A Comparison of Dielectric Properties of Palm Oil with Mineral and Synthetic Types Insulating Liquid under Temperature Variation

Abdul Rajab[1], **Aminuddin Sulaeman**[2], **Sudaryatno Sudirham**[1] **& Suwarno**[1]

[1]School of Electrical Engineering and Informatics, Institut Teknologi Bandung,
Bandung, Indonesia
[2]Faculty of Mathematics and Natural Science, Institut Teknologi Bandung,
Bandung, Indonesia
E-mail: rajabdri@students.itb.ac.id

Abstract. Mineral oil is known to have a low biodegradability level and high susceptibility to the fire. These conditions motivate many researchers to look for alternative sources for insulating oil. One of the alternative liquid is palm oil. To verify the suitability of using palm oil as an insulating liquid, it is important to make dielectric properties comparison with the commonly used insulating liquid. This paper presents comparison of temperature effect on dielectric properties of palm oil with mineral type insulating liquid and silicone oil. The measured parameters were breakdown voltage, dissipation factor (tan δ), and dielectric constant. Breakdown voltage measurement was performed in accordance with IEC 156 standard, whereas, the dissipation factor and dielectric constant measurement were conducted based on IEC 60247 standard test methods. The results showed that variations of dielectric properties of palm oil to the temperature change, in general, have the same tendency with those of commonly used insulating liquids i.e. mineral oil and silicone oil. Breakdown voltages and dissipation factors of all tested oils were increased, while their dielectric constants were slightly decreased with the increase of temperature.

Keywords: *breakdown voltage; dielectric constant; dissipation factor; Insulating liquid; palm oil.*

1 Introduction

Insulating liquid provides two main purposes in the transformer operation, as the insulation material and the cooling medium. Up to this day, mineral oils derived from crude petroleum were the most widely used as insulating and cooling liquids in electrical equipment, especially transformer. Such oils are not considered nonflammable, and because they are petroleum based, they are considered to cause a negative effect to environment, especially when there are any incidents during operational time like transformer explosion which may cause a spill of oil to the soil or water stream. Insulating oils should fulfill the following minimum health and environmental requirements: non-toxic,

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biodegradable, stable thermally, recyclable, readily disposable, and not listed as a hazardous material [1].

In order to settle down the flammability and environmental issues, many researchers started to look for alternative sources for insulating oil. Vegetable oil is considered to be the most potential source to replace the mineral oil. The advantage of using vegetable (natural ester) oil is the non-toxic material characteristic which will not produce any toxic product during fire. Carbon dioxide and water are the only products that are formed during the biodegradation process. They are also less flammable liquids with a minimum flash point of about 300°C. Accelerated aging test showed a better performance of the natural ester oil compared to the mineral oil, which enables it to extend the life time of natural ester immersed transformer than the mineral oil ones [1, 2].

One of the alternative liquid is palm oil. Investigation on electrical, physical and chemical properties of palm oil shows that the oil possesses good properties to be used as substitutes for mineral oils in high voltage equipments [3]. However, in transformer application, insulating liquid experiences temperature variation due to the fluctuation nature of electricity consumption. Palm oil must be able to withstand the temperature variation up to the highest tolerable level, i.e. 110^{o}C at the transformer winding [4], without losing its functional dielectric properties, if the oil will be implemented in high voltage transformer in the future. This paper presents comparison of dielectric properties of palm oil with the commonly used insulating liquid, mineral and synthetic oils, under temperature variation ranging from room temperature, 25^{o}C up to 100^{o}C or 120^{o}C.

2 Experimental Setup

2.1 Breakdown Voltage Measurement

Breakdown voltage measurement was performed using *Liquid Dielectric Test Set, Model LD60,* produced by *Phoenix Technologies* as shown in Figure1. This equipment is equipped with the VDE electrode pairs as suggested by IEC 156 standard [4]. Rate of rise of 2 kV/s was chosen during the experiment. Due to the limitation in capacity of the equipment of 60 kV, electrode gap was modified to be 1.05 mm, instead of 2.5 mm as recommended by IEC 156 standard. Figure 2 shows the new oil chamber with modified electrode gap.

Application of voltage was started at least 5 minutes after pouring the mineral oil sample into the test chamber [5], and at least 15 minutes for palm oil [6]. This delay time is needed to ensure that all gas bubbles formed during the pouring process have been expelled before the measurements were started. The measurements were conducted six times with a time delay between two consecutive measurements at least 2 minutes for mineral oil [5], and 6 minutes for palm oil. The delay time after measurement is intended to allow breakdown of products to disperse and gas to expel, before subsequent measurement was conducted so that the later measurement was not influenced by the previous one [7]. The longer delay time for palm oil was due to the higher viscosity of palm oil than that of mineral oil. Measurements procedure for silicone oil was performed in the same manner with palm oil's one.

Figure 1 Liquid Dielectric Test Set, Model LD60 for breakdown measurement.

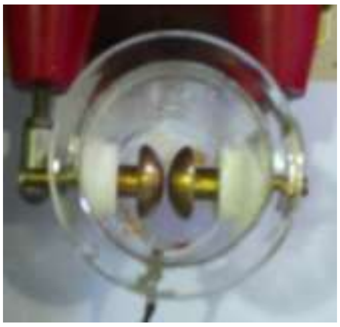


Figure 2 Modified oil chamber for breakdown voltage measurement; electrode gap is 1.05 mm, instead of 2.5 mm as suggested by IEC-156 standard.

In order to investigate the effect of temperature on the breakdown voltage of oils, the measurement was performed at several different temperatures. The temperature was increased up to the temperature level of 120^{o}C with the increment of 10^{o}C. At each temperature level, it was maintained relatively constant using a special design temperature control system. Components of the temperature control system are shown in Figure 3. The temperature sensor detects the liquid temperature. Based on information sent by the temperature sensor, the controller orders the contactor to perform ON/OF operation to connect/disconnect power supply to the electric heater. Blower works to push the temperature down when the temperature was higher than the expected one.

Figure 3 Components of the temperature control system; (a) Temperature Sensor embedded on the oil chamber's wall, (b) heater, (c) blower, (d) controller, and (e) contactor.

2.2 Dielectric Constant and Dissipation Factor Measurements

Dielectric constant and dissipation factor of oils were measured using *Schering* circuit test and null indicator oscilloscope, in accordance with IEC 60247 standard [8], which is schematically shown in Figure 4. The balance of *Schering* circuit was indicated by the occurrence of Lissajous curve in the form of straight line on null indicator's display. The oil sample was put in a test cell from Tettex Instruments. The test cell, made from stainless steel, is a three terminals test cell that form capacitance system where liquids or gases as its dielectric. The test cell equipped with the electric heater and thermometer to monitor the temperature as shown in Figure 5.

Considering the fact that mass of the stainless still, test cell, was much higher than that of oil sample, then the way the temperature was varied was in reverse mode. At first, the oil was heated up to 100°C, then the temperature of oil was let to go down. At each temperature level, after a decrement of 10°C, dissipation factor and capacitance of oil were measured.

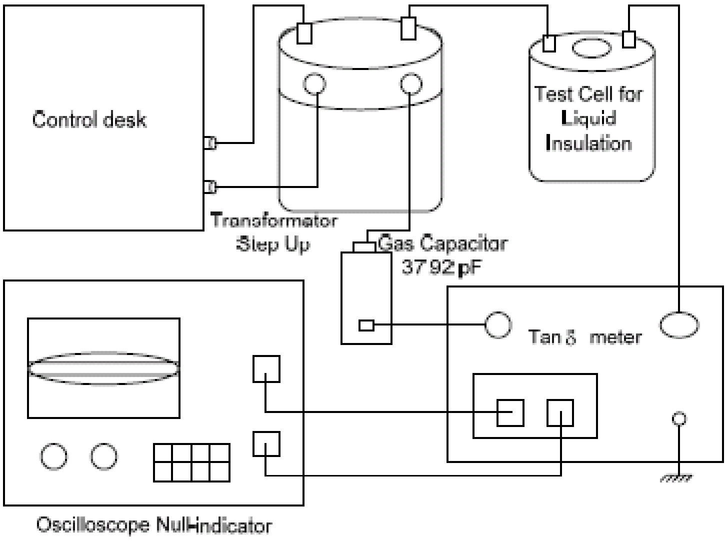


Figure 4 Schematic diagram of dielectric constant and dissipation factor measurements.

Figure 5 Liquid test cell from Tettex Instruments for dielectric constant and dissipation factor measurements; (a) Thermometer, and (b) heater's terminal.

3 Experimental Results and Discussion

3.1 Breakdown Voltage

Breakdown voltage measurements were conducted at several temperatures level, ranging from room temperature 25°C up to 120°C. At each voltage level measurements were carried out six times, and the average value of those six measurement results are shown in Figure 6.

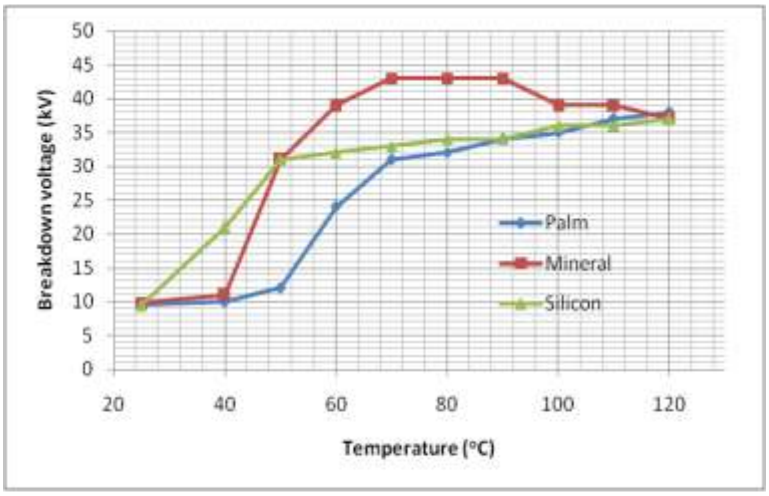


Figure 6 The average value of breakdown voltage of palm oil, mineral oil, and silicon oil as a function of temperature

Breakdown voltage of all tested oils, as shown in Figure 6, increased significantly with temperature up to 70°C. This is caused by the decreased relative water content of oils. It is well known that the breakdown voltage of any insulating liquid is inversely proportional to its relative water content [9, 10]. Relative water content (wt_r) of the oil is the ratio between absolute water content (wt_{abs}) to water solubility (wt_l) of the oil, as expressed by Eq. (1). The water solubility in oil increased with temperature, based on Eq. (2).

$$wt_r = \frac{wt_{abs}}{wt_l} x100\% \tag{1}$$

$$wt_l = wt_0 exp\left(\frac{-H}{T}\right) \tag{2}$$

Where wt_0, and H are the oil parameters. The values of wt_0 and H for palm oil, mineral oil, and silicon oil are 2.61 x 10^5 and 1340, 19.2 x 10^6 and 3805, and 5.66 x 10^5 and 2328.8, respectively [8, 11]. The graphical relationship between water solubility and absolute temperature of palm oil, mineral oil, and silicone oil is shown in Figure 7.

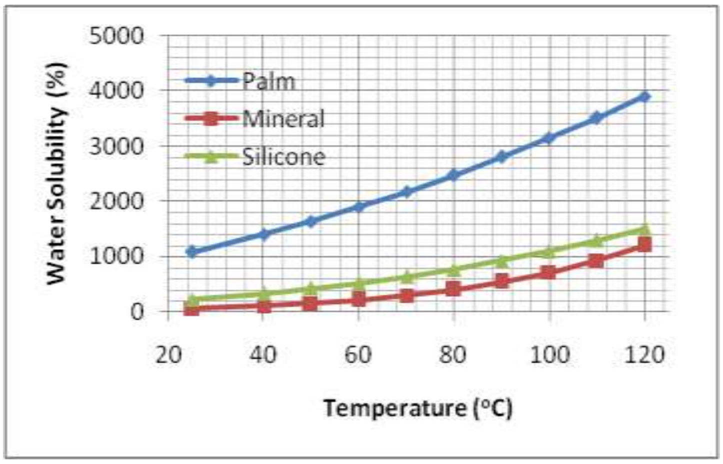


Figure 7 Water solubility of palm oil, mineral oil, and silicone oil, as a function of temperature.

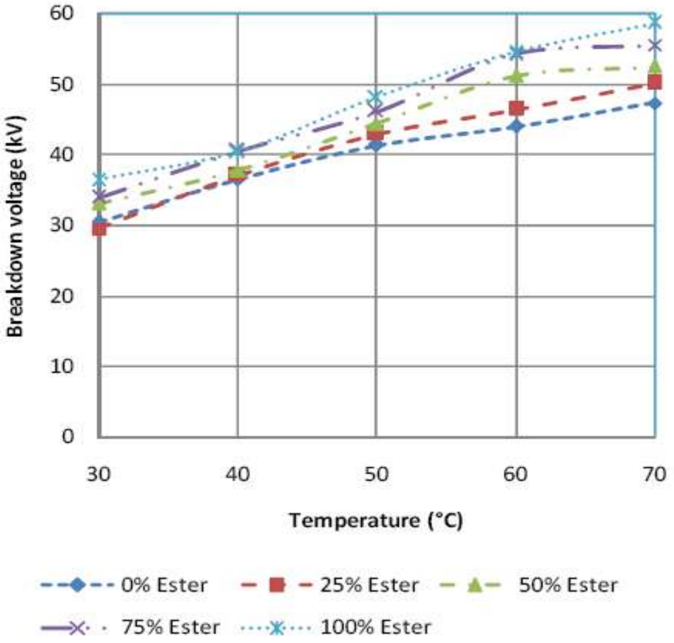


Figure 8 Breakdown voltages of a mixture of palm oil methyl ester and mineral oil as a function of temperature. [9]

Increasing temperature caused a significant reduction in the relative water content of the oil. Consequently, breakdown voltage of the oil was raised. The similar trend was reported by Suwarno and Irawan S.D. [9], who performed breakdown voltage measurement on a mixture of palm oil methyl ester and mineral oil under temperature variation, ranging from 30°C up to 70°C, as shown in Figure 8.

The similar result was also reported by C. Yeckel, *et al.* [12] who performed experiment to compare breakdown voltage of sparged oils and non-sparged oils for two types insulating liquid, mineral oil DIALLA, and synthetic oil Poly Alfa Olefin (PAO). Sparging is a technique to reduce water content in a viscous liquid. They conducted the experiment at several temperature levels, ranging from 10 °C up to 50°C. The breakdown voltage of sparged oils, either mineral oil or PAO oil, relatively unchanged to the temperature variation in the range of 10°C up to 50°C. On the other side, the breakdown voltage of non-sparged oils, tends to increase as the temperature rose.

Breakdown voltage significantly changes only to the temperature variation of wet liquids [13]. The presence of waters influences the breakdown voltage of oil in two ways, i.e. they are absorbed by particles resulting in conductive particles and forming water clusters [14]. At the low temperature where relative water content is very high, both types of water inclusion plays an important role to reduce breakdown voltage of the oil. As the temperature increased, water in oil in the form of water clusters were the first to reduce, resulting in a slow increased in breakdown voltage of the oil. This was evidently shown by palm oil at temperature rising up to about 50°C and for mineral oil at the temperature up to about 40°C (see Figure 6). Silicone oil did not experience this change as it has the fewest relative water content at low temperature among all the tested oils. Figure 9 shows the relative water content of palm oils, mineral oils, and silicone oil under temperature variations ranging from room temperature, 25°C up to 120°C. Further increase in temperature caused the waters absorbed by particles to reduce leading to significant increase in the breakdown voltage of the oil. Palm oil experienced changes in temperature between 50°C and 70°C, whereas, mineral oil and silicone oil experienced changes in temperature ranging from 40°C to 70°C, and 25°C to 50°C, respectively (Figure 6). For dry liquid, the breakdown voltage is relatively insensitive to the temperature variation [13]. This phenomenon was experimentally shown by mineral oil. As can be seen from Figure 6, the breakdown voltage of mineral oil relatively unchanged in the temperature range of 70°C and 90°C.

However, an exceptional applies for the dry liquid at the temperature level of slightly below the boiling point. There, the breakdown voltage of dry liquid starts to go down due to the formation and growth of vapor bubble [13]. It is well known that the presence of bubble(s) in insulating liquid can be a precursor to the breakdown event. Experimental results on mineral oil showed that the oil experienced this stage, where its breakdown voltage started to fall at temperature level of 100^oC (Figure 6). Due to the higher boiling point of palm oil and silicone oil, both oils need to be further heated to reach this condition.

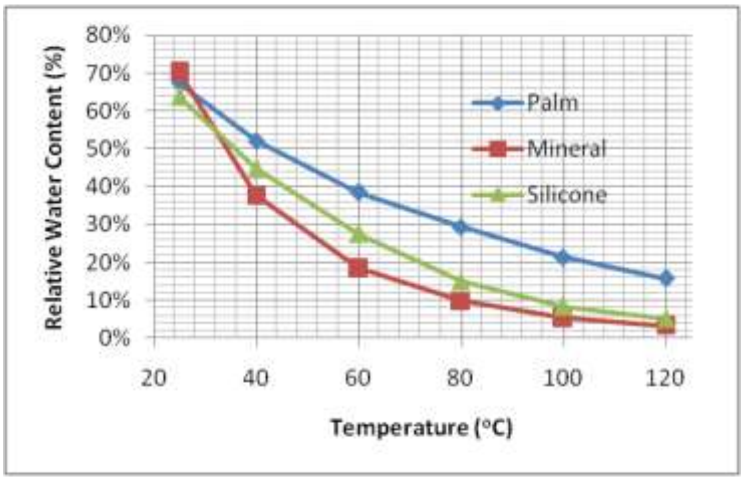


Figure 9 Relative water content of palm oil, mineral oil, and silicone oil as a function of temperature.

From the breakdown voltage view point, mineral oil is still the best choice for temperature level up to 100^oC. However, using palm oil seems to enable enhancing allowable temperature loading of transformer as its breakdown voltage tends to continuously increase up to the temperature level of 120^oC. At this point, breakdown voltage of palm oil became higher than that of mineral oil. From the breakdown voltage trend of all tested oils shown in Figure 6, it is reasonable to assume that beyond the temperature level of 120^oC, the breakdown voltage of palm oil will be much higher than the mineral oil one. This assumption seems to apply also for silicone oil. This assumption cannot be experimentally proved at this time, since the temperature cannot be further increased due to the design limitation of the oil chamber.

3.2 Dielectric Constant

The measured parameter in dielectric constant measurement was capacitance of test cell. The ratio between capacitance of oil filled test cell to the capacitance of empty cell represents the dielectric constant of the oil, as described by Eq. (3) [8]. The measurement results on palm oil, mineral oil and silicon oil at several level of temperature in the range of room temperature, 25^oC up to 100^oC are shown in Figure 9.

$$\boldsymbol{\varepsilon_r} = \frac{\boldsymbol{C_x}}{\boldsymbol{C_0}} \tag{3}$$

Where $\boldsymbol{\varepsilon_r}$ is the dielectric constant of tested oil, $\boldsymbol{C_x}$ is capacitance of the oil filled test cell, and $\boldsymbol{C_0}$ is Capacitance of empty cell. In this experiment we found $\boldsymbol{C_0}$ = 1.974 x 37.92 pF.

Figure 10 show that variation of the dielectric constant of palm oil to the temperature change possesses the same tendency with those of mineral oil and silicone oil. The dielectric constant of palm oil slightly decreased from 3.26 at room temperature, 25 ^{o}C to 3.23 at the temperature level of 100 ^{o}C. For the same temperature range, the dielectric constant of mineral oil and silicone oil change from 2.21 to 2.14 and from 2.56 to 2.49, respectively.

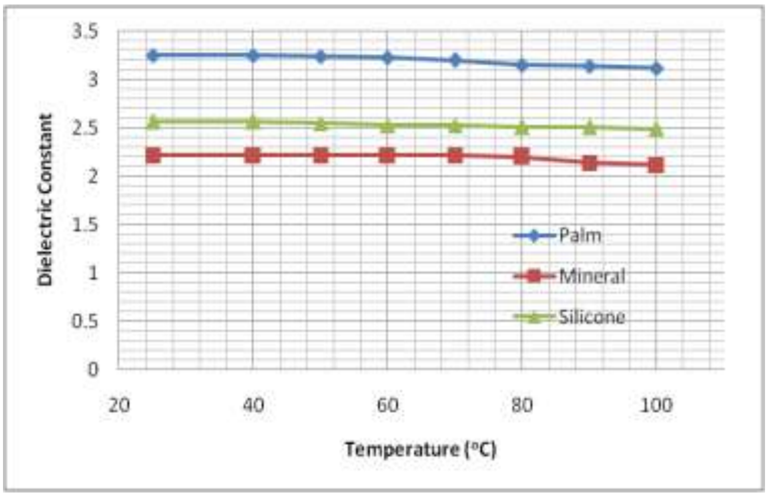


Figure 10 Dielectric constants of palm oil, mineral oil and silicon oil as a function of temperature.

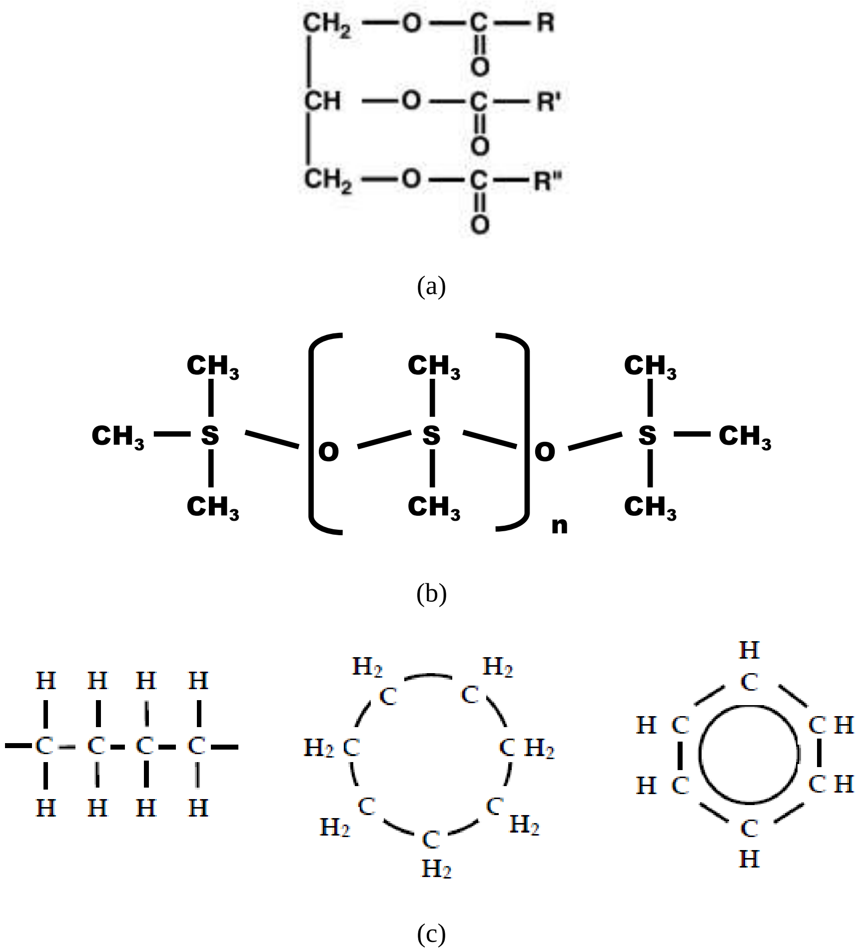
Dielectric constant of any dielectric material is related to the susceptibility (Eq. (4)), which is a measure of how easily a dielectric polarizes in responses to an electric field, as described by Eq. (5). Like susceptibility, permittivity proportional to the Polarization, P [15].

$$\boldsymbol{\varepsilon_r} = \chi + 1 \tag{4}$$

$$P = \chi\,\varepsilon_0 \mathrm{E} \tag{5}$$

Where $\boldsymbol{\varepsilon_r}$ is dielectric constant, χ is susceptibility, P is polarization and E is electric field.

Application of electric field to a dielectric material directed dipoles inside the material, which are initially random, in the same direction of applied electric field. The increase of thermal agitation due to the temperature rise would make more difficult for the dipoles to orient [16]. For the constant magnitude of electric field, based on equation (5), then the difficulty of polarization means the decreasing of susceptibility and permittivity as well. Therefore, it can be understood that dielectric constant of all tested oils decreased slightly with the increase of temperature.



(a)

(b)

(c)

Figure 11 Chemical structures of: (a) palm oil, (b) silicone oil, and (c) mineral oil [17,18].

For the same temperature level, palm oil possesses the highest dielectric constant, and then followed by silicone oil and mineral oil. This experimental evidence indicates a correlation between degree of polarity and susceptibility of the oil, as well as, its dielectric constant. As the degree of polarity of a liquid is determined by its dipole moment which is a vector summation of all bond moments composing the molecule of the liquid, then the higher unbalance level of geometrical chemical structure of the molecule, the higher its polarity degree. Figure 11 shows the chemical structure of palm oil, silicone oil and mineral oil. The highest unbalance degree of palm oil molecule, as can be clearly seen from the Figure 11, leads to the highest polarity degree, and hence, it is easiest for palm oil molecule forming dipoles compare to the other oils. The molecule of palm oil in the form of dipoles is more susceptible to polarize under influenced of an electric field, so that its dielectric constant is higher than the other oils.

The higher dielectric constant value of palm oil is an advantage for more uniformly electric field. Electric field for two dielectric materials connected in series is inversely proportional to their dielectric constants. The dependence of electric field E on the dielectric constants (ε_1 and ε_2) of two dielectrics connected in series expressed by Eqs. (6) and (7):

$$\boldsymbol{E_1} = \frac{\boldsymbol{V}}{\boldsymbol{\varepsilon_1}\left(\frac{\boldsymbol{d_1}}{\boldsymbol{\varepsilon_1}}+\frac{\boldsymbol{d_2}}{\boldsymbol{\varepsilon_2}}\right)} \tag{6}$$

$$\boldsymbol{E_2} = \frac{\boldsymbol{V}}{\boldsymbol{\varepsilon_2}\left(\frac{\boldsymbol{d_1}}{\boldsymbol{\varepsilon_1}}+\frac{\boldsymbol{d_2}}{\boldsymbol{\varepsilon_2}}\right)} \tag{7}$$

Where V is applied voltage, and d_1 and d_2 are the thickness of dielectric 1 and dielectric 2 respectively.

3.3 Dissipation Factor (Tan δ)

The measurement results of dissipation factor of palm oil, mineral oil and silicone oil are shown in Figure 12.

Figure 12 shows that all tested oils possess the similar tendency of dissipation factor change to the temperature variation. The dissipation factor of all oils increased with temperature in the range of room temperature, 25^{o}C until the temperature level of 100^{o}C. Palm oil was experiencing dissipation factor change of 0.018, whereas, mineral oil and silicone oil were experiencing that of 0.023 and 0.015, respectively.

Dissipation factor (tan δ) represents the dielectric losses due to the application of an AC electric field. In insulating liquid electric conductivity represents a considerable part of its dielectric losses, in addition to the hysteresis losses due to the polarization of oil molecule. The dissipation factor (tan δ) is proportional to electric conductivity, as expressed by Eq. (8).

$$\tan\delta = \frac{\sigma}{\omega\varepsilon} \quad (8)$$

Where σ is the electric conductivity, ω is the angular frequency, and ε is the permittivity of oil. If the angular frequency and permittivity of oil and test cell system were considered constants during the experiment, then the change of dissipation factor to the temperature variation would depend on the change of the electric conductivity.

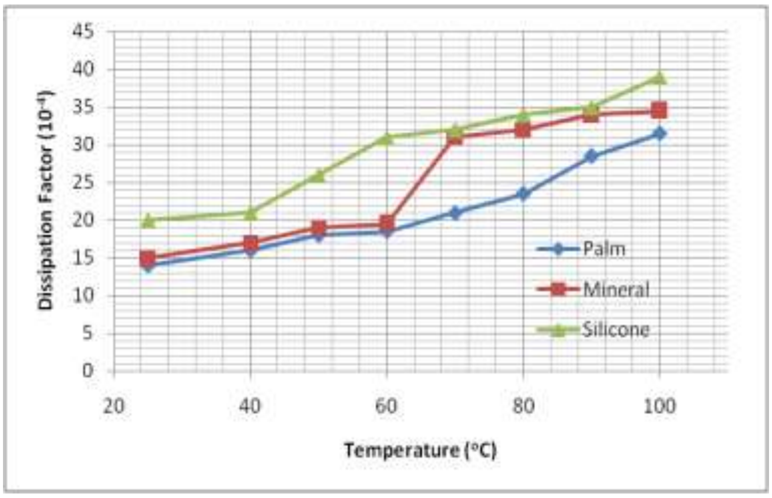


Figure 12 Dissipation factor (tan δ) of palm oil, mineral oil, and silicone oil as a function of temperature.

Electric conductivity significantly increases with the temperature as a result of both the increased dissociation of oil molecule and the decreasing oil viscosity. The electric conductivity of oil due to the dissociation of oil molecule can be expressed by Eqs. (9), (10) and (11) as below [13]:

$$\sigma = ne(\mu_+ + \mu_-) \quad (9)$$

Where σ is electric conductivity, e is electronic charge, μ is ion mobility (subscript + and – indicate the positive and the negative charge) and n is number of dissociated molecules per unit volume. Number of dissociated molecules increase exponentially with temperature as expressed by Eq. (10) below:

$$n = N\exp(-W/kT) \quad (10)$$

Where N is number of molecule per unit volume of oil, W is dissociation energy, k is Boltzmann's content and T is temperature. Hence, temperature dependent of electric conductivity can be expressed by Eq. (11) below:

$$\sigma = e(\mu_+ + \mu_-)Nexp(-W/kT) \qquad (11)$$

In addition, based on equation (12), the decreasing in viscosity also has influence on the increasing of electric conductivity of the oil:

$$\sigma = \frac{2ZC_0}{\alpha<R>\eta} \qquad (12)$$

Where σ is electric conductivity, Z ionic valance, generally is set to unity, α is constant with reasonable value of 4π, <R> is the size of charged molecule and η is viscosity. Due to the decreasing of viscosity with the increasing of temperature as expressed by Eq. (13):

$$\eta = Aexp(B/(T - T_0)) \qquad (13)$$

Where A, and B are constants, then the change of electric conductivity due to the viscosity variation mechanism can be expressed by Eq. (14) below [19]:

$$\sigma = \frac{2ZC_0}{\alpha<R>A} exp(-B/(T - T_0)) \qquad (14)$$

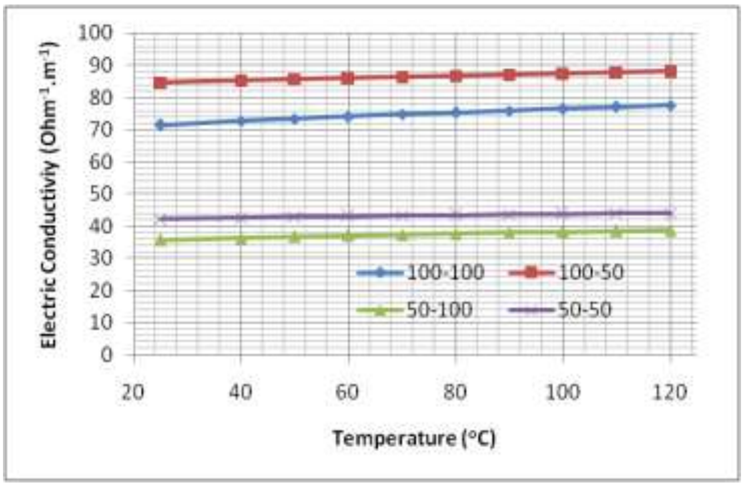
If the electric conductivity of a liquid was allowed to vary only with temperature (where $T_0 = 273^oC$), and let the other variables were constants, then the Eq. (11) and Eq. (14) were modified and they can be expressed by Eq. (15) and Eq. (16), respectively. By varying the constants value of K1 and K2 with the combination of 100-100, 100-50, 50-100, and 50-50, then the theoretical graphs of the electric conductivity of the liquid as shown in Figure 13 can be developed.

$$\sigma = K_1 exp(-K_2/T) \qquad (15)$$

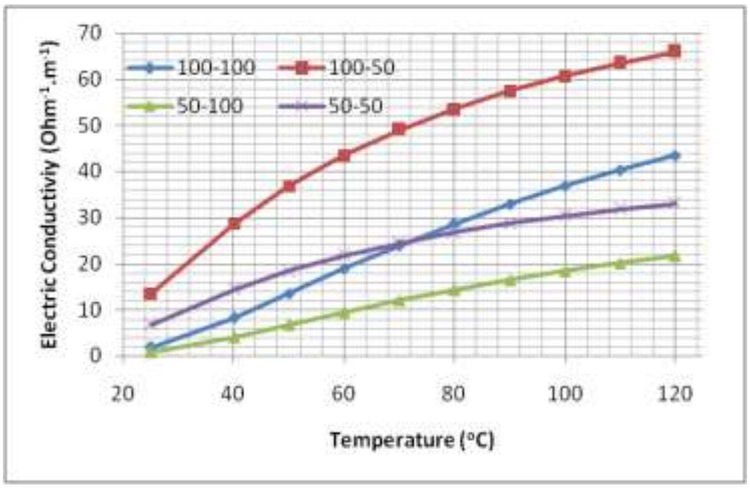
$$\sigma = K_1 exp(-K_2/(T - T_0)) \qquad (16)$$

From the theoretical graphs of the electric conductivity as a function of temperature shown in Figure 13, it can be seen that the variation of curve shape is determined by the values of K1 and K2. Choosing the 100-100 (blue color) or 50-100 (green color) as the value for K1-K2, then it can be expected to get similarity between theoretical graphs of electric conductivity and the experimental results ones for palm oil, mineral oil, and silicon oil.

Over all testing temperature range, the dissipation factor of palm oil is lower than other tested oils. This is an advantage as the palm oil possesses the lowest dielectric losses.



(a)



(b)

Figure 13 Theoretical graphs of electric conductivity of insulating liquid as function of temperature; (a) based on equation (10), and (b) based on equation (11). All variables were constant unless temperature.

4 Conclusions

Dielectric properties of palm oil, mineral oil and silicone oil under temperature variation have been investigated and compared. The results are summarized as follows:

1. Variations of dielectric properties of palm oil to the temperature change, in general, have the same tendency with those of mineral oil and silicone oil.
2. From the breakdown voltage view point, mineral oil is still the best choice for the temperature level up to 100°C. However, using palm oil seems to enhance allowable temperature loading of transformer as its breakdown voltage tends to continuously increase up to the temperature level of 120°C. Breakdown voltage of mineral oil, on the other side, started to fall at the temperature level of 100°C and became lower than that of palm oil at temperature level of 120°C.
3. For the same temperature level, palm oil possesses the highest dielectric constant. This is an advantage as the palm oil would be experiencing the lowest electric field stress if the palm oil used as an impregnation to paper insulation as the case in transformer application.
4. Dissipation factor of palm oil is lower than the other tested oils over all testing temperature range. This is also the advantage as the palm oil possesses the lowest dielectric losses.

From the above works, it is seen that the low breakdown voltage of palm oil at low temperature was due to the high water concentration contained in it. Therefore, reducing water content is one of the future tasks.

Reducing water from a viscous liquid sample can be realized through a technique called sparging. In sparging process a gaseous substance containing little or no water content is passed through a viscous liquid sample. Dissolved water in the liquid sample, where the water concentration is high, diffuses into the gas bubbles, in which the water concentration is low.

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