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Study of Dielectric Properties of a Potential RBD Palm Oil and RBD Soybean Oil Mixture as Insulating Liquid in Transformer

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Abstract – This paper reported the experimental result of dielectric properties of Refined, Bleached and Deodorized Palm Oil (RBDPO) combined with 0-50% of Refined, Bleached and Deodorized Soybean Oil (RBDSO). The dielectric strength and relative permittivity of RBDPO/RBDSO was higher compared to mineral oil at all ranges of ratios and temperatures which indicated a positive sign for its possible use as insulating liquid in a transformer. All ratios of the RBDPO/RBDSO mixture also demonstrated lower dissipation factor compared to mineral oil at 40˚C, 70˚C and 90˚C. Apart from that, the kinematic viscosity for the oil mixtures shown exceeded the IEC 60296 as well as the mineral oil results. 70%RBDPO/30%RBDSO mixture ratio was chosen as the best mixing percentage after comparison was made with the mineral oil and IEC 60296 standard where the mixture accumulated the most satisfactory of dielectric properties hence making it as the potential candidate for palm and soybean-based transformer oil.

Keywords: RBDPO, Dielectric strength, Relative permittivity, Kinematic viscosity, Mineral oil

1. Introduction

A Transformer is one of the crucial equipments in electric power transmission and distribution system. In order to perform its function, electrical power transformers need an insulating liquid to function as a cooler and insulator. There are a few characteristics that an insulating medium is required to have in order to function effectively in transformers. These characteristics include long term stability due to possible problems brought about by oxidation, contamination and excessive temperature which can affect the reliability of the equipment and the suitability of the oil in rheological aspect. These characteristics implicate the dielectric properties of the insulating liquid which used inside the transformers.

Generally, petroleum-based mineral oil is used to permeate the high voltage transformer to function as an insulating liquid. However, due to the considerations of the environment, costs and its working life span, suitable replacements are being sought for this petroleum based oil [1]. Numerous researches [2-7] have been conducted and the findings indicated that environmentally friendly insulating oil such as vegetable oil (natural ester) was shown to be the best candidate for this replacement.

Moreover, in the last five years, numerous researches pertaining to the uses of natural ester as an insulating liquid in electrical power transformer had been extensively conducted either singly or in combination with mineral oil [8-17]. The selection is due to its compatible dielectric properties which best suit its function as an insulating liquid, fire safety advantageous and most importantly it is renewable and environmentally friendly product. In Europe, vegetable oil such as soybean oil, sunflower oil and rapeseed oil have already been utilized as the transformer oils [18]. Thus, it is implied that the used of vegetable oil as an insulating liquid has been well developed in outside range of Malaysia.

One biodegradable vegetable oil that is available in Malaysia is palm oil. There has been extensive research into the use of palm oil as alternative transformer oil [19-28]. The extensive research has shown that palm oil is a potential candidate for the replacement of petroleum based insulating oil. Refined, Bleached and Deodorized Palm Oil (RBDPO) has shown its potential as dielectric fluids [19-21]. Some of its dielectric properties are at par with the existing standard. Compared to mineral oil, palm oil has shown to have more elevated breakdown voltage (BDV), flash point and fire point. However, the kinematic viscosity of RBDPO does not comply with the IEC 60296 standard. Elimination of this weakness should be considered to make the use of palm oil as an insulating fluid in transformer more effective. One of the suggestions to improve the kinematic viscosity is by mixing palm oil with soybean oil. Nevertheless, the dielectric properties of the oil mixture have yet to be investigated. Therefore, the aims of this research are to investigate and to compare the dielectric properties of palm oil and soybean oil mixture with mineral oil of various ratios and temperatures. The compared dielectric properties of mineral oil were obtained from the past researches at various ratios and temperatures too. The

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mixing formulation of the oil mixture which has the most effective dielectric properties to be utilized as an insulating liquid in a transformer is then selected.

2. Experimental Test Setup

2.1 Samples preparation

Two vegetable oil products were used in the experiments and they were palm oil and soybean oil. The palm oil product was Refined Bleached and Deodorized Palm Oil (RBDPO) which was bought from the Wilmar Edibles Oil Sdn. Bhd. The soybean oil product was Refined, Bleached, and, Deodorized Soybean Oil (RBDSO) which was a commercial cooking oil known as Vesoya Cooking Oil and manufactured by Yee Lee Corporation Berhad. No treatment has been conducted on any of the oils. RBDPO does not performed any treatment due to the breakdown voltage of 100%RBDPO found in this experiment was higher compared to the past researches (19-21). The breakdown voltage of 100%RBDPO reported by Suwarno (19, 20) and U. U. Abdullahi (21) was approximately 53kV, 43kV and 75kV, respectively at 40°C. Whereas 100%RBDPO in this research gives high value of 84.23kV at the same temperature. Thus, it was considered that the oil has relatively low contamination and no further treatment need to be done. Meanwhile, the RBDSO used in the experiments was commercial cooking oil which is freshly poured out from the container and free from the contaminants. Therefore, no pretreatment was conducted on the RBDSO.

The samples used in the experiments were the mixture of RBDPO and RBDSO. The mixture ratio of RBDSO and RBDPO varies from 0 % to 50%. The mixing formulations are shown in Table 1. The RBDSO was limited to 50% due to the main focus in this research which is to utilize the palm oil as the insulating liquid in transformer.

Table 1. BDPO/RBDSO mixture

Samples symbol	RBDPO	RBDSO
S1	100%	0%
S2	90%	10%
S3	80%	20%
S4	70%	30%
S5	60%	40%
S6	50%	50%

2.2 Electrodes configuration and breakdown voltage measurement

Fig. 1 shows the electrodes configuration of Fully Automatic Portable Breakdown Voltage Test Set which was used to evaluate the breakdown voltage. The equipment was capable of supplying the voltage up to 100kV. The breakdown voltage test was implemented according to IEC 60156 [29]. The test cell had a volume capacity of 400ml,

Fig. 1. The electrode used for measuring BDV of oil mixture

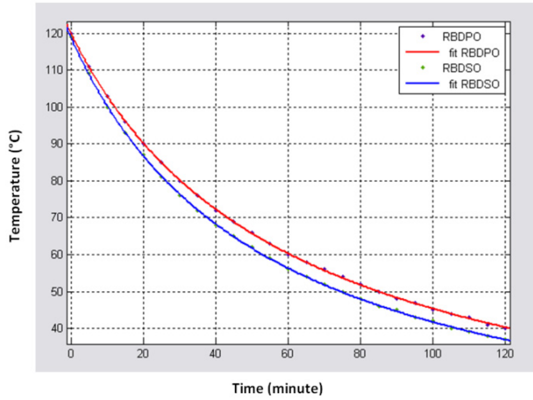


Fig. 2. Temperature drop of RBDPO and RBDSO

consisted of VDE electrodes of 12.5mm diameter with the gap of 2.5mm. The temperature of 40°C to 100°C was determined by using a stirring hot plate which can sustain the temperature up until 540°C. The stirring hot plate can also stir with the speed range between 60 to 1200 rpm.

Since the BDV test device operated automatically to measure six consecutive breakdown voltages nonstop, the temperature of the oil mixture could drop slightly in between the operation of BDV test after placing the test cell from the hot plate into the BDV test device. Thus, the temperature dropping of RBDPO and RBDSO at starting point of 120°C was recorded and plotted by using Matlab Software as shown in Fig. 2. From the plotted graph, an equation was obtained. Thus, by using the equation, the temperature dropping within a time range can be evaluated. The equation for temperature dropping for RBDPO and RBDSO is as follows:-

RBDPO: $f(x)=p1/(x+q1)$ where $p1=7232$ and $q1= 59.96$
RBDSO: $f(x)=p1/(x+q1)$ where $p1=6439$ and $q1= 54.25$

The drop in the temperature of the oil mixture from 0% to 50% ratio of RBDSO was evaluated by using the temperature dropping of RBDPO and RBDSO recorded.

As a result, the BDV test of the oil mixture was performed within the time range of the dropping temperature in between ±4°C. The test cell was filled with the oil mixtures with 0% to 50% of RBDSO content being directly heated until it reached the required temperature on the hot plate for 5 to 10 minutes. At the same time, it was stirred at 250 to 300 rpm to ensure that the temperature's equilibrium in the test cell. After the required temperature was reached, the test cell then was quickly inserted into the BDV device. The BDV device was automatically run by applying the voltage at the rise rate of $2kVs^{-1}$ until breakdown occurs. The breakdown voltage was recorded in the average of six measurements with 2 minutes pause between each consecutive breakdown. The experiment was conducted in the laboratory at 40˚C to 100˚C.

2.3 Dielectric strength calculation and simulation

The mean value of six breakdown voltage measurements obtained from the experiment were used in the calculation and simulation of dielectric strength. The simulation result was then compared with the calculation result. For further analysis, a simulation on the data of dielectric strength was conducted according to Weibull distribution. This statistical analysis was carried out by analyzing the dispersion of ten data of the dielectric strength. The function of the Weibull distribution was to identify the lowest withstands dielectric strength from the dispersion data of the dielectric strength. The result from the analysis of the Weibull distribution was then compared with the simulation and calculation of the dielectric strength.

Opera 2D and Minitab Software were used in the simulation process. For Opera 2D simulation, the spherical electrode configuration was modeled as shown in Fig. 3. Then, the simulation was performed and the result of electric field distribution was obtained as shown in Fig. 8.

Meanwhile the calculation was performed by using the approximate formula for quasi-uniform electric field near the symmetrical axis of the same radius of spherical electrode which is valid in narrow gap as follows [30]:

$$E \approx \frac{V}{d + 2R(1 - \cos\theta)} \tag{1}$$

where V is the applied AC voltage which is the breakdown

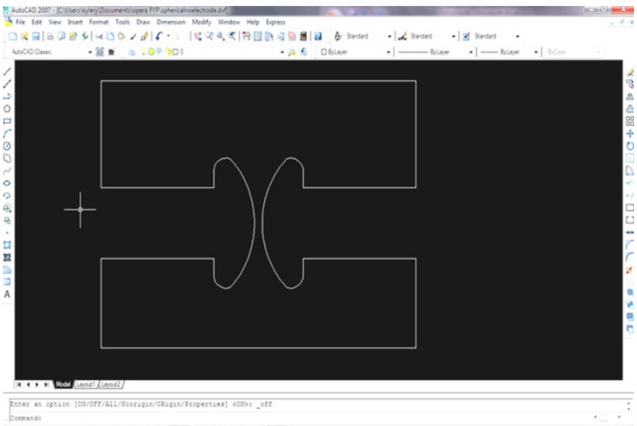


Fig. 3. Model of spherical electrode configuration

Fig. 4. AVOX ADTR-2k fully automatic Tan delta, dielectric constant and resistivity test set

voltage (in kV), d is the gap distance between the spherical electrodes (in mm) and R is the radius of the spherical electrodes (in mm). The polar angle, θ = 0˚ corresponds to the apex of the sphere; which means that only a small part of the spherical electrode surface area near the symmetrical axis contributed to the breakdown voltage.

2.4 Dissipation factor (Tan Delta) and Relative Permittivity (Dielectric Constant) measurement

Fig. 4 shows AVOX ADTR-2k fully automatic tan delta, dielectric constant and resistivity test set. It is equipped with oil test cell heater for controlling the temperature. The test was conducted according to the standard of IEC 60247 [31] at 40˚C, 70˚C and 90˚C. The oil sample was filled into a liquid test cell. Then, the dissipation factor was obtained automatically by subjecting the electrical stress to the oil in between 0.03kV/mm to 0.1kV/mm.

2.5 Kinematic viscosity measurement

Fig. 5 shows Petrolab TV4000 Constant Temperature Viscosity Bath using with RTE 111 temperature controller bath which was used to measure the kinematic viscosity. The kinematic viscosity was measured according to ISO 3104 [32]. The experiment was conducted at 40˚C in laboratory. The glass capillary viscometer was filled with approximately 10ml of oil sample. Two levels of viscometer

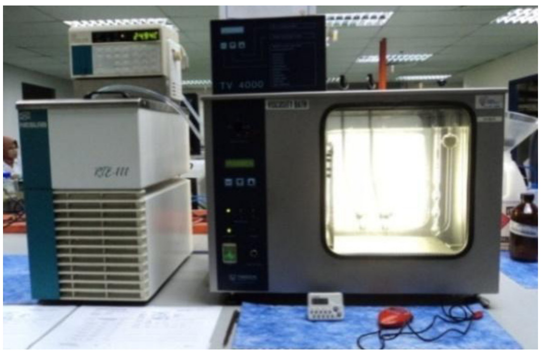


Fig. 5. Petrolab TV4000 constant temperature viscosity bath with RTE 111 temperature controller bath

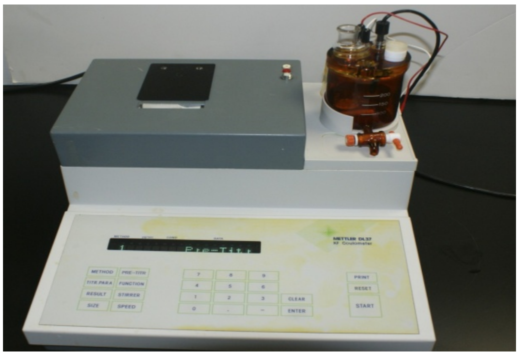


Fig. 6. Mettler toledo DL 37 karl fisher coulometer

were used to determine the kinematic viscosity. Time was taken for the oil to flow from the high level to low level of the capillary viscometer. The kinematic viscosity was determined by using the following formula:

$$V = C\,x\,t \tag{2}$$

where V is the kinematic viscosity (in mm^2/s), C is the viscometer constant (in mm^2/s^2) and t is the time taken for the oil to flow from high level to low level of the glass capillary viscometer (in s).

2.6 Water content measurement

Fig. 6 shows Mettler Toledo DL 37 Karl Fisher Coulometer which is used to measure the water content. The water content is measured according to IEC 60814 [33]. The experiment was conducted in the laboratory at room temperature. The sample used was 2ml and it was taken by using a syringe. The tip of the syringe's needle was then closed with silicone rubber block. The syringe was filled with 2ml of oil sample with silicone rubber block on the tip of needle which was weighed to obtain W1. After that, the syringe was injected into the titration cell through the rubber septum. After the injection process into titration cell was completed, the empty syringe with silicone rubber block on the tip of needle was weighed to obtain W2. After the titration process was completed, the value of W1 and W2 was keyed in into the instrument for determination of the mass of the oil mixture. The water content was determined using the following formula:

$$\text{Water content} = \frac{m}{M} \tag{3}$$

where m is the quantity of water titrated (in mg/kg) and M is the mass of sample obtained from value of W1 and W2 inserted into the measurement instrument (in mg/kg).

2.7 Chemical composition analysis

The oil samples were first converted into fatty acid methyl ester (FAME) by using based catalyzed methyl ester method. The FAME were then analyzed by using Perkin Elmer Clarus 600T Gas Chromatograph-Mass Spectrometers as shown in Fig. 7. The GC/MS consisted of 30m length column with 250µm diameter. The initial temperature of the oven was held for 2 minutes at 65˚C. Then, the temperature of the oven was gradually increased at the rate of 8˚C/min until it reached 300˚C. The temperature was held for 10 minutes at 300˚C. The chemical composition was separated by using helium gas which was utilized as a carrier gas. A 0.1µl volume of FAME was used in the analysis and the test was run for 40 minutes. Software Turbomass was used to integrate the chromatograms where the peak areas of different components were measured. The identification of the components was achieved by comparing them with National Institute of Standards and Technology (NIST) standard reference database.

Fig. 7. Perkin elmer clarus 600T gas chromatograph-mass spectrometers

3. Results & Discussion

3.1 Dielectric strength characteristics

The dielectric strength (electric field strength) is the maximum stress which the insulation can withstand before breakdown. It depends on the insulation material, impurities and the geometries of electrodes under the applied electric field. The quality of an insulating liquid is usually determined by the mean breakdown values. However, transformers are designed according to the minimum withstand dielectric strength, rather than the mean breakdown values. Thus, statistical analyses need to be used for estimation of the lower probability of the dielectric strength. In order to evaluate the dielectric strength, the value of breakdown voltage should be known. The breakdown voltage experiment of RBDPO/RBDSO mixture was conducted for further analysis of its dielectric strength.

In this analysis, the dielectric strength was obtained from the mean value breakdown voltage through calculation and simulation and it was compared with the estimated lowest dielectric strength from dispersion data of Weibull

Table 2. Breakdown voltage measurements of RBDPO/RBDSO mixture

Temperature (˚C)	Breakdown Voltage (kV)					
	RBDSO (%)					
	0	10	20	30	40	50
40	84.23	75.72	69.78	61.40	59.25	49.72
50	92.40	87.68	78.27	70.58	64.78	54.25
60	94.38	89.78	80.78	73.73	78.90	66.60
70	91.88	92.58	87.77	86.30	83.43	85.25
80	96.97	95.63	96.00	92.03	92.92	95.00
90	94.27	85.20	96.90	96.18	97.53	96.53
100	95.33	92.32	93.65	99.00	98.37	94.27

distribution. The purpose of comparing the result of calculation and simulation with the Weibull distribution was to establish whether the dielectric strength obtained through calculation and simulation was aligned with the lowest required dielectric strength obtained from the Weibull distribution.

Table 2 shows the results of breakdown voltage from 0% to 50% of RBDSO content in the RBDPO mixture at 40˚C to 100˚C. The breakdown voltage results listed in Table 2 were the mean value of six breakdown voltage measurements. The breakdown voltage was measured based on the RBDSO ratio and the temperature.

All the results of breakdown voltage from 0% to 50% of RBDSO were above 30kV, which fulfilled the IEC 60296 standard. The breakdown voltage of 100% RBDPO obtained in this experiment was relatively higher than that reported by Suwarno et al. [19] which was only around 53kV at 40˚C. Furthermore, the breakdown voltage of 100% RBDPO obtained in this experiment was also relatively higher than the conventional mineral oil which was only around 37kV at 40˚C [23]. The mixture of RBDSO with up to 50% ratio in RBDPO also gave a higher breakdown voltage compared to this mineral oil at 40˚C.

Based on Eq. 1 written previous, the dielectric strength of RBDPO/RBDSO mixture was calculated by using the mean value of breakdown voltage from Table 2. The calculation results of dielectric strength are tabulated in Table 3. For comparison, a simulation has been conducted

Table 3. Calculation of dielectric strength of RBDPO/RBDSO mixture

Temperature (˚C)	Dielectric Strength (kV/mm)					
	RBDSO (%)					
	0	10	20	30	40	50
40˚C	33.692	30.288	27.912	24.560	23.700	19.888
50˚C	36.960	35.072	31.308	28.232	25.912	21.700
60˚C	37.752	35.912	32.312	29.492	31.560	26.640
70˚C	36.752	37.032	35.108	34.520	33.372	34.100
80˚C	38.788	38.252	38.400	36.812	37.168	38.000
90˚C	37.708	34.080	38.760	38.472	39.012	38.612
100˚C	38.132	36.928	37.460	39.600	39.348	37.708

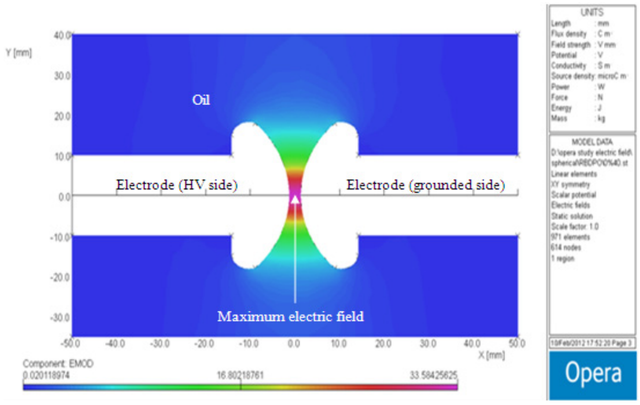


Fig. 8. Electric field distribution of quasi-uniform electrodes of RBDPO/RBDSO mixture

Table 4. Simulation of dielectric strength of RBDPO/RBDSO mixture

Temperature (˚C)	Dielectric Strength (kV/mm)					
	RBDSO (%)					
	0	10	20	30	40	50
40˚C	33.58	30.19	27.82	24.48	23.62	19.82
50˚C	36.84	34.96	31.21	28.14	25.82	21.62
60˚C	37.63	35.80	32.21	29.40	31.45	26.55
70˚C	36.63	36.91	35.00	34.41	33.26	33.98
80˚C	38.66	38.13	38.28	36.69	37.04	37.87
90˚C	37.59	33.97	38.64	38.34	38.88	38.48
100˚C	38.01	36.81	37.34	39.46	39.21	37.58

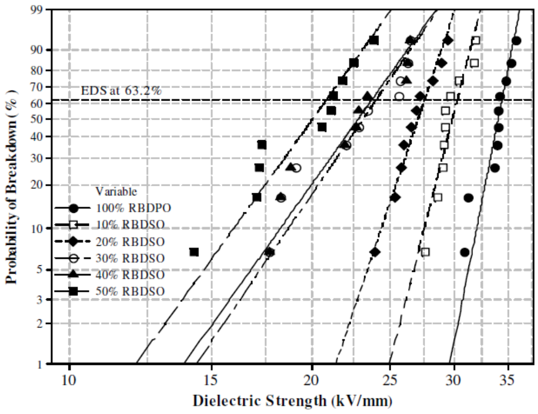
using Software Opera 2D to simulate the electric field distribution of RBDPO/RBDSO mixture. The simulation of electric field distribution is shown in Fig. 8. The maximum electric field is indicated by pink color between the gaps concentrated at the symmetrical axis of spherical electrode. The simulations results of dielectric strength are listed in Table 4.

A withstand dielectric strength is regarded not as the fixed value but rather as a statistical variable which corresponds to a low breakdown probability [34]. One of common statistical distributions used to analyze the failure in dielectric materials is Weibull distribution [35, 36]. In liquid dielectric, the breakdown field strength has shown to have a good agreement with the two parameters (scale and shape) of failure density in Weibull distribution. The equation which is expressed below is based on the weakest link theory:

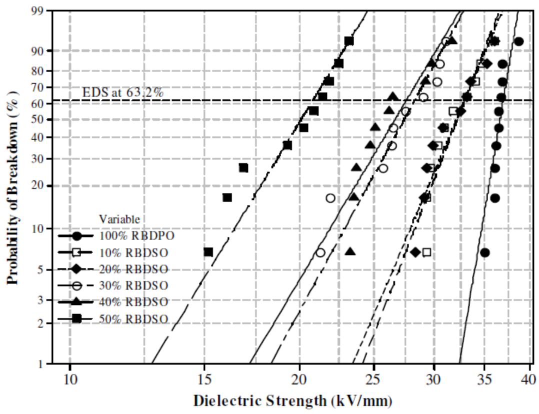
$$F\left(Et\right) = 1 - \exp\left[-\left(\frac{Et}{Ets}^{\beta}\right)\right] \tag{4}$$

where $F(Et)$ is the cumulative failure probability for the Weibull distribution, Et is the random variable (the measuring values of the cumulative breakdown field strength), Ets is the scale parameter which represents the cumulative dielectric breakdown field strength required for

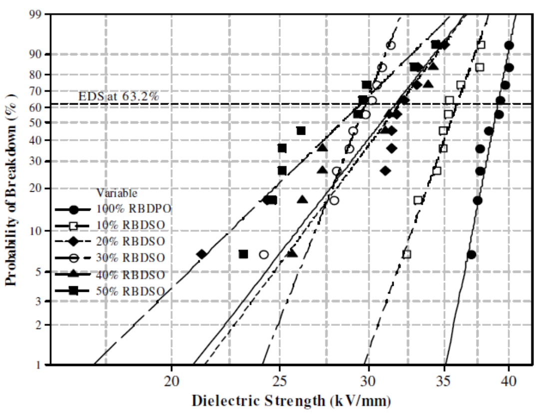
63.21% of the tested specimens to fail and β is the shape parameter which is a dimensionless number, a measure of scattered values of the cumulative breakdown field strength for $Et=Ets$ and determine the shape of the probability density function. In failure distribution and reliability function, Ets plays an important role where it defines the characteristics life of the Weibull distribution at probability failure of 63.21% [37, 38]. Therefore, in this statistic analysis, the sample which fit best the Weibull distribution was identified by having the highest dielectric strength at 63.21% of failure. Moreover, at probability failure of 63.21%, the lowest withstand of dielectric strength was also estimated.



(a) Weibull distribution of RBDPO/RBDSO mixture at 40˚C



(b) Weibull distribution of RBDPO/RBDSO mixture at 50˚C



(c) Weibull distribution of RBDPO/RBDSO mixture at 60˚C

Fig. 9. Weibull distribution of RBDPO/RBDSO mixture at 40˚C, 50˚C and 60˚C

In order to determine the probability of dielectric strength of RBDPO/RBDSO mixture, p-value plays an important role to identify whether the dielectric strength data follows the distribution. P-value is the probability of making a mistake if the null hypothesis is rejected [36]. P-value should be higher than the significant levels test (α = 0.05) to accept null hypothesis which means the dielectric strength data belongs to the distribution.

Ten data has been used in this statistical analysis. The probability distribution of dielectric strength of RBDPO/RBDSO mixture was analyzed from 0% to 50%, at 40˚C to 60˚C. The results of Weibull distribution analysis at 40˚C, 50˚C and 60˚C are tabulated in Table 5. Figs. 9 (a), (b), and (c), shows the probability plot of dielectric strength for 40˚C, 50˚C and 60˚C, respectively. It shows that the conformity of Weibull distribution started to decrease below than 63.2% probability in certain ratios of RBDSO. However, all the data showed a good linearity and are well scattered along the curve fitting which showed that the dielectric strength of RBDPO/RBDSO mixture generally followed the Weibull distribution. Moreover, the result of p-value in Table 5 has shown that the data sufficiently fitted into the Webull distribution. It appears that only one dielectric strength data has the p-value less than 0.05 at 50˚C and 60˚C. Thus, the dielectric strength data was assumed to fit in the Weibull plot.

Table 5. Weibull distribution analysis of RBDPO/RBDSO mixture

RBDSO (%)	EDS at 63.2%			P-value			Conformity to Weibull distribution		
	40˚C	50˚C	60˚C	40˚C	50˚C	60˚C	40˚C	50˚C	60˚C
0	34.43	37.01	39.16	0.203	0.011	0.197	Yes	No	Yes
10	30.32	33.00	36.03	0.064	>0.250	>0.250	Yes	Yes	Yes
20	27.63	32.99	32.06	>0.250	>0.250	0.023	Yes	Yes	No
30	24.11	28.40	29.86	0.189	>0.250	>0.250	Yes	Yes	Yes
40	23.82	27.70	31.82	0.214	0.146	0.199	Yes	Yes	Yes
50	20.93	20.90	29.64	>0.250	>0.250	0.249	Yes	Yes	Yes

*EDS at 63.2% : Estimated Dielectric Strength at 63.2%

Fig. 10 shows the comparisons of the dielectric strength of RBDPO/RBDSO mixture between calculation, simulation and Weibull distribution analysis. The electric field strength of RBDPO/RBDSO mixture determined from the calculation supported the simulation results. In addition, the dielectric strength obtained from the calculation and simulation of mean value breakdown voltage shows slightly close to the estimated lowest dielectric strength obtained from Weibull plot at 40˚C, 50˚C and 60˚C with approximate difference from 0% to 11%.

Fig. 10 also shows that the dielectric strength depended on the RBDSO content. The dielectric strength of RBDPO/RBDSO mixture decreased with the increment of RBDSO ratio into RBDPO. The decrement of dielectric strength was explained by the breakdown mechanism in liquid dielectric as illustrated in Fig. 11. RBDPO/RBDSO mixture at various ratio of RBDSO may yield to different stressed oil volume mechanism which might be due to the water content in the commercial liquid of RBDSO [39]. It is believed that in this case, the stressed oil volume in the oil mixture increased with the increment of RBDSO content which resulted in a decrease the breakdown voltage. The differences in stressed oil volume might form a number of gas bubbles bridging the gap at different voltage. As stated in the cultivation and bubble mechanism theory [39], the production of large number of gas bubbles will form a bridge along the region from the high voltage electrode to the grounded electrode side. The generation of gas bubbles in RBDPO/RBDSO mixture at each ratio of RBDSO might occur at the voltage below the breakdown voltage level and the gas bubbles completely bridged the gap when the voltage applied reached the breakdown voltage. The bridging process of the gas bubbles can be explained according to the suspended particle theory [39, 40]. The permittivity of the gas bubble, ε_g is smaller than the permittivity of the oil, ε_l. Under the electric field intensity, the gas bubbles experienced a force directed towards areas of minimum stress. When the voltage applied approached the breakdown voltage, the number of gas bubbles formation is large and aligned between the electrodes due to the existing force. The gas bubbles finally form a stable chain bridging the gap and lead to the breakdown of the oil at each ratio of RBDPO mixture.

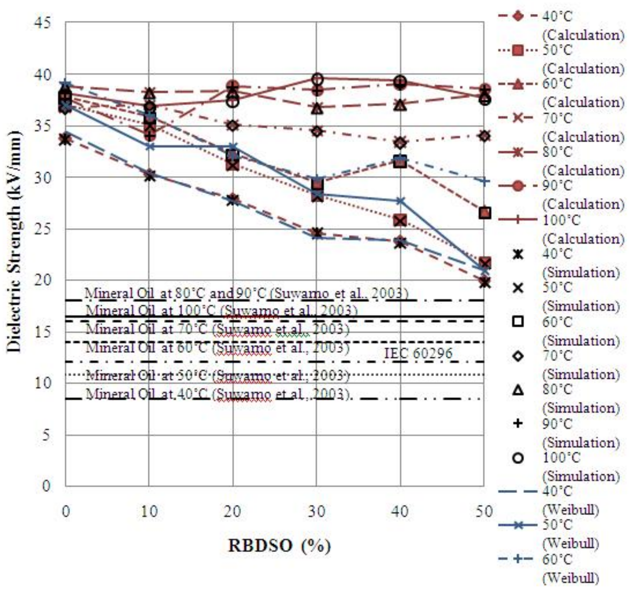


Fig. 10. Dielectric strength of RBDPO/RBDSO mixture dependence on RBDSO content compared with mineral oil [9] and IEC 60296 standard

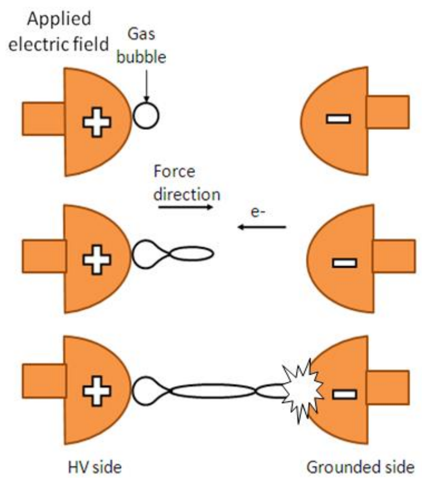


Fig. 11. Breakdown mechanism in liquid dielectric

The graph plotted also shows the dielectric strength of mineral oil at 40˚C to 100˚C reported by Suwarno et al. [19]. It shows that the dielectric strength of mineral oil is lower compared to the dielectric strength of the oil mixture from 0% to 50% of the RBDSO content. The two results of mineral oil at 40˚C and 50˚C also showed slightly lower than IEC 60296 standard while the rest of dielectric strength for the mineral oil and the oil mixtures were higher compared to the standard. Meanwhile, Liao et al. [41] and Rajab et al. [42] found that the dielectric strength of mineral oil at 40°C was approximately 10.4kV/mm and 4.4kV/mm, respectively which was lower than all the mixtures and the standard. However, Yusnida et al. [43] reported that mineral oil possesses high dielectric strength which was approximately 32kV/mm at 40°C. Gockenbach and Borsi [44] found that the dielectric strength of mineral oil at 60°C and 90°C was approximately 29.2kV/mm, which was lower than all the mixtures except for 50% RBDSO content at 60°C. Thus, these results indicated that the RBDPO/RBDSO mixture can be considered to be used as insulating liquid in transformer.

Fig. 12 shows the dielectric strength of RBDPO/RBDSO mixture dependence on temperature. As comparison, the dielectric strength of mineral oil dependence on temperature obtained from Suwarno et al. [13] was also included. The dielectric strength of RBDPO/RBDSO mixture increased with the increase of temperature. Similar to the RBDPO/RBDSO oil mixture, the dielectric strength of mineral oil also increased with the increment of temperature. The increment of the dielectric strength might occur due to the presence of dissolved water in the RBDPO/RBDSO mixture and mineral oil.

There are three types of water in oil which are known as dissolved water, emulsified water and free water. The dissolved water is hydrogen bonded to the hydrocarbon molecules of which oil is composed, emulsified water is supersaturated in solution but has not totally separated from the oil and free water is also supersaturated in solution and exists in the form of water droplets when the moisture in oil has exceeded the saturation value. Free

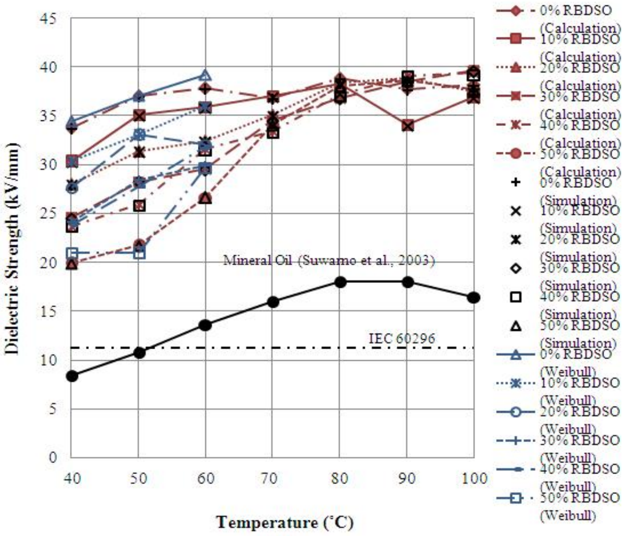
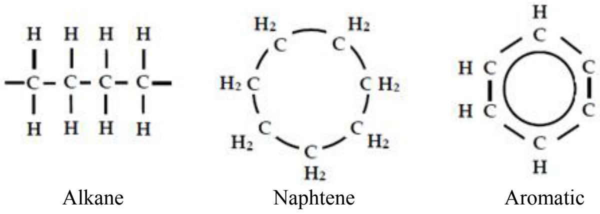


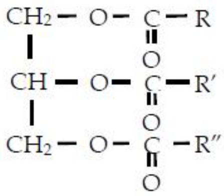
Fig. 12. Dielectric strength of RBDPO/RBDSO mixture dependence on temperature compared with mineral oil [9] and IEC 60296 standard

water is measured in parts per million (ppm) [45, 46]. The dissolved water increased in tandem with the increment of temperature which also depends on the solubility of the oil. As the water dissolved effectively with the increase in temperature, the water molecule also dispersed actively with the molecule of oil mixture, known as intermolecular water bridge [47]. This water bridge can restrain the kinetic mobility of electron to participate in the conduction process which resulted in the increment of breakdown strength of the oil mixture and mineral oil.

Comparison between the mineral oil and the RBDPO/RBDSO mixture for all ratios indicated that mineral oil has considerable lower dielectric strength with the increment of temperature. This difference was due to the chemical structural difference between these two distinct oils. The difference of chemical structure caused the vegetable oil possess higher solubility compared to the mineral oil at the same temperature. Mineral oil consists of hydrocarbon which is divided into alkanes, naphthenes and aromatics [48] as shown in Fig. 13(a). On the other hand, vegetable oil consists of hydrocarbon attached to carboxyl group (-COOH) to produce ester group (-COOR) [49] as shown in Fig. 13(b). The presence of carbonyl group (C=O) causes the vegetable oil to become more polar compared to mineral oil. The two lone pair electrons owned by oxygen in the vegetable oil can participate in hydrogen bonded as hydrogen acceptor which confers additional solubility to the vegetable oil [50]. Due to the absence of carboxyl group in the mineral oil, the formation of hydrogen bonded with water molecules diminish. Therefore, the solubility of mineral oil increased less with the temperature which was the cause to the slower dispersion of water molecules within molecules of the mineral oil. This caused less restriction to the electron movement in the conduction process which yields to low breakdown voltage. Similar



(a) Chemical structure of hydrocarbon in mineral oil.



(b) Chemical structure of vegetable oil [33].

Fig. 13. Chemical structure of mineral oil and vegetable oil

results of breakdown strength increment with the increase of temperature were reported in numerous papers where vegetable oil and mineral oil were utilized as the samples in the experiments [23, 41, 42, 51, 52].

3.2 Dissipation factor (tan δ) characteristics

The dissipation factor is the measurement of energy loss within the dielectric liquids subjected to AC voltage. This energy loss is the heat energy which dissipated in the liquid due to the presence and movement of charge carriers under the influence of alternating electric field. The insulating liquid is characterized by the low value of the dissipation factor [54]. Fig. 14 depicts the dissipation factor of 10%, 30% and 50% RBDSO ratio mixture in the RBDPO at 40˚C, 70˚C, and 90˚C. In comparison, the results of dissipation factor of mineral oil reported by Suwarno et al. [19] at 40˚C, 70˚C, and 90˚C were also included. The

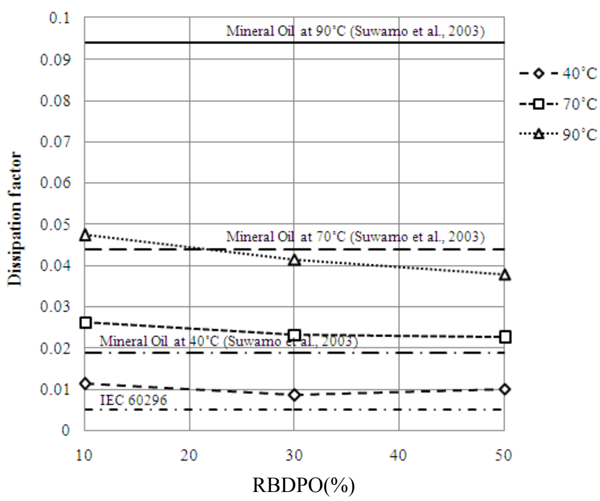


Fig. 14. Dissipation factor of 10%, 30% and 50% of RBDPO content at 40°C, 70°C and 90°C compared with mineral oil [9] and IEC 60296 standard

dissipation factor of the RBDPO/RBDSO mixture has shown descending trend from 10% to 50% RBDSO ratio. This result shows that the addition of 0% to 50% RBDSO into RBDPO gives a positive effect on the dissipation factor. On the other hand, the dissipation factor for the oil mixture and mineral oil increased with the increase of temperature. The temperature rise caused the reduction of oil viscosity, which caused less friction or resistance to the movement of mobile ions. As a consequence, the mobility of ions increased with the reduction of viscosity [54]. Thus, the increment of ion mobility will result in more energy dissipating in the liquid. Jian Li et al. [55], Caixin et al. [56] and Suwarno et al. [52] also discovered the same ascending trend of dissipation factor with the increment of temperature when using vegetable oil and mineral oil as their specimen. Comparison between the oil mixture and mineral oil indicated that the dissipation factor of the oil mixture from 0% to 50% was lower compared to mineral oil of all ranges of temperatures. This result shows a positive result in using the palm oil and soybean oil mixture as transformer oil.

3.3 Relative permittivity (dielectric constant) characteristics

The relative permittivity is a measure to describe the polarization in dielectric liquid under applied electric field. High value of relative permittivity means more charges are stored in the dielectric liquid which could reduce the mismatch between the liquid and solid insulation for attaining higher withstand field strength [57]. Fig. 15 shows relative permittivity of 10%, 30% and 50% of RBDSO ratio in RBDPO/RBDSO mixture compared to the mineral oil [56] at 40˚C, 70˚C, and 90˚C. The results of relative permittivity of RBDPO/RBDSO mixture were higher compared to conventional mineral oil which was only 2.0 at 90˚C. The relative permittivity of mineral oil at

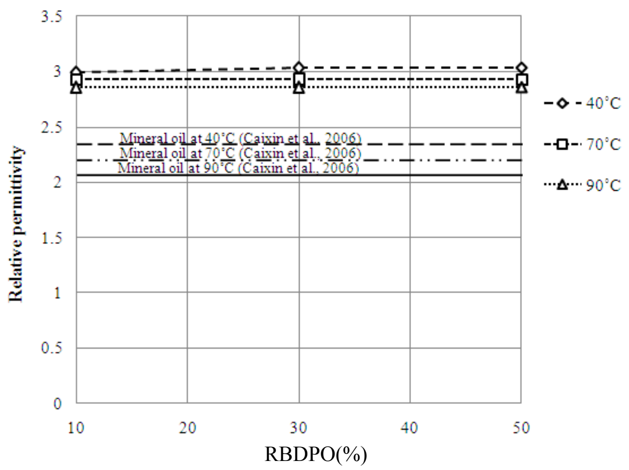


Fig. 15. Relative permittivity of 10%, 30% and 50% of RBDPO content at 40°C, 70°C and 90°C compared with mineral oil [36]

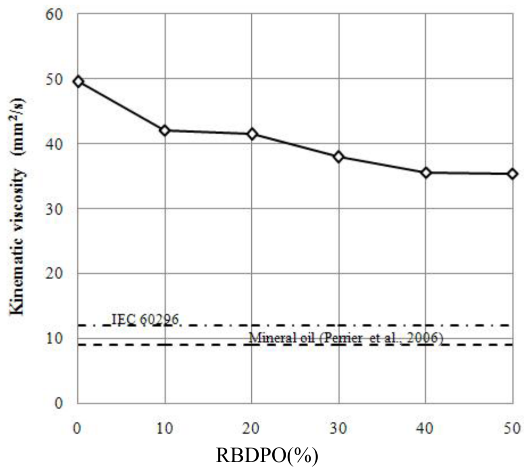


Fig. 16. Kinematic viscosity of RBDPO/RBDSO mixture dependence on RBDSO content at 40°C compared with mineral oil [39] and IEC 60296 standard

90˚C reported by Suwarno et al. [19] and Hemmer et al. [58] also showed a close value with Caixin et al. [56] which indicated that the relative permittivity of RBDPO/ RBDSO mixture of 0% to 50% were better compared to mineral oil.

From the plotted graph, the relative permittivity also was nearly constant with the addition of the RBDSO ratio of 10% to 50%. Meanwhile, the relative permittivity shows a descending trend with the increased of temperature from 40˚C to 90˚C for RBDPO/RBDSO mixture and mineral oil.

3.4 Kinematic viscosity characteristics

Fig. 16 shows the plotted graph of kinematic viscosity of RBDPO/RBDSO mixture dependence on RBDSO ratio at 40˚C. In comparison, the kinematic viscosity of mineral oil [59] was also included. It is shown that the kinematic viscosity of mineral oil was under the limit of IEC 60296 standard. Rozga et al. [60] reported that the kinematic viscosity of mineral oil at 40°C also showed lower than the standard which is 9mm^2/s. Other than that, Sun-Ho and Chang-Su [14] also reported low kinematic viscosity of mineral oil at 40°C which was 7.8mm2/s. Meanwhile, the kinematic viscosity of various ratios of the RBDPO/ RBDSO mixture exceeded the standard limit. However, it also showed that the kinematic viscosity of RBDPO/ RBDSO mixture decreased with the increment of RBDSO ratio into RBDPO. This result showed a significant positive result of reducing the kinematic viscosity of the palm oil which might improve its heat transfer characteristic.

3.5 Water content characteristics

Fig. 17 shows the plotted graph of water content in the RBDPO/RBDSO mixture at room temperature. In comparison, the water content of mineral oil at room temperature reported by Krins et al. [61] was also included

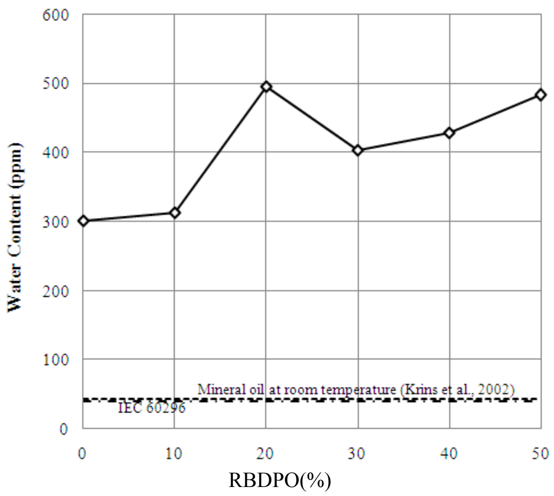


Fig. 17. Water content of RBDPO/RBDSO mixture dependence on RBDSO content at room temperature compared with mineral oil [61] and IEC 60296 standard

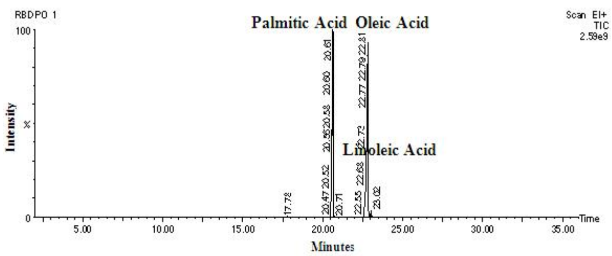
in Fig. 17. Fig. 17 shows an ascending trend of water content from 0% to 50% of the RBDSO content in RBDPO while mineral oil shows slightly close result to the maximum limit of IEC 60296 standard which is 40 parts per million (ppm). Meanwhile, Gockenbach and Borsi [44], Lewand [45] and Miyagi and Wakimoto [62] found that the water content in mineral oil is approximately 70-80 ppm which is slightly higher than the standard. This suggested standard limit represents a maximum limit of relative saturation of 50% in the mineral oil at room temperature. Relative saturation is the concentration of water which the oil can hold at the measurement temperature. It is governed by the equation below:

$$RS = \frac{Wc}{So}\left(100\%\right) \tag{5}$$

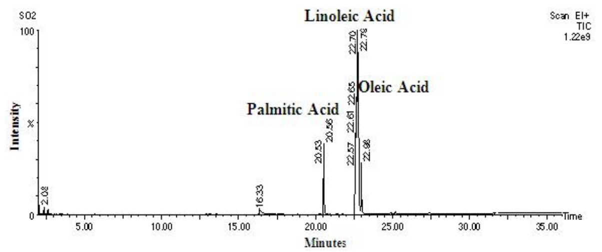
where *RS* is relative saturation (in percent), *Wc* is absolute water content in the oil at the measurement temperature (in ppm) and *So* is solubility of the oil at the measurement of temperature (in ppm). Solubility of the oil is highly dependent on the temperature where it increased with the increment of temperature. Fig. 17 shows absolute water content of the RBDPO/RBDSO mixture is greater compared to the mineral oil. Vegetable oil and mineral oil possess huge difference of solubility at the same temperature due to its difference in chemical composition. As proof, an experiment conducted by Caixin et al. [56] has shown that the solubility of vegetable oil is 10 times greater than the solubility of mineral oil at room temperature. High solubility of vegetable oil gives advantageous to the solid insulator (paper and pressboard) of the transformer. Due to high solubility owned by vegetable oil, the water that resides in the paper will be forced into the oil efficiently which could retain the dryness of the paper. This gives way to prolong the aging rate of the insulating paper in the transformer. The relative saturation plays an important role to diagnose the condition of the transformer systems. To maintain the reasonable breakdown strength of the transformer oil, the relative saturation should remain below 50% of the water saturation in the oil [45]. Therefore, it is believed that the increment of RBDSO content from 0% to 50% had caused a gradually increase of relative water content which might resulted in gradual reduction of dielectric breakdown voltage of the oil mixture.

3.6 Chemical composition analysis

The chemical composition of RBDPO/RBDSO mixture in various ratios have been analyzed. In addition, the chemical composition of 100% RBDPO and 100% RBDSO were also analyzed. The purpose of analyzing the chemical composition of the oil mixtures was to prove that the ratios between RBDPO and RBDSO are aligned with the general standard of chemical composition of palm oil and soybean oil. Figs. 18(a) and 18(b) show the GC-MS result of fatty acid composition of 100% RBDPO and RBDSO, respectively. Table 6 depicts the results of fatty acid composition in percentage of weight of 100% RBDPO and



(a) GC-MS result of fatty acid composition of 100% RBDPO

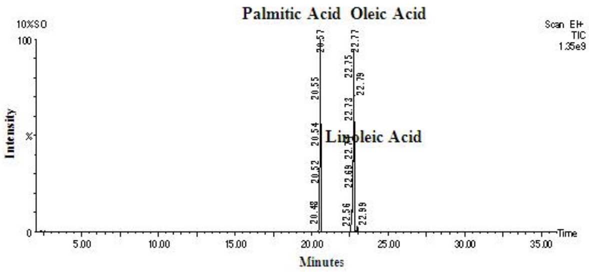


(b) GC-MS result of fatty acid composition of 100% RBDSO

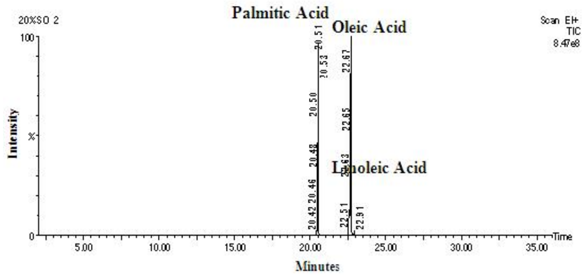
Fig. 18. GC-MS result of fatty acid composition of 100% RBDPO and 100%RBDSO

Table 6. Fatty acid composition of 100% RBDPO and 100%RBDSO

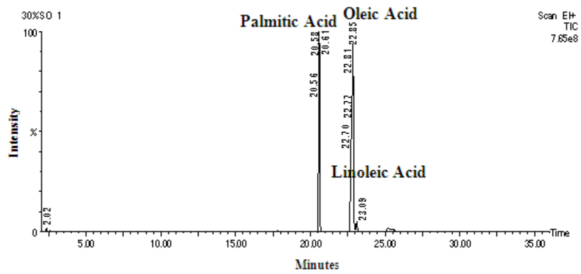
Fatty acid composition	Weight (%)	
	RBDPO	RBDSO
Palmitic acid (C16:0)	45.5	11.6
Oleic acid (C18:1)	40.6	23.4
Linoleic acid (C18:2)	9.4	55.6
Others	4.5	9.4



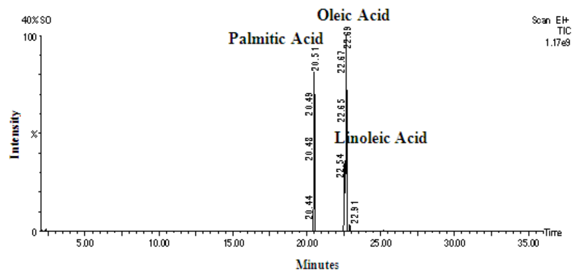
(a) GC-MS result of fatty acid composition of 10% RBDPO



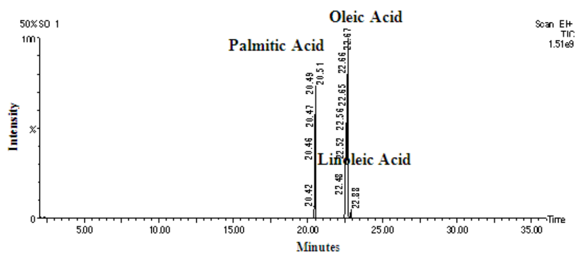
(b) GC-MS result of fatty acid composition of 20% RBDPO



(c) GC-MS result of fatty acid composition of 30% RBDPO content



(d) GC-MS result of fatty acid composition of 40% RBDPO content



(e) GC-MS result of fatty acid composition of 50% RBDPO content

Fig. 19. GC-MS result of fatty acid composition of 10% to 50%RBDSO content

RBDSO analysis. 100% RBDPO showed a balance ratio of saturated fatty acid to unsaturated fatty acid which was almost 50:50 where the highest percentage of saturated fatty acid was Palmitic acid which contributed around 45.5%. On the other hand, Oleic acid was the highest percentage of unsaturated fatty acid which contributed around 40.6%. Meanwhile, 100% RBDSO showed higher total number of unsaturated fatty acid where the total ratio of unsaturated fatty acid to the saturated fatty acid in 100% RBDSO was almost 80:20. The highest percentage of unsaturated fatty acid and saturated fatty acid in RBDSO was held by Linoleic acid and Palmitic acid which contributed around 55.6% and 11.6%, respectively.

Figs. 19 (a), (b), (c), (d) and (e) show the GC-MS results of fatty acid composition from 10% to 50 % of RBDSO in RBDPO mixture. The result revealed the presence of Palmitic acid (C16:0), Oleic acid (C18:1) and Linoleic acid (C18:2) in all ratios of RBDSO in RBDPO/RBDSO mixture, which was the major fatty acid components in the oil mixture. Fig. 20 and Table 7 depicted the trend of fatty acid composition and listed the result obtained, respectively. The result in Fig. 20 shows the increasing of RBDSO ratio from 0% to 50% causes a gradually decreased in Palmitic and Oleic acid, while significantly increased the Linoleic acid. McShane [6] mentioned in his paper that a high percentage of unsaturated fatty acid in oils will result in lower kinematic viscosity and better low temperature properties. Thus, due to the gradually increase of the unsaturated fatty acid with RBDSO content, the kinematic

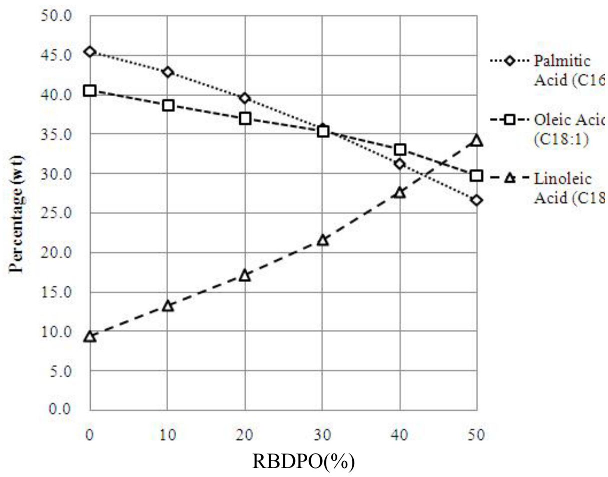


Fig. 20. Major fatty acid components from 0% until 50% RBDSO content

Table 7. Fatty acid composition of RBDPO/RBDSO mixture

Fatty acid composition	Weight (%)					
	RBDSO (%)					
	0	10	20	30	40	50
Palmitic Acid (C16:0)	45.5	42.9	39.6	35.7	31.2	26.6
Oleic Acid (C18:1)	40.6	38.7	36.9	35.4	33.1	29.8
Linoleic Acid (C18:2)	9.4	13.3	17.1	21.6	27.6	34.2
Others	4.5	5.1	6.4	7.3	8.1	9.1

viscosity of the oil mixtures also tended to reduce. This explains the descending trend of kinematic viscosity with increment ratio of RBDSO.

Meanwhile, in terms of electrical strength, Forster [63] has suggested that the presence of unsaturated hydrocarbon will create the electron jumping process which is unavailable in saturated substances. Unsaturated hydrocarbon contained a double bond which has pi electrons inside. This pi electron could partake in the conduction process when electric field is applied. Thus, the increment of unsaturated hydrocarbon with the increment of RBDSO content might increase the pi electron which resulted in the increment of conductivity. This situation might reduce the breakdown strength of RBDPO/RBDSO mixture with the increment of RBDSO content.

3.7 Summary

From the result and discussion above, comparison between RBDPO/RBDSO mixtures with mineral oil reported by past researchers have shown that oil mixture can be considered as an insulating liquid in power transformer. The dielectric strength for all ratios of RBDPO/RBDSO mixture has proven far superior to mineral oil where all the breakdown voltage of oil mixture has exceeded the breakdown voltage of mineral oil from 40˚C to 100˚C. The dissipation factor of RBDPO/RBDSO mixture from 0% to 50% is also considerably lower compared to mineral oil at 40˚C, 70˚C and 90˚C. The relative permittivity for all ratios of the oil mixture was also higher compared to mineral oil at 40˚C, 70˚C and 90˚C. Although the kinematic viscosity of all ratios of RBDPO/RBDSO mixture was higher than the mineral oil, it indicates an improvement with the gradual increase of RBDSO. Despite this, there is increment of relative water content from 0% to 50% of RBDSO ratio which caused the gradual reduction of breakdown voltages. Nevertheless, the breakdown voltages of the oil mixture are still higher than mineral oil at the same temperature. From the above results, it can also be concluded that between the ranges of 0% to 50% ratio of RBDSO into RBDPO, 30% RBDSO content has shown to be the most suitable mixture of RBDPO/RBDSO to be used as an insulating liquid. 30% RBDSO content is the intermediate content which accumulates better dielectric properties. This is due to its high and reasonable dielectric strength for all ranges of temperatures, sufficiently low dissipation factor for various temperatures, high relative permittivity for various temperatures and improved kinematic viscosity. Table 8 summarizes and compares the result of 30% RBDSO content with mineral oil. The breakdown voltage and the relative permittivity of 30% of RBDSO content are higher compared to the mineral oil. Although the dissipation factor and the kinematic viscosity of 30% ratio of RBDSO do not agree with IEC 60296 standard as well as higher compared to the mineral oil, yet it has higher breakdown voltage and relative permittivity. Thus, it has shown better potential mixture of palm and soybean-based transformer oil. Therefore, it can be summarized that 70%RBDPO/30%RBDSO is considered as a better mixture as dielectric insulating fluid in transformer.

Table 8. Comparison between 70%RBDPO/30%RBDSO content and Mineral Oil

Dielectric Properties	70%RBDPO/ 30%RBDSO	Mineral oil	IEC 60296 standard
Breakdown voltage (kV/mm) at 40˚C	61.40	21[a]	≥ 30[d]
Dissipation factor (tan δ) at 90˚C	0.0414	0.005[a]	≤ 0.005
Relative permittivity at 90˚C	2.854	2.0[b]	-
Kinematic Viscosity (mm^2/s) at 40˚C	37.9	9[c]	≤ 12

[a] Reference from Suwarno et al., 2003
[b] Reference from Caixin et al., 2006
[c] Reference from Perrier et al., 2006
[d] Reference from Krins et al., 2002
[d] 30kV at ambient temperature of 20˚C±5˚C

4. Conclusion

The experiment of dielectric properties of RBDPO/ RBDSO mixture was performed. It is reveals that the breakdown voltage decreases with the increase of RBDSO ratio from 0% to 50%. All the breakdown voltage of the oil mixture were above 30kV which fulfilled the IEC standard. The breakdown voltage of the oil mixture shows slight increases with the increment of temperatures. The dielectric strength obtained from the calculation and simulation of mean value breakdown voltage shows slightly close to the estimated lowest dielectric strength obtained from Weibull distribution at 40˚C, 50˚C and 60˚C with approximate difference from 0% to 11%. Comparisons between RBDPO/ RBDSO mixture with mineral oil reported by past researchers have shown that the dielectric strength for all ratios of RBDPO/RBDSO mixture are far superior than mineral oil where all the breakdown voltage of oil mixture has exceeded the breakdown voltage of mineral oil from 40˚C to 100˚C. The dissipation factor of RBDPO/RBDSO mixture has shown to decrease from 10% to 50% of RBDSO content. In comparison between the oil mixture and mineral oil, the dissipation factor of the oil mixture was lower compared to mineral oil for all ranges of temperatures. Meanwhile for relative permittivity, no significant changes has been observed when the ratio of RBDSO was increased from 10% to 50%. The relative permittivity of the RBDPO/RBDSO mixture is also shown to be higher than mineral oil. Although the kinematic viscosity exceeded the IEC 60296 standard and mineral oil result, the value of kinematic viscosity decrease with the increment of RBDSO into RBDPO which shows a positive result. In this paper, 70%RBDPO/30%RBDSO has been selected as the optimum mixing ratio as the potential insulating liquid in transformer.

Acknowledgements

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