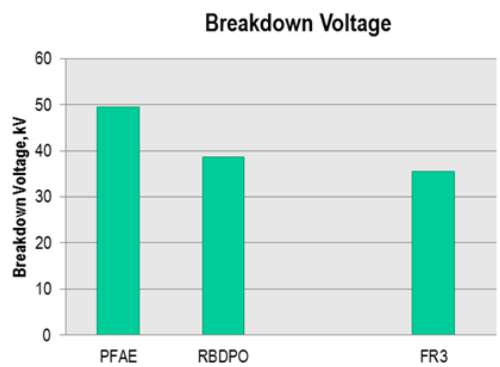


Figure 8: Breakdown voltage test result for oil samples.

D. Dissipation Factor (tan δ)

Figure 9 shows the experiment results for dissipation factor (tan δ) of the oil samples. The tan δ for RBDPO sample has the highest value, which is 0.0048 and meet the standard requirement (below 0.0005), whereas PFAE and FR3 are 0.0136 and 0.0094, respectively.

Figure 9: Dissipation factor result for the oil samples

E. Partial Discharge

Figure 10 shows the average partial discharge (PD) charges performance of all oil samples for 5, 10, 15, and 20 kV of voltage application. Referring to Figure 10, it can be seen that PD increases as voltage increased. FR3 and RBDPO have lower PD charge compared to the PFAE. Figure 11 shows the NQP analysis result for all oil samples. Furthermore, NQP analysis was conducted to get the relationship between PD occurrence (PD number; N), PD magnitude/PD charge; (Q) and also phase angle (P) of PD occurrence at AC waveform. This figure confirmed of average PD charge results as shown in figure 10. It is clearly observed that FR3 and RBDPO samples have lower PD charge (below 20pC and 10pC) as compared to the PFAE.

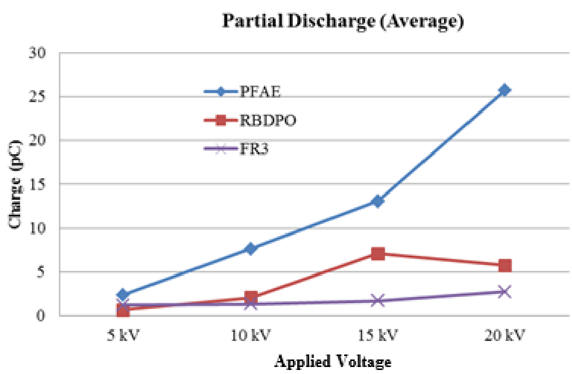
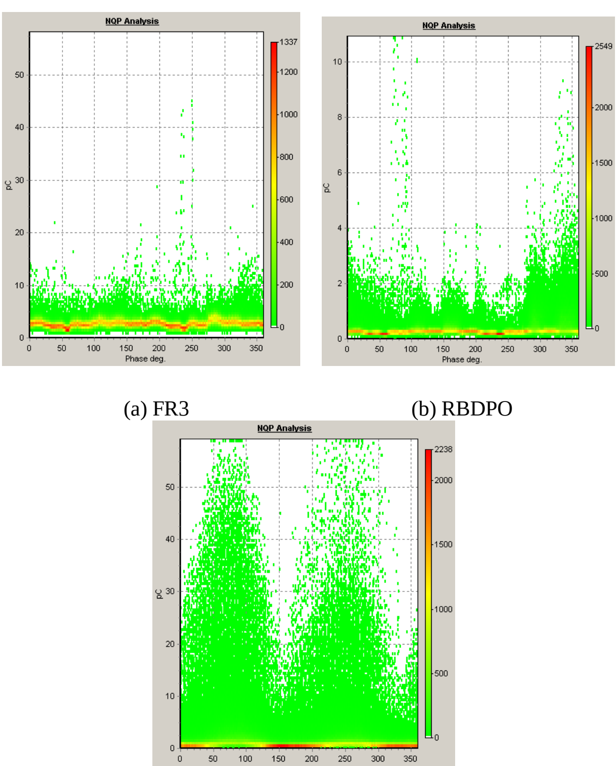


Figure 10: Average partial discharge results.



(a) FR3 (b) RBDPO

(c) PFAE

Figure 11: NQP analysis result for oil samples at 10 kVrms of applied voltage.

F. Breakdown Voltage after Ageing Test

The results on the effect of electrical ageing on breakdown voltage (BDV) for the biodegradable oil samples are shown in Figure 12. The BDV results shown in the figure are the average value of three BDV repeated on the same oil samples and ageing hours. Applied voltage for ageing process is 10 kV_{rms} in 5 hours of ageing time. The BDV of the oil samples slightly fluctuated during the ageing time. It seemed the BDV was not much affected by ageing process. The breakdown voltages of all test samples are relatively stable and did not experience much change.

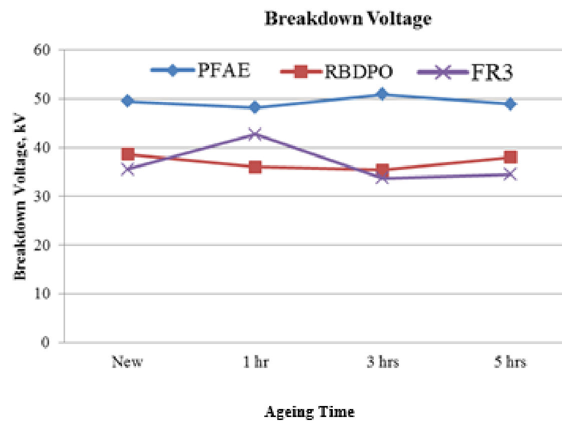


Figure 12: Breakdown voltage result for oil samples after ageing test.

F. Dissipation Factor (tan δ) after Ageing Test

Figure 13 shows the effect of electrical ageing on dissipation factor, (tan δ) of the biodegradable oil samples. Tan δ results shown in the figure are the average value of three repeated tan δ values on the same oil samples and ageing time. Applied voltage for ageing process was 10 kV_{rms}. It is found that the dissipation factor, (tan δ) has been significantly affected by aging process. Tan δ results of oil samples increase as ageing time increased. The PFAE and FR3 show a similar increment trend as compared to the RBDPO sample which has low tan δ results during the ageing time.

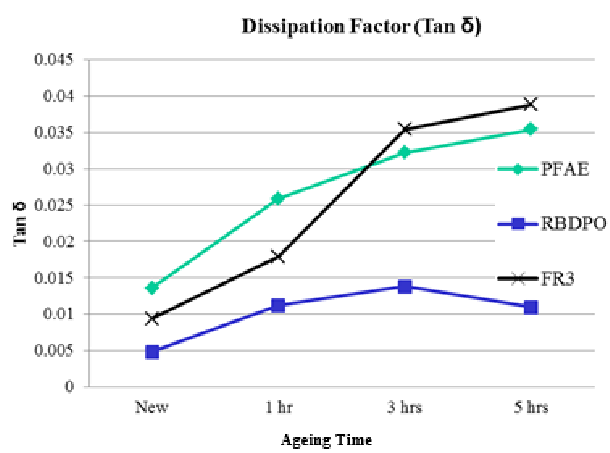


Figure 13: Dissipation factor result for the oil samples after ageing test.

This indicates that energy loss or leakage current in PFAE and RBDPO samples are slightly high due to the ageing process as a consequence of lower resistivity or insulating capabilities compared to the FR3 sample.

In our investigation, it is found that palm-based oil samples show good results for the physical properties of kinetic viscosity (PFAE) and flash point. For the electrical properties, palm-based oil gave positive results on breakdown voltage before and after ageing. Similar results were observed for dissipation factor before ageing and partial discharge characteristics as well. However, palm-based oil sample need some improvement for dissipation factor after ageing test. Several important properties that are required for the palm-based oil in order to be used as an alternative to mineral oil in power transformer are summarized in Table 1.

Table 1
Standard properties of mineral oil for power transformer oil application [2]

Properties		Method	Value
Kinematic Viscosity, cSt	10˚C	ISO 3104	9.24
	40˚C		2.36 – 3.0
Flash Point, ˚C		ISO 2719	>145
Pour Point, ˚C		ISO 3016	-50
Density, kg/dm^3, 20˚C		ISO 3675	0.875 – 0.88
Water Content, ppm		ISO 60814	<20
Breakdown Voltage, kV		ISO 60156	>30
Dissipation Factor		ISO 60247	0.0005

IV. Conclusion

The experimental investigation on palm-based oil samples have been performed successfully in this research work. The palm-based oil samples of the PFAE and RBDPO show good insulating characteristics except for viscosity of the RBDPO sample. There are several characteristics of the palm-based oils that indicate good electrical properties like breakdown voltage and dissipation factor. Therefore, it can be concluded that palm-based oils have good potentials to be established as alternative power transformer oil. Further improvement on the viscosity, dissipation factor and other characteristics like long-term ageing test are necessary to be conducted in order to improve the practical utilization of the palm-based oil samples.

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