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AC Breakdown Voltage and Viscosity of Palm Fatty Acid Ester (PFAE) Oil-based Nanofluids

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Abstract - Mineral oils are commonly used as transformer insulation oils but these oils are obtained from non-renewable and non-sustainable sources, which is highly undesirable. For this reason, natural ester oils are now being used in replacement of mineral oils because of their good biodegradability, high cooling stability, good oxidation stability and excellent insulation performance. Nanotechnology has gained prominence in both academic and industrial fields over the years and it has been shown in previous studies that nanoscale materials are useful for transformers due to their favourable dielectric properties. The objective of this study is to compare the AC breakdown voltage and viscosity of natural ester oil with three types of nanofluids. The natural ester oil-based nanofluids are prepared by mixing palm fatty acid ester (PFAE) oil with three types of nanoparticles at a concentration of 0.01 g/l: (1) Fe_3O_4 conductive nanoparticles, (2) TiO_2 semi-conductive nanoparticles and (3) Al_2O_3 insulating nanoparticles. The AC breakdown voltage of the oil samples is analysed using Weibull statistical analysis and the results reveal that the PFAE oil-based Fe_3O_4 nanofluid gives exceptional dielectric performance compared to other oil samples, whereby the AC breakdown voltage increases by 43%. It can be concluded that the PFAE oil-based Fe_3O_4 nanofluid is a promising dielectric liquid to substitute mineral oils.

Keywords: Transformer oil, Palm fatty acid ester, Nanofluids, Weibull statistical analysis

1. Introduction

Nowadays, there is a great demand for the heavy electrical industry to 'go green' due to growing concerns over environmental issues such as global warming, acid rain and pollution [1]. The use of natural ester oils as dielectric liquids in transformers has gained importance in electrical engineering since the 1990s. Natural ester oils offer several advantages over conventional petroleum-derived mineral oils since they are non-toxic and biodegradable. In short, they are environmentally friendly [2-4]. In addition, natural ester oils have excellent insulating performance, high cooling stability and good oxidation stability [5, 6]. Insulation oils provide dielectric protection for high voltage cables, capacitors, transformers and circuit breakers and therefore, insulation oils should possess good dielectric properties. Mineral oils are typically used for this purpose because they are excellent dielectric and cooling media. Moreover, these oils are inexpensive and commercially available in the market. However, mineral oils are derived from petroleum (which is a non-renewable and non-sustainable source) and therefore, there is a need to formulate alternative insulation oils from renewable, sustainable sources. Natural ester oils have been shown to be promising alternatives for mineral oils [7-9].

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Palm fatty acid ester (PFAE) oil is one of the more common natural ester insulation oils. PFAE oil was originally developed by Lion Corporation in 2006 for use as transformer insulation oils. PFAE oil is attractive since it is not only environmentally friendly but it also has excellent dielectric properties, making it ideal as transformer insulation oil [1]. According to Kojima et al. [5], PFAE oil has lower kinematic viscosity, higher flash point and high electric permittivity compared to mineral oils. In 2013, Murad et al. [8] investigated the effect of moisture absorption level on the AC breakdown voltage of insulation oils and the results showed that PFAE oil has higher AC breakdown voltage than that for mineral oil. For this reason, PFAE oil has great potential for use as dielectric liquid in heavy-duty electrical equipment.

In recent years, a number of studies [10-15] have been carried out to improve the dielectric properties of transformer insulation oils by mixing the base oil (host fluid) with nanoparticles. It has been shown that nanoscale materials offer a number of benefits for various applications including transformers. According to Yuzhen et al. [16], there are two techniques used to produce transformer oil-based nanofluids: (1) one-step method and (2) two-step method [16-18]. According to Jin [18], the one-step method reduces agglomeration while disperses the nanoparticles in the base fluid simultaneously. This method has been reported as a more effective method compared to the two-step method to prepare a long-term stable nanofluid [19], based on the size of nanoparticle found in the mixture. However, it is not commonly used in the research of transformer oil-based nanofluids as it is less economic and due to the commercially available of nanopowders. The two-step method, on the other hand, involves preparing the nanofiller by means of chemical synthesis, followed by dispersing the nanofiller into the dispersion medium using ultrasonicator or homogenizer. It shall be noted here that nanofluids are not merely liquid-solid mixtures since the nanoparticles tend to agglomerate during chemical synthesis. In general, nanofluids should fulfil the following criteria: (1) the suspensions should be homogeneous, stable and durable, (2) there should be minimum agglomeration of the nanoparticles in the base fluid and (3) there should be no chemical changes in the fluid when the nanoparticles are dispersed into the base fluid [17].

The objective of this study is to determine and compare the AC breakdown voltage and viscosity of PFAE oil with PFAE oils mixed with three types of nanoparticles, whilst mineral oil is used as a benchmark. To note, the similar nanoparticles were also used in research by Sima et. al. [20] in mineral oil. The PFAE oil-based nanofluids are prepared by dispersing the filler material into the PFAE oil using homogenizer treatment. Weibull statistical analysis is then used to analyse and interpret the data obtained from AC breakdown voltage tests and viscosity tests. It is believed that the findings of this study will provide insight on the potential use of PFAE oil-based nanofluids as dielectric liquids for transformers.

2. Experiment Setup

2.1 Test material

Palm fatty acid ester (PFAE) oil was chosen as the test material in this study. Three types of nanoparticles were used, namely: (1) conductive Fe_3O_4 nanoparticles, (2) semi-conductive TiO_2 nanoparticles and (3) insulating Al_2O_3 nanoparticles. The nanoparticles, having size range of 15-20 nm, were purchased from US Research Nanomaterial. The physicochemical properties of the nanoparticles are listed in Table 1. Oleic acid was used as the surfactant and 0.50 ml oleic acid was added into each

Table 1. Physical and chemical properties of nanoparticles

Nanoparticles	Fe_3O_4	TiO_2	Al_2O_3
Form	Powder	Powder	Powder
Colour	Black	White	White
Odor	Odorless	Odorless	Odorless
Melting Point (°C)	1538	1830 - 1850	-
Density at 20 °C (g/cm^3)	4.8-5.1	3.9	3.5-3.9
Material type	Conductive	Semi-conductive	Insulating

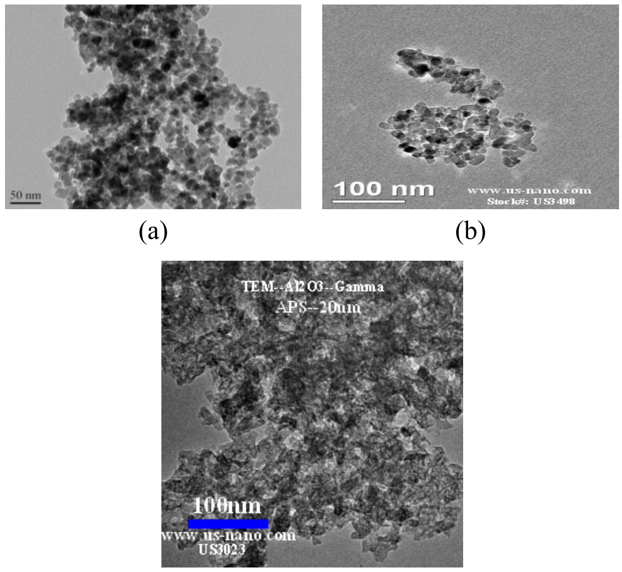

Fig. 1. TEM image of (a) Fe_3O_4 (b) TiO_2 and (c) Al_2O_3 [25]

oil sample prior to the addition of nanoparticles in order to modify the stability of the mixture [21]. To note, iron oxide nanoparticles surface-functionalized using an oleic acid surfactant showed good long-term dispersion stability in transformer oil at room temperature over a period of 24 months [22]. The mineral oil (Brand: Libra) was chosen as a baseline in this experiment.

Hwang [23] reports that, Fe_3O_4 has a value of conductivity from $1x10^{-4}$ - $1x10^{5}$, while the value of Al_2O_3 is $1x10^{-12}$. For TiO_2, Du et. al. [24] reported that, the value of its conductivity is $1x10^{-11}$. Based on the conductivity values of different types of nanoparticles, it can be seen that the values of Al_2O_3 and TiO_2 are very close and this reflects the results in this paper. The dry nanopowders can be examined by using transmission electron microscopy (TEM). Based on the datasheet [25] from US Research Nanomaterial, Fig. 1 (a), (b) and (c) shows the TEM image of Fe_3O_4, TiO_2 and Al_2O_3 nanoparticles, respectively.

2.2 Nanofluids preparation

The PFAE oil-based nanofluids were prepared in a well-ventilated work area and the materials were handled in accordance with the material safety data sheets. Safety gloves and chemical splash goggles were used to prevent contact with skin and eyes during sample preparation. The samples were prepared using the following procedure: (1) sample weighing, (2) homogenizer treatment and (3) vacuum process.

The nanoparticle concentration was the same for all samples (*i.e.* 0.01 g/l), measured by weight [20]. Four nanofluid samples were prepared for each type of nanoparticles. Homogenizer treatment was then carried out after the sample weighing process in order to disperse the nanoparticles and prevent them from agglomerating [17, 18, 20]. Fig. 2 shows the homogenizer equipment (Labsonic Brand) that used to disperse the nanoparticles in the PFAE oil samples. The settings used for the homogenizer treatment are as follows: 50% pulse-mode operation (cycle) and homogenizer power (amplitude), as shown in Fig. 3. A homogenizer probe (diameter: 40 mm, length: 100 mm) was used to disperse the nanoparticles in the oil samples.

The vacuum process was carried out after homogenizer treatment, whereby the samples were placed in a vacuum oven to remove residual moisture and gases after the homogenizer treatment. The samples were left in the vacuum oven for at least 72 hours at 70°C [20, 26].

2.3 Moisture content treatment

It is known that the presence of moisture has a significant effect on the AC breakdown voltage of insulation oils. According to [9], the maximum amount of moisture in a good-quality insulation oil should be less than 50 parts per million (ppm) at an atmospheric temperature less or equal to 30°C. Du et al. [27] discovered that there is enhancement in the AC breakdown voltage of the insulation oil-based nanofluid when the sample has a moisture content less than 100 ppm whereas the AC breakdown voltage decreases drastically when the sample has a moisture content of more than 100 ppm. According to the ASTM D6871 standard, the moisture content of insulation oils must be less than 200 ppm. In this study, moisture was removed from the samples by injecting nitrogen into the samples. The laboratory set-up used for moisture content treatment consists of a 500 ml conical flask, stopper and tube. Nitrogen was flowed into the samples for 15 minutes.

Fig. 2. Photograph of the homogenizer used to disperse the nanoparticles in the PFAE oil samples

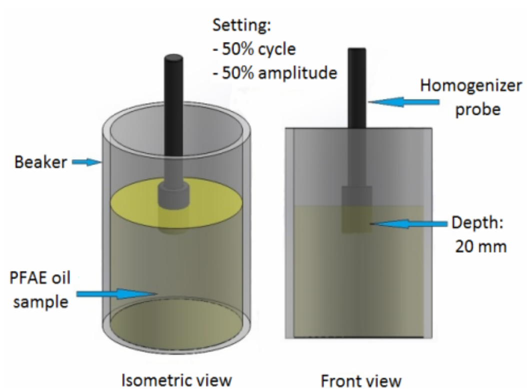

Fig. 3. Schematic diagram of the laboratory set-up used for homogenizer treatment

2.4 Water content

The presence of water in insulation oils has a negative effect on the electrical properties of these oils. In this study, the water content was measured during each stage of nanofluid preparation (*i.e.* pre-processing stage). Karl Fisher coulometer (Model: KFC 899) was used to measure the water content of each sample in (ppm). The water content of mineral oil, virgin PFAE oil and PFAE oil-based nanofluid containing Fe_3O_4, TiO_2 and Al_2O_3 nanoparticles at different stages of nanofluid preparation is summarized in Table 2. The water content of PFAE oil taken fresh from the tank is within a range of 58.1-66.8 ppm. However, the water content of the PFAE oil-based nanofluids increases significantly to within a range of 338.2-401.6 ppm after homogenizer treatment, which may be due to the fact that the oil samples are exposed to air throughout the process. The water content of mineral oil from the tank is within a range of 35.5 - 48.3 ppm. After nitrogen treatment, the water content drops until a range 7.4 - 9.9 ppm.

The vacuum process was carried out to remove residual moisture and gases from the samples. Indeed, Table 2 shows that the water content of the PFAE oil-based nanofluids

Table 2. Water content of mineral oil, virgin PFAE oil, PFAE oil-based Fe_3O_4 nanofluid, PFAE oil-based TiO_2 nanofluid and PFAE oil-based Al_2O_3 nanofluid at different stages of nanofluid preparation

Types of sample	Test samples	After homogenizer treatment (ppm)	After vacuum process (ppm)	After nitrogen treatment (ppm)
Mineral Oil	S1	-	-	7.5
	S2	-	-	9.9
	S3	-	-	8.3
	S4	-	-	7.4
Virgin PFAE Oil	S1	-	-	13.9
	S2	-	-	12.6
	S3	-	-	18.0
	S4	-	-	10.5
PFAE based Fe_3O_4 Nanofluids	S1	401.6	319.3	10.6
	S2	382.4	318.4	8.6
	S3	357.3	329.2	10.2
	S4	400.1	343.4	24.9
PFAE based TiO_2 Nanofluids	S1	348.2	339.0	24.9
	S2	343.2	347.0	7.9
	S3	351.2	341.8	21.5
	S4	338.2	363.4	22.5
PFAE based Al_2O_3 Nanofluids	S1	340.7	356.6	9.5
	S2	345.2	359.6	13.0
	S3	378.4	366.9	14.4
	S4	363.0	361.3	25.9

falls within a range of 318.4-366.9 ppm after the vacuum process, which indicates that the vacuum process removes moisture from the samples by 6.22 to 9.46%. However, it was suggested in [27] heating oil at 70°C in vacuum condition may be inadequate to remove moisture from the insulation oils, particularly of the water content in the oil samples is relatively high. Hence, nitrogen treatment needs to be carried out to further remove the residual moisture from the oil samples [28]. It can be seen from Table 2 that the water content of the PFAE oil-based nanofluids is within a range of 7.9-25.9 ppm after nitrogen treatment, which is less than 50 ppm. This indicates that the oil samples are of good quality after nitrogen treatment. The water content of the oil samples is reduced for the following reasons [29]:

- Nitrogen prevents air, moisture and other contaminants from entering the vapour space which would otherwise degrade the product.
- Nitrogen eliminates both oxygen and water vapour from the container.

2.5 AC breakdown voltage test

In general, electrical equipment should be tested to ensure that all of its components (including insulation oil) are in good condition during operation. Insulation oils play a vital role in providing electrical insulation in transformers and therefore, they must be able to withstand electrical stresses. The quality of insulation oils is reflected by their resistivity, permittivity and AC breakdown voltage. AC breakdown voltage test is one of the common techniques used to assess the quality of insulation oils. In this study, AC breakdown voltage test was carried out using Megger OTS60PB portable oil tester which complies with the ASTM D1816 standard. In this study, spherical electrodes with a diameter of 36 mm were used and the gap distance between the electrodes was kept fixed at 1.0 mm. The volume of each oil sample was approximately 460 ml. The AC breakdown voltage test was carried out by increasing the voltage gradually at a rate of 0.5 kV/s until breakdown occurs. A total of 100 breakdown voltage data were recorded for statistical analysis. It is worthwhile noting that, sedimentation of nanoparticles may be observed after the nanofluids were left for about 2 weeks. Hence, the AC breakdown test is conducted within 1 week after the homogenizer treatment (this is within 4 days after the samples were taken out from the vacuum oven). This is also applicable in the viscosity test that will be discussed in the next section.

2.6 Viscosity test

Heat transfer is an important characteristic of dielectric liquids. Viscosity is one of the main factors that influence the heat transfer characteristics of insulation oils [9]. It refers to the resistance of a fluid to flow. In general, the temperature will increase in various parts of the transformer because of losses. These losses originate from the magnetic circuits and windings of the transformer [30]. Hence, insulation oils play an important role to dissipate heat in the transformer and reduce the temperature of the parts to allowable levels in order to ensure smooth operation of the transformer. The viscosity was measured using Brookfield viscometer (Brookfield Model DV-II+PRO Viscometer) fitted to a water bath.

2.7 Statistical-weibull analysis

Weibull statistical analysis (Weibull++10 software, Standard Edition, Demo License) was used to analyse the AC breakdown voltage data for all samples. The two-parameter Weibull plot was used for this analysis. The breakdown probabilities were determined using the following formula [31]:

$$F(x) = 1 - \exp\left[-\left(\frac{x}{\eta}\right)^{\beta}\right] \quad (2)$$

where $F(x)$ is the probability of the AC breakdown voltage, x is the AC breakdown voltage, β is the shape parameter and η is the scale parameter. The Weibull plot was plotted based on the estimation of the shape parameter, scale parameter and correlation coefficient. The correlation coefficient, ρ is a measure of how well the linear model fits the data between the median ranks. The correlation coefficient has a value between -1 to +1. In general, a correlation coefficient close to +1 indicates that there is a strong positive correlation between two variables. On the other hand, a correlation coefficient close to -1 indicates that there is a strong negative correlation between two variables. Plotting the Weibull probability plot is easy for those who are familiar with linear plots and basic algebra. The equation used to produce a linear plot is given by Equation (3), where y is the dependent variable, x is the independent variable, m is the slope and b is the intercept.

$$y = mx + b \quad (3)$$

Eq. (2) was manipulated in order to give the following equation:

$$y = \beta x - \beta \ln(\eta) \quad (4)$$

Eq. (4) is a linear equation, whereby β is the slope and $\beta\ln(\eta)$ is the intercept. The slope can be determined from the linear plot, which in turn, gives the value of the shape parameter, β. It shall be noted that the x-axis represents the AC breakdown voltage, which is arranged from the lowest to the highest value. The y-axis represents the median rank. The median rank is determined for each AC breakdown voltage value and is given by the following equation [30]:

$$MR = \frac{j - 0.3}{N + 0.4} \quad (5)$$

where j is the sequence of data from 1 to N and N is the number of data. For example, if the number of AC breakdown voltages recorded per experiment is 100 (which is the case in this study), then N = 100. Thus, the median rank needs to be determined 100 times, *i.e.* one median rank for each AC breakdown voltage where j = 1,…,100. The median rank is in the form of a ratio, with a value greater than 0 and less than 1.

The scale parameter, η, indicates the spread of the distribution and it can be used to stretch or squeeze the graph [30]. In this case, the probability of the AC breakdown voltage when $x=\eta=\beta$ is shown in Eq. (6).

$$F(x) = 1 - \exp\left[-\left(\frac{x}{\eta}\right)^{\beta}\right] = 1 - \exp(-1) = 0.632 = 63.2\% \quad (6)$$

In general, the shape parameter can be determined once the correlation coefficient and median rank are known. The scale parameter can be best estimated after plotting the graph.

2.8 Visualization of nanofluids

The colour of the oil samples changes once the PFAE oil is mixed with the nanoparticles during homogenizer treatment. The initial colour of the virgin PFAE oil is clear whereas the colour becomes light yellow, cloudy white and semi-translucent when the PFAE oil is mixed with Fe_3O_4, TiO_2 and Al_2O_3 nanoparticles, respectively.

3. Results and Discussion

3.1 AC breakdown voltage

The AC breakdown voltage values of the mineral oil, virgin PFAE oil, PFAE oil-based Fe_3O_4 nanofluid, PFAE oil-based TiO_2 nanofluid and PFAE oil-based Al_2O_3 nanofluid are indicated by the orange, blue, red, green and violet data markers correspondingly as shown in Fig. 4, 5, 6, 7 and 8, respectively. The shape parameter (β), scale parameter (η) and correlation coefficient (ρ) for the virgin PFAE oil and PFAE-based nanofluids based on the two-parameter Weibull plots (Figs. 4-8) are summarized in Table 3. It can be seen from Table 3 that the correlation coefficient (ρ) is 0.92, 0.99, 0.98, 0.98 and 0.97 for the mineral oil, virgin PFAE oil, PFAE oil-based Fe_3O_4 nanofluid, PFAE oil-based TiO_2 nanofluid and PFAE oil-based Al_2O_3 nanofluid, respectively. It is evident that there is a strong positive correlation between the Weibull probability and AC breakdown voltage for all samples, judging from the correlation coefficient values which are close to 1.

Based on the linear lines in Figs. 4-6, the shape parameter (β) for the mineral oil, virgin PFAE oil, PFAE oil-based Fe_3O_4 nanofluid, PFAE oil-based TiO_2 nanofluid and PFAE oil-based Al_2O_3 nanofluid is 6.07, 6.40, 4.00,

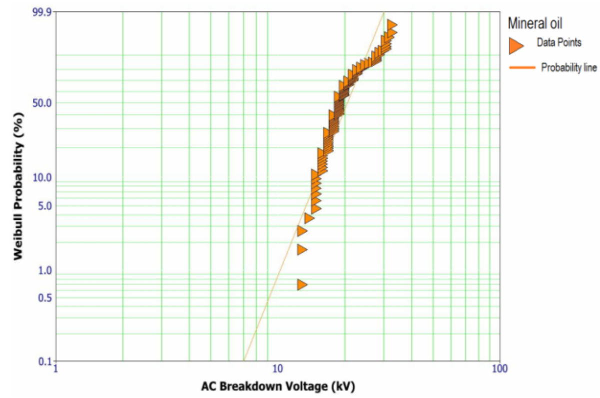

Fig. 4. Two-parameter Weibull plot of the AC breakdown voltage for mineral oil

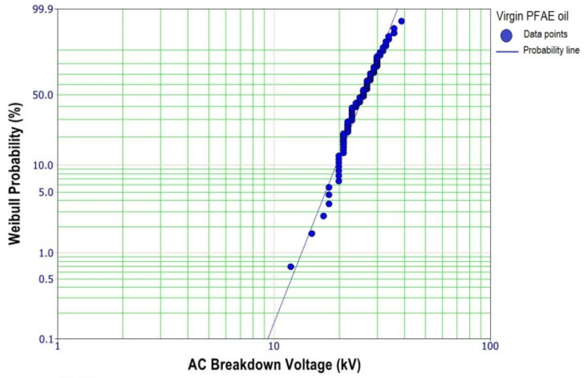

Fig. 5. Two-parameter Weibull plot of the AC breakdown voltage for virgin PFAE oil

Table 3. Shape parameter, scale parameter and correlation coefficient obtained from the two-parameter Weibull plots for mineral oil, virgin PFAE oil and PFAE oil-based nanofluids

Parameter	Samples				
	Mineral oil	Virgin PFAE oil	PFAE oil-based Fe_3O_4 nanofluid	PFAE oil- based TiO_2 nanofluid	PFAE oil- based Al_2O_3 nanofluid
β	6.07	6.40	4.00	5.38	4.84
η	21.85	27.50	39.92	35.67	36.87
ρ	0.92	0.99	0.98	0.98	0.97

Table 4. Weibull probability of the AC breakdown voltage for all oil samples based on the two-parameter Weibull plots

Weibull Probability (%)	AC breakdown voltage (kV)				
	Mineral oil	Virgin PFAE oil	PFAE oil-based Fe_3O_4 nanofluid	PFAE oil- based TiO_2 nanofluid	PFAE oil- based Al_2O_3 nanofluid
1	10.26	13.40	12.69	15.24	14.28
5	13.40	17.30	19.03	20.50	19.96
10	15.08	19.34	22.75	23.46	23.14
50	20.57	25.98	36.42	33.32	34.17
63.2	21.85	27.50	39.92	35.67	36.87

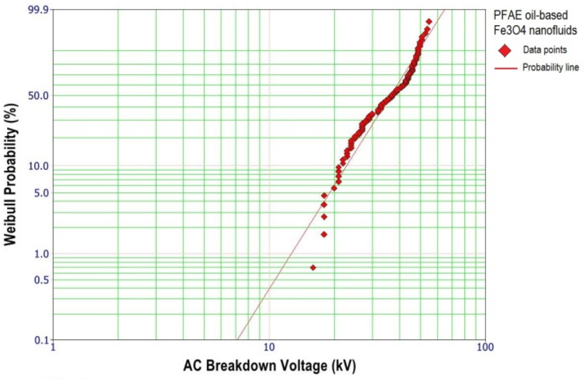

Fig. 6. Two-parameter Weibull plot of the AC breakdown voltage for PFAE oil-based Fe_3O_4 nanofluid

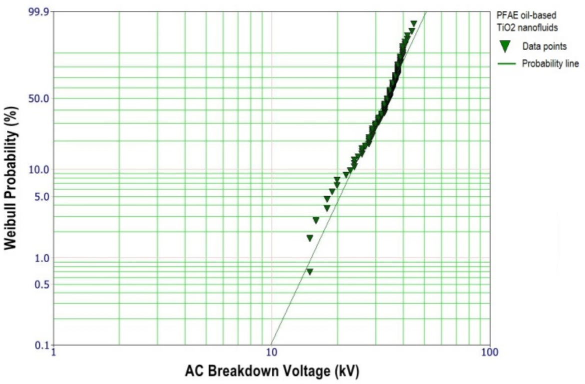

Fig. 7. Two-parameter Weibull plot of the AC breakdown voltage for the PFAE based TiO_2 nanofluids

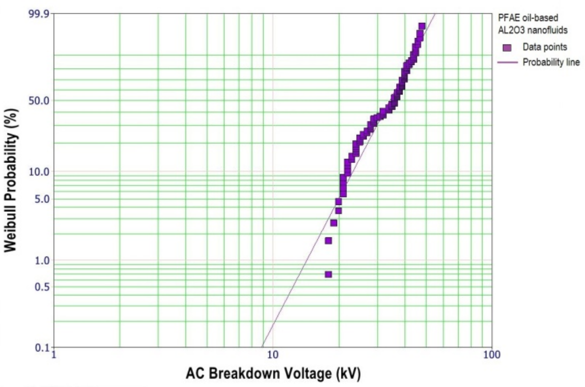

Fig. 8. Two-parameter Weibull plot of the AC breakdown voltage for the PFAE based Al_2O_3 nanofluids

5.38 and 4.84, respectively. The shape parameter indeed affects the shape of the Weibull plots. The population of $\beta<1$ exhibit a probability that decrease with the AC breakdown voltage, the population of $\beta = 1$ have a constant probability and the population of $\beta > 1$ have a probability that increase with the AC breakdown voltage. Table 4 shows the AC breakdown voltage for all oil samples based on the two-parameter Weibull probability plots.

Based on the Weibull probability of 63.2% (Table 4), the AC breakdown voltage is the lowest for the mineral oil, with a value of 21.85 kV. It can be seen that the PFAE oil is performed 20.5% higher than mineral oil. According to [32], natural ester insulation oil has a better performance in terms of AC breakdown voltage compared to mineral oil. In contrast, the AC breakdown voltage is the highest for the PFAE oil-based Fe_3O_4 nanofluid, with a value of 39.92 kV. Indeed, the addition of Fe_3O_4 nanoparticles increases the AC breakdown voltage of the PFAE oil by 45% at a Weibull probability of 63.2%, whereas the addition of TiO_2 and Al_2O_3 nanoparticles increases the AC breakdown voltage by 29 and 34%. It is worthwhile noting that the use of homogenizer equipment does not give critical effect on samples. The Weibull probability result from 100 data at 63.2% for virgin PFAE oil after treatment is 26.74kV, whilst the ones that did not go through homogenizer equipment for ultrasonic treatment is 27.50 kV (Table 4).

A simulation work in [23], based on the experimental results of Segal in [33], has suggested that conductive nanoparticles act as electron scavengers in the insulation oil when the oil is subjected to electrical stresses. The fast electrons are converted into slow negatively charged particles and the streamer process takes a longer time to breakdown under electrical stresses. Fig. 9 shows an illustration of the streamer process for the insulation oil with and without conductive nanoparticles. It can be seen that the streamer is in direct contact between the high voltage electrode and ground for the insulation oil without conductive nanoparticles and therefore, the streamer process takes a shorter time to breakdown.

The semi-conductive and insulating nanoparticles can also improve the AC breakdown voltage of insulation oils because both types of nanoparticles produce shallower traps in the oils [14]. The semi-conductive nanoparticles produce many shallow electron traps in the nanofluid. The electrons are captured by these shallow traps and these traps then release the electrons rapidly. The fast electrons convert into slower electrons by repeated trapping and de-trapping in the insulation oil when the electrons travel from higher to lower electric field. The high shallow traps contribute to the rapid charge dissipation and improve the breakdown performance of the insulation oil.

The addition of insulating nanoparticles into the PFAE oil produces more shallow traps, which is consistent with the results for semi-conductive nanoparticles [14]. These shallow traps are capable of capturing fast electrons created high electric fields and these traps then release the electrons rapidly. The fast electrons are converted into slower electrons by the hopping process in the shallow traps. This process decreases the speed of electrons and prevents the accumulation of space charge in the insulation oil, which in turn, enhances the oil's dielectric strength. In general, it can be deduced that the PFAE oil-based Fe_3O_4 nanofluid is the best prospect in terms of AC breakdown strength compared to the other two nanofluids.

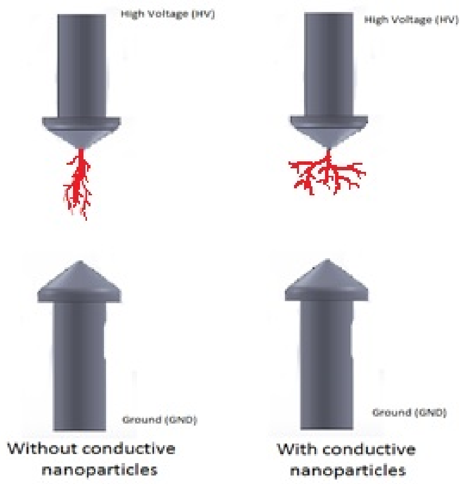

Fig. 9. Illustration of the streamer process of insulation oils with and without conductive nanoparticles

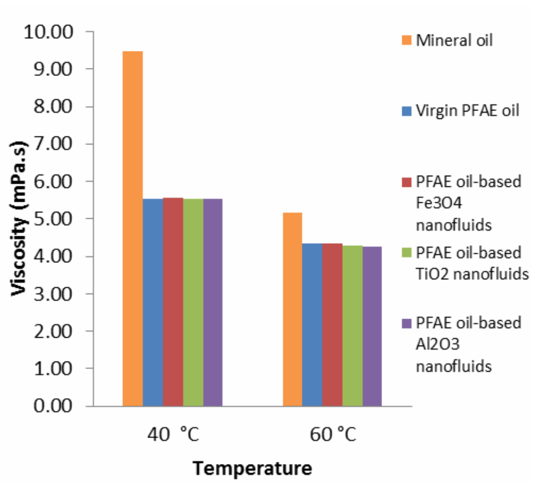

Fig. 10. Viscosity of mineral oil, virgin PFAE oil, PFAE oil- based Fe_3O_4 nanofluid PFAE oil-based TiO_2 nanofluid and PFAE oil-based Al_2O_3 nanofluid at 40 and 60°C

3.2 Viscosity

Viscosity is an important physical property of insulation oils since it affects the electrical properties and heat transfer characteristics of the oils [10]. The effect of different types of nanoparticles (*i.e.* conductive, semi-conductive and insulating nanoparticles) on the viscosity of PFAE oil is investigated in this study. The viscosity of the mineral oil, virgin PFAE oil and PFAE oil-based nanofluids is measured using Brookfield viscometer (Brookfield Model DV-II+PRO Viscometer) at a temperature 40 and 60°C and the results are shown in Fig. 8.

The orange, blue, red, green and purple bar represents the viscosity for the mineral oil, virgin PFAE oil, PFAE oil-based Fe_3O_4 nanofluid, PFAE oil-based TiO_2 nanofluid and PFAE oil-based Al_2O_3 nanofluid, respectively. The result shows that the viscosity of PFAE oil is better than mineral oil at both of temperature. The percentage difference in viscosity of the PFAE-based nanofluids containing Fe_3O_4, TiO_2 and Al_2O_3 nanoparticles relative to the virgin PFAE oil at 40°C is less than 0.5%. The percentage difference is lower at 60°C, whereby the values are less than 0.2%. This indicates that the addition of nanoparticles has an insignificant effect on the viscosity of the PFAE oil at 40 and 60°C. More importantly, it can be seen from Fig. 10 that the addition of nanoparticles into the PFAE oil results in lower viscosity at 60°C, which is highly desirable for insulation oils.

4. Conclusion

The effect of different types of nanoparticles (*i.e.* conductive, semi-conductive and insulating nanoparticles) on the AC breakdown voltage and viscosity of PFAE oil is investigated in this study. The conclusions of this study are listed as follows:

The PFAE oil-based nanofluids are prepared by dispersing three different types of nanoparticles into PFAE oil using homogenizer at a concentration of 0.01 g/l. The nanoparticles used in this study consist of: (1) Fe_3O_4 conductive nanoparticles, (2) TiO_2 semi-conductive nanoparticles and (3) Al_2O_3 insulating nanoparticles. Vacuum process followed by nitrogen treatment is carried out to ensure that the water content of the oil samples is less than 100 ppm.

The mineral oil, virgin PFAE oil and PFAE oil-based nanofluids are tested in order to determine the AC breakdown voltage of the oil samples. The results reveal that the PFAE oil-based Fe_3O_4 nanofluid gives the best dielectric performance compared to the other samples investigated in this study because of electron scavenger action.

The viscosity of the mineral oil, virgin PFAE oil and

PFAE oil-based nanofluids is determined using Brookfield viscometer. The percentage difference in viscosity of the PFAE oil-based nanofluids relative to virgin PFAE oil at 40 and 60°C is less than 0.5 and 0.2%, respectively. However, it is apparent that the viscosity of the PFAE oil-based nanofluids is lower at an operating temperature of 60°C.

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