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ARTICLE

Comparing the Dielectric Properties of Papaya Oil with Mineral Insulating Liquid under Temperature Variation

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Abstract: The world's energy requisite has been controlled by petroleum oil for a long time in transportation, household and power sectors. Mineral Transformation Oil (MTO), being an essential insulating material in transformers, has been used for over fifteen decades. MTO application in the power sector could be hazardous to the environment, especially during a transformer explosion which may cause a spill of oil to the soil or water stream. Owing to the threat of MTO to environment aspects, alternative insulating oil with biodegradable characteristics has attracted a lot of devotions in recent studies. To validate the aptness of using Purified Papaya Seed Oil (PPSO) as an insulating fluid in an electric transformer, it is vital to compare dielectric properties of PPSO with that of MTO insulating liquid. This study presents a comparison of temperature effect on dielectric properties of PPSO with the MTO insulating liquid. Breakdown voltage, dissipation factor (tan δ) and dielectric constant were measured by existing established testing standards. The breakdown voltage was determined by IEC 156 standard test method, whereas the dissipation factor and dielectric constant were determined based on IEC 60247 standard test method. The results revealed that the variation of dielectric properties of PPSO due to temperature change was similar to that of MTO. However, the dissipation factors and breakdown voltages of dielectric properties of PPSO were better when compared with those of MTO at higher temperatures, but with a slight decrease in dielectric constants with the increase in temperature.

Keywords: Papaya seed oil, Dissipation factor, Dielectric constant, Breakdown voltage, Temperature, Transformer.

PACS: 77.84. Nh, 88.05. Lg.

Introduction

Power transformers are indispensable fragments to power-transmission setups [1]. Most of the problems that arouse in them were associated with the weakness and defects of the insulation materials. About fifty percent of transformer failure's costs are initiated by dielectric, insulation and oil-associated faults [2]. The necessity for superior dielectrics and transformer oils for insulation is undisputable. For liquid-filter transformers, the insulating fluid plays a vital role by offering electrical insulation and transferring thermal losses to the cooling system. Insulating fluid in transformer must warrant the transfer of heat, which is achieved by thermal conductivity and convection [3]. Three types of insulating fluids are currently in use; namely, mineral oils, synthetic oils and natural esters [4]. The usage of each fluid type is

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stimulated by the area of application. In spite of the rising call for the utilization of environment-friendly materials, more researches are ongoing on developing especially natural esters for use as insulating fluids in power transformers.

Mineral oils produced from crude petroleum are the most utilized insulating and cooling fluids in electrical transformers. These oils are considered as flammable and since they are petroleum products, they cause harmful effects to the environment, particularly when there are incidents such as transformer explosions when operational, which might cause a spillage of oil to the soil or water stream. A good insulating oil must satisfy the following minimum requirements: being biodegradable, non-toxic, recyclable, thermally stable, readily disposable and not be listed as a hazardous fluid [5]. Mineral oils are acknowledged as possessing low biodegradability with high vulnerability to fire. These factors motivated many researchers to strive for alternative sources of transformer-insulating oils. According to many researches, vegetable oil is considered to be the most potential source to replace mineral oil. The merit of using vegetable oil, also called natural ester, is its non-toxic properties. The only products formed during the biodegradation process are water and carbon dioxide. Esters are also less flammable with about 300°C as minimum flash point. Banumathi and Chandrasekar [6] wrote that paper absorption of water in natural ester oils is significantly lower when compared with mineral oils. Natural ester oil also showed a better performance compared to mineral oil after accelerated aging test, which permits it to prolong the life time of natural ester than mineral oil immersed in the transformer [7, 8].

Papaya fruit is an edible fruit which is also used for the manufacture of cosmetics. Papaya fruit is a fruit available throughout the year with only a little fraction used as seed crop, leaving the rest to rot away as waste. Patel and Nayak [9] wrote that papaya fruit seeds are thrown away as a bad practice. Humans or animals consume about 15% of the fruit and the oil content in the seeds is about 30.7% [10]. Compared with 19.63% for soybean oil and 22.23% for sunflower seeds oil, papaya has a great prospect if developed as feedstock for bio-transformer production. Papaya is currently cultivated in Hawaii, Florida, Eastern British Africa, Sri-Lanka, South Africa, India, Malaysia, the Canary Islands and Australia. It is now present in every tropical and sub-tropical country of the world. Since the usage of papaya seed oil for cooking is not visible as a result of benzyl isothiocyanate carcinogenic compounds, its availability as an uneatable oil is an advantage, being not in competition with food. Insulating oil in transformers, undergoes temperature variations owing to the fluctuating nature of electricity consumption. Vegetable oil that will be used as a transformer oil should be capable of bearing the maximum tolerance level of temperature variation of 110°C at the transformer windings [5], devoid of losing its dielectric properties for use in high-voltage transformers. To validate the appropriateness of using papaya oil as an insulating fluid, it is imperative to compare the dielectric properties of papaya oil with those of the frequently used insulating liquids that are mineral oils. This paper compares the dielectric properties of papaya oil with those of mineral oils, under temperature variation ranging from room temperature, 25°C up to 100°C or 120°C.

Material and Methods

Experimental Procedure

Papaya fruits were obtained from Ogbomoso, Nigeria. The fruits were cut into two halves and the seeds were removed, dried in an oven at 60ºC for 24 hours, ground into powder and the oil was extracted using the soxhlet extraction method with n-hexane as a solvent. A modified Dijkstra and Opstal purification method used by Abdelmalik et al., [11] and Oyelaran et al, [12] was adopted for the purification of the oil to obtain the refined papaya seed oil. An amount of 200 ml of papaya seed oil (PSO) was heated in a 500 ml conical flask to 70°C and 8 volume % of 64 volume % aqueous citric acid solution was gently added and mixed vigorously for 15 minutes with a magnetic stirrer. An amount of 4 ml of 8 volume % NaOH solution was gently added and stirred at 400 rpm for 15 min. The mixture was then dried for 30 minutes in a vacuum oven at 85°C to reduce the water content. To the mixture, an amount of 2 g of silica gel was added at 70°C and stirred at 300 rpm for 30 minutes to avert settling. Fuller's earth was again added and stirred continuously for 30 min at 8 wt %. The sample was then filtered in a vacuum oven at 85°C with filter paper.

Degumming Process

The degumming process was carried out using the method of Sutapa et al, [13] by adding 20% phosphoric acid at 0.5% (w/w) of oil. After heating for 15 minutes at 80 ºC, the oil was then separated from the phosphatide compound and washed with warm distilled water and the oil was then dried with a vacuum dryer to obtain purified papaya seed oil (PPSO).

Characterization of PPSO

Some of the physicochemical properties of PPSO were determined using methods described by the American Society for Testing and Materials. Properties, such as kinematic viscosity, flash and fire points and cloud point of PPSO, were ascertained following ASTM D445 and ASTM D93 standards, respectively.

Flash Point and Fire Point

Pensky-Martens closed-cup tester was used to measure the flash point in accordance to ASTM D 93 standard [14]. The brass test cup fitted with lid was filled with 50ml of the sample. The container with the sample was heated under stirring at specified rates with flame test carried out at regular intervals until a flash spreading inside the cup was realized for a second. The resultant temperature at which the flash spreads throughout the cup is the flash point of the sample. The fire point on the other hand is the temperature at which the flash is sustained for more than five seconds after ignition by open flame.

Viscosity Determination

Brookfield viscometer with the appropriate spindle was used to measure the viscosity of the liquid sample in accordance with ASTM D445 [15]. Viscosity aids in the heat-convection process in the transformer. The lesser the value of viscosity, the greater the heat-transfer rate in the transformer [12].

Breakdown Voltage

The measure of an insulating fluid capability of withstanding electric stress without failure is known as dielectric breakdown voltage. It is also an indication of the presence of contaminating agents, such as air bubbles, water, cellulosic fibers, dirt or conducting particles in the fluid. The IEC 60156 standard was used to measure the breakdown voltage with a kit voltage capacity of 60 kV. The experiment was carried out with spherical head electrodes of standard diameters and a gap of 2.5 mm between them. An amount of 500ml of the sample oil was filled up to 40mm level above the electrodes. Bubbles in the container were allowed to settle about 5 – 15 minutes after filling of the sample before increasing the test voltage at a rate of 2 kV/s. Application of voltage was started at least 5 minutes after pouring the mineral-oil sample into the test chamber [16] and about 15 minutes for papaya oil [5]. The delay time is required to guarantee that gas bubbles which formed during the pouring process have been expelled completely before the commencement of measurements. The measurements were performed six times with a time delay between two successive measurements of at least 2 minutes for mineral oil [16] and 6 minutes for papaya oil. The delay time after measurement was also carried out to allow breakdown of products to disperse and gas to expel, before succeeding measurement was conducted so that the later measurement was not influenced by the previous one [17]. The longer delay time for papaya oil was due to the higher viscosity of the oil than that of mineral oil.

In order to study the temperature effect on the breakdown voltage of oils, measurement was carried out at different temperatures. The temperature was raised up to 120℃ with 10℃ increment. The temperature was kept relatively constant using temperature sensors embedded on the oil chamber’s wall, heater, blower, controller and contactor as a temperature-control system. The temperature of the liquid is detected by the temperature sensor. Upon receiving information sent by the temperature sensor, the controller commands the contactor to connect or disconnect the electric heater from the power supply. The blower helps reduce the temperature when the temperature is higher than required.

Dielectric Constant and Dissipation Factor Measurements

The IEC 60247 standard [18] with Schering circuit test and null indicator oscilloscope was used to measure the dielectric constant and dissipation factor of oils, as schematically shown in Fig. 1. The *Schering* circuit balance is shown by the presence of Lissajous curve as a straight-line display on null indicator. The oil sample from Tettex Instruments was poured into the test cell. The test cell is a three-terminal test cell that forms a capacitance system with liquids or gases as dielectrics. To monitor the temperature, the test cell has an electric heater and a thermometer with it. Since the test cup is made of stainless steel, the mass of the test cell is relatively higher than that of the oil sample; hence, the temperature was varied in reverse order. After heating the oil to 100°C, the temperature of oil was allowed to decrease to each temperature level. After a reduction of 10°C, the capacitance and dissipation factor of oil were then measured.

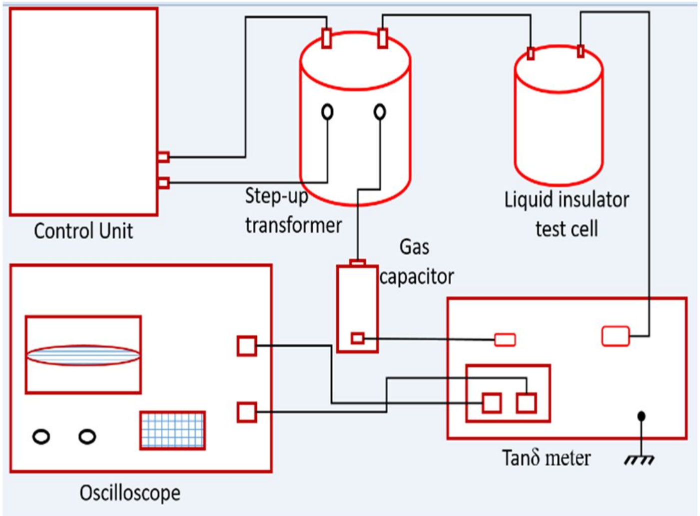

FIG. 1. Schematic diagram of dielectric constant and dissipation factor measurements.

Results and Discussion

Kinetic viscosity	3.57	mm^2/s	ASTM D445
Flash point	389	K	ASTM D93

Breakdown Voltage

Breakdown voltage of all tested oils was measured at 25°C up to 120°C with six measurements carried out at each temperature level. The mean values of the measurements are shown in Fig. 2. The breakdown value significantly increases with temperature rise up to 70°C. This is a result of the relative decrease in water content of oils. It is a known fact that the breakdown voltage of all insulating fluids is inversely proportional to their relative water content [19, 5]. The ratio between absolute water content (wt_{abs}) and water solubility (wt_l) of oil is the relative water content (wt_r) of oil, which is mathematically expressed by Eq. (1). The water solubility in oil on the other hand increases with temperature, as established in Eq. (2).

$$wt_r = \frac{wt_{abs}}{wt_l} \times 100\% \tag{1}$$

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

where, wt_0 and H are the oil parameters. The values of wt_0 and H for papaya oil and mineral oil are 2.61 x 10^5 and 1340 and 19.2 x 10^6 and 3805, respectively [18, 5]. The graphical relationship between water solubility and absolute temperature of papaya oil and mineral oil is shown in Fig. 3.

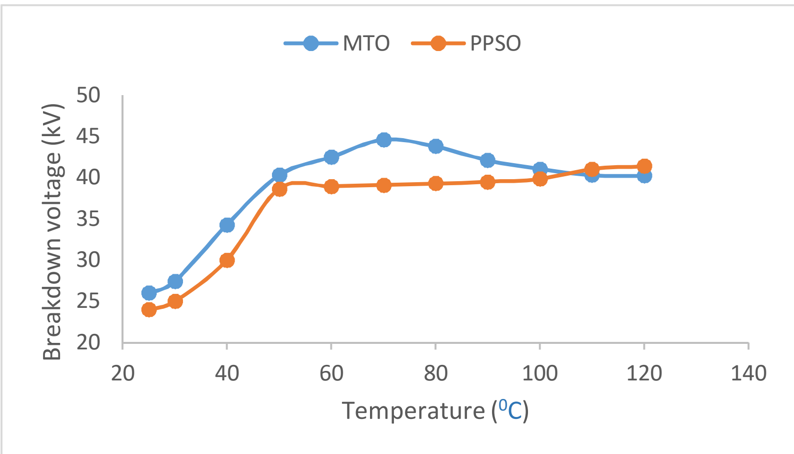

FIG. 2. The mean values of breakdown voltage of papaya oil and mineral oil as functions of temperature.

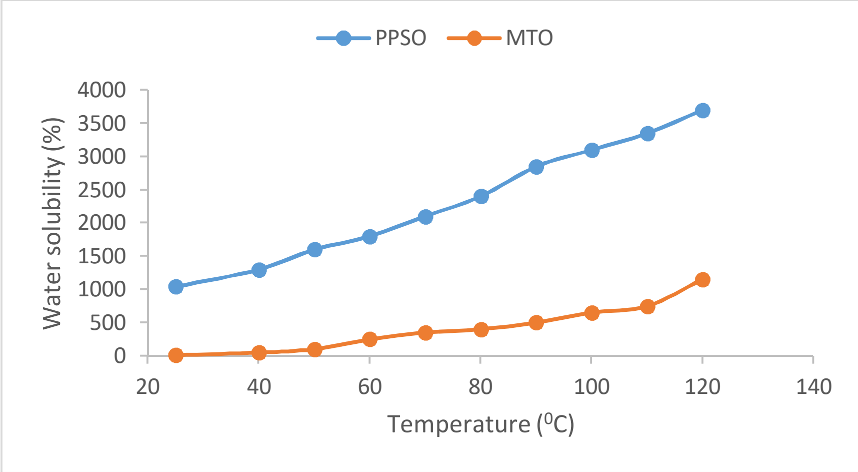

FIG. 3. Water solubility of papaya and mineral oils as a function of temperature.

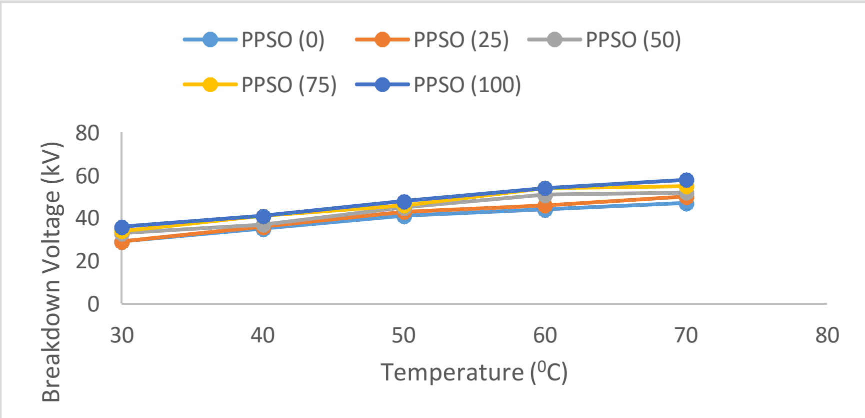

FIG. 4. Breakdown voltages of a mixture of papaya and mineral oils as a function of temperature.

Increasing the temperature causes a substantial reduction in the relative water content of the oil, resulting in raising the breakdown voltage of the oil. A similar trend was reported by Suwarno and Irawan [19] and Rajab et al. [5], who performed breakdown voltage measurements on a mixture of papaya and mineral oils under temperature variation, ranging from 30 to 70°C, as displaced in Fig. 4.

The existence of water in oil affects the breakdown voltage of oil in two ways; by forming water clusters and being absorbed by particles making them conductive particles [20]. As temperature increased, water in the form of water clusters in oil reduced due to increase in temperature, triggering a slow breakdown voltage increase in the oil. This was clearly revealed by papaya oil at temperatures up to about 50°C and about 40°C for mineral oil, as seen in Fig. 2. The relative water contents of papaya and mineral oils under temperature variation range of 25 to 120°C are shown in Fig. 5. Additional rise in temperature resulted in water being absorbed by particles to reduce the substantial rise in the breakdown voltage of the oil. Between 50 and 70°C, papaya oil experienced changes, while mineral oil experienced changes between 40 and 70°C. However, breakdown voltage of dry liquid is relatively unaffected by temperature variation [5]. This was experimentally shown by mineral oil, as displayed in Fig. 2, which is relatively unaffected in the temperature range between 70 and 90°C. However, this happens for dry liquid at a temperature a little below the boiling point. Here, breakdown voltage of dry liquid begins to go down as a result of the formation and growth of vapor bubbles [5]. From Fig. 2, it can be seen that mineral oil experienced this stage, where its breakdown voltage begins to fall at 100°C. Owing to the higher boiling point of papaya oil, the oils need to be heated further to achieve this condition.

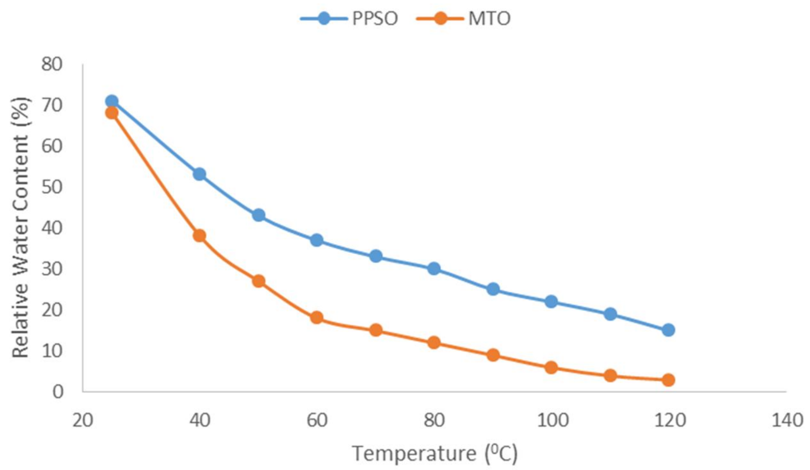

FIG. 5. Relative water content of papaya and mineral oils as a function of temperature.

From the results obtained, mineral oil is better for temperatures up to 100°C from the breakdown voltage point of view. However, using PPSO appears to enable improving allowable temperature as its breakdown voltage appears to constantly rise up to the temperature of 120°C. At this point, breakdown voltage of papaya oil is higher than that of mineral oil. From the breakdown voltage trend of the tested oils, one can assume that beyond 120°C, the breakdown voltage of papaya oil will be considerably higher than that of mineral oil. However, the assumption cannot be proved experimentally now, as a result of the oil chamber design limitations.

Dielectric Constant

The dielectric constant of oil is the ratio of capacitance of oil-filled test cell to that of empty cell, as shown mathematically by Eq. (3) [19]. The results at different temperatures in the range of 25 up to 100°C are shown in Fig. 5.

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

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

From Fig. 6, it can be seen that the variation of the dielectric constant of papaya and mineral oils due to temperature change is the same. The dielectric constant of papaya oil slightly decreased from 3.25 at 25°C to 3.10 at 100°C, while the dielectric constant of mineral oil decreases from 2.35 to 2.22 for the same temperature range.

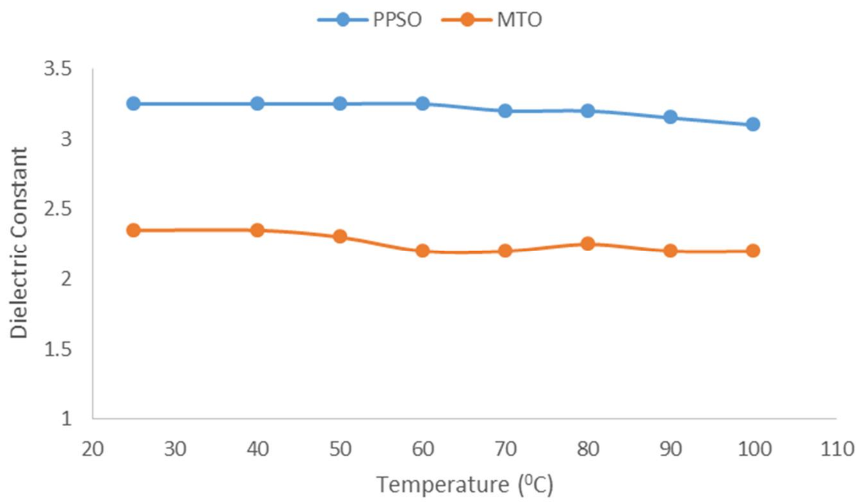

FIG. 6. Dielectric constants of papaya and mineral oils as functions of temperature.

The dielectric constant of any dielectric material refers to its susceptibility (Eq. 4), which is a measure of how easily a dielectric polarizes in reaction to an electric field, as shown mathematically in Eq. 5. Likewise, permittivity is proportional to polarization as susceptibility [21].

$$\varepsilon_r = \chi + 1 \quad (4)$$

$$P = \chi\, \varepsilon_0 E \quad (5)$$

where ε_r is the dielectric constant, χ is the susceptibility, P is the polarization and E is the electric field.

When an electric field is applied to a dielectric material, dipoles inside the material that are originally random are directed in the same direction of the applied electric field. Increasing the thermal agitation owing to the temperature increase will make it more difficult for the dipoles to orient [22]. The difficulty of polarization shows the decreases of permittivity and susceptibility based on Eq. 5 for a constant magnitude of electric field. Hence, we can agree that the dielectric constants of tested oils decreased slightly with the increase in temperature.

At the same temperature, papaya oil has a higher dielectric constant than mineral oil. This experimental proof shows a correlation between susceptibility, degree of polarity of the oil and its dielectric constant. Note that the degree of polarity of a fluid is determined by the vector summation of all bond moments comprising the molecule of the fluid; hence, the higher the unbalance level of geometrical chemical structure of the molecule, the higher its degree of polarity. It is easier for papaya-oil molecules to form dipoles compared to mineral oil as a result of its highest degree of unbalance, leading to the highest degree of polarity; hence, it is easier for papaya oil molecules to form dipoles compared to mineral oil molecules. Therefore, papaya oil is more susceptible to polarize under the effect of an electric field, making its dielectric constant higher than that of mineral oil.

The higher value of papaya oil dielectric constant is a merit for a better uniform electric field. When two dielectric materials are connected in series, the electric field is inversely proportional to their dielectric constants. The dependence of electric field E on the dielectric constants ($\varepsilon_1$and ε_2) of two dielectrics connected in series is expressed by Eqs. 6 and 7.

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

$$\boldsymbol{E}_2 = \frac{V}{\varepsilon_2 \left(\frac{d_1}{\varepsilon_1} + \frac{d_2}{\varepsilon_2}\right)} \quad (7)$$

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

Dissipation Factor (Tan δ)

Fig. 7 shows the results of dissipation factor of papaya and mineral oils. From the results obtained, all oils show a similar trend of dissipation factor with temperature variation. From 25 to 100°C, there is an increase in the dissipation factor of all oils. For papaya oil, the increase is from 0.013 to 0.033 and for mineral oil, the dissipation factor changes from 0.025 to 0.035. Dissipation factor (tan δ) refers to the dielectric losses owing to an AC electric field application. Electric conductivity in insulating liquids denotes a substantial part of their dielectric losses, besides the hysteresis losses owing to the polarization of oil molecules. Dissipation factor (tan δ) is proportional to electric conductivity, as shown in 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. The change in dissipation factor due to temperature variation will depend on the change of the electric conductivity when the angular frequency and permittivity of oil and test cell system are considered constants.

The electric conductivity considerably increases with increasing temperature due to decreasing oil viscosity and increasing dissociation of oil molecules. The electric conductivity of oil owing to the oil molecule dissociation is mathematically expressed in Eqs. 9, 10 and 11, as shown below [23]:

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

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

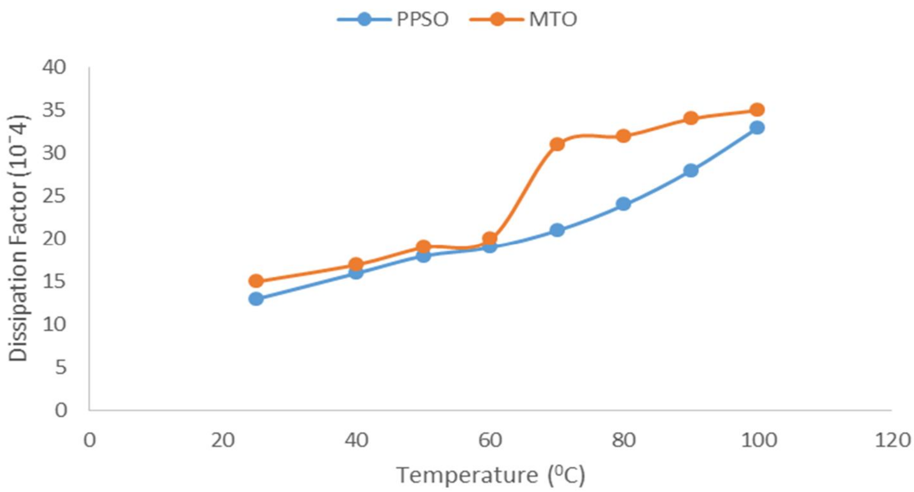

FIG. 7. Dissipation factor (tan δ) of papaya and mineral oils as functions of temperature.

$$n = Nex\,(\frac{-W}{kT}) \tag{10}$$

where N is the number of molecules per unit volume of oil, W is the dissociation energy, k is the Boltzmann's content and T is the temperature. Therefore, temperature dependent of electric conductivity might be mathematically expressed as in Eq. 11.

$$\sigma = e(\mu_+ + \mu_-)\, Nexp\,(\frac{-W}{kT}). \tag{11}$$

Furthermore, established on Eq. 12, the decrease in viscosity also has an impact on the increase of electric conductivity of the oil:

$$\sigma = \frac{2ZC_0}{a<R>\eta} \tag{12}$$

where σ is the electric conductivity, Z the ionic valance, usually set to unity, α is a constant with reasonable value of 4π, <R> is the size of charged molecule and η is the viscosity. As a result, decreasing viscosity with the increase of temperature is shown mathematically in Eq. 13.

$$\eta = Aex\,(\frac{-B}{T - T_0}). \tag{13}$$

When A and B are constants, the change of electric conductivity due to the viscosity variation mechanism can be mathematically expressed in Eq. 14. [24].

$$\sigma = \frac{2ZC_0}{a<R>\eta} exp\,(\frac{-B}{T - T_0}). \tag{14}$$

If all variables are constants and only electric conductivity of a liquid is variable only with temperature (where T_0 = 273°C), then Eqs. 11 and 14 can be expressed in a modified form as Eqs. 15 and 16, respectively. By changing the constants' values of K1 and K2 with the combination of 100-100, 100-50, 50-100 and 50-50, the theoretical graphs of the electric conductivity of the liquid as shown in Fig. 8 and Fig. 9 can be developed.

$$\sigma = K_1 \exp(\frac{-K_2}{T}) \tag{15}$$

$$\sigma = K_1 \exp\left(\frac{-K_2}{T - T_0}\right). \tag{16}$$

From the theoretical graphs of the electric conductivity as a function of temperature shown in Fig. 8 and Fig. 9, 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 values for K1-K2, it can be expected to get similarity between the theoretical graphs of electric conductivity and the experimental results for papaya and mineral oils. Over all the testing temperature range, the dissipation factor of papaya oil is lower than that of mineral oil. This is an advantage as the papaya oil possesses the lowest dielectric losses. Fig. 8 and Fig. 9 show the theoretical graphs of electric conductivity of PPSO as functions of temperature based on Eq. 10 and Eq. 11, respectively, taking all variables as being constant except temperature.

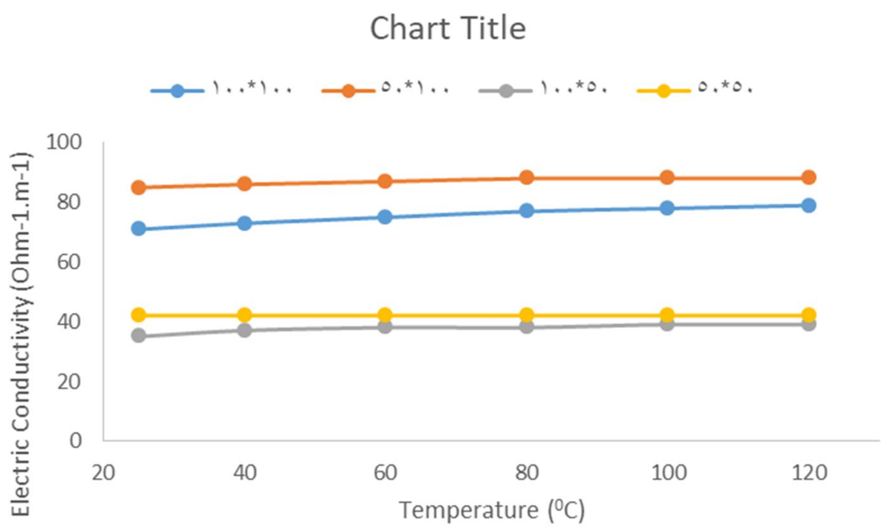

FIG. 8. Theoretical graphs of electric conductivity of insulating liquid as a function of temperature based on Eq. 10, taking all variables as being constant except temperature.

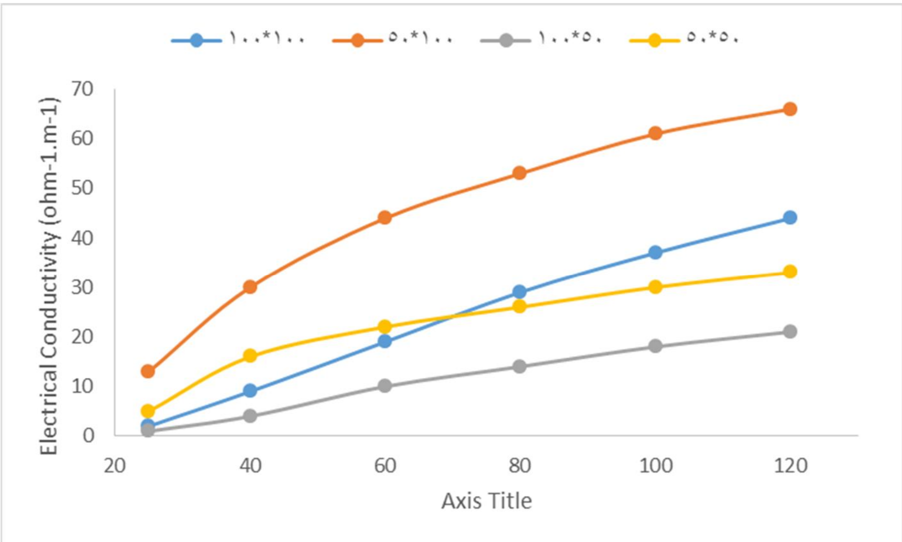

FIG. 9. Theoretical graphs of electric conductivity of insulating liquid as a function of temperature based on Equation 11, taking all variables as being constant except temperature.

Conclusions

Dielectric characteristics of papaya oil and mineral oil have been investigated and compared under temperature variation. The results reveal that both oils have the same variation tendency of dielectric properties under temperature change. Mineral oil possesses better breakdown voltage properties for temperatures up to 100°C. However, the use of papaya oil appears to boost permissible temperature loading of transformers, as the papaya oil breakdown voltage tends to increase continuously up to 120°C, while that of mineral oil starts to fall at 100°C, becoming lower than that of papaya oil at 120°C. For the same temperature level, papaya oil possesses the higher dielectric constant than mineral oil at the same temperature. This is a benefit, since papaya oil will be experiencing lower electric field stress if used as an impregnation to paper insulation for transformer applications. Papaya oil possesses the lowest dielectric losses, since it possesses lower dissipation factor than mineral oil over all temperatures tested. As seen in this research, the low breakdown voltage of papaya oil at low temperatures was due to the high content of water in it. Hence, reducing water content to the barest minimum is a future task.

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