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Dielectric Characterization of Calabash Seed Oil as Substitute for Mineral Oil in Power Transformers

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Abstract:- Mineral oil used in electrical applications for insulation and heat transfer has a high flammability rate and is non-biodegradable and thus dangerous for the environment. This work is aim to examine the dielectric properties of oil based on calabash seeds as a substitute for mineral oil in power transformers. The dielectric properties such as permittivity, conductivity and dielectric losses were measured and the influence of temperature and frequency factors on these is highlighted. Dielectric spectroscopy is the main characterization method used throughout this study. The results show that calabash oil has a higher dielectric constant (permittivity) than mineral oil. Dielectric constant and dielectric loss of the studied oil decrease with the increase in the temperature. Also, calabash seeds oil has a lower conductivity at low temperatures. It is suggested that calabash oil be used as a substitute for mineral oil in power transformers.

Keywords:- *Calabash oil; dielectric properties; power transformer; mineral oil; electrical insulation.*

I. INTRODUCTION

Dielectric oils are increasingly used in electrical applications (transformers, capacitors, circuit breakers, etc.), providing not only electrical insulation but also cooling and even information support functions. For their proper functioning and by nature, transformers have active parts at different potentials that must be insulated from each other and cooled. Thanks to their better physical-chemical and dielectric properties and their low cost, mineral oils are the most commonly used in liquid power transformers [1]. Indeed, mineral oil is a good thermal conductor, and its circulation through heat sinks allows the evacuation of heat produced by coils and the magnetic circuit of the transformer. It also allows the dielectric insulation of windings between them. However, because of its low resistance to fire [2] and its non-biodegradability leading to adverse effects on the environment, several studies were conducted to find alternative oils. It was partially replaced by non-flammable liquids such as polychlorinated biphenyls (PCBs) between the 1930s and 1970s [3]. However, because of it pollutes, harms humans, animals and the environment, PCBs have been banned [4].

In order to fight flammability and pollution (ecological reasons), and for economic reasons (depletion of oil resources, gradual increase in its price), many researchers have embarked on the quest for substitute oils. Thus, substitute oils have been developed in recent decades, such as silicone oils, synthetic and vegetable ester oils [4]. Due to their biodegradability and above all their renewable character, vegetable oils are becoming more and more popular as an alternative to mineral oil in processors. Danikas and Sarathi [5] have conducted a literature review on vegetable oils already studied as a substitute of mineral oil in transformers. They concluded that although vegetable oils seem to be promising candidates as replacements of transformer oil, further experimental work must be done. Milan Spohner et al [6], studied the properties of vegetable oils and their constituents and concluded that these natural oils can be used as substitutes for mineral oils. Oyelaran et al. [7], showed that papaya seed oils can be used as an alternative raw material for the production of bio-transformers, although they did not evaluate the dielectric properties such as dielectric constant, dielectric loss and conductivity. Other work has shown that vegetable oil is a good substitute to mineral oil because it is biodegradable, non-toxic and has high fire/flash points, which ensures greater safety in service [8-9].

Despite vegetable oils are a good alternative to mineral oil, they come from increasingly edible vegetable sources all over the world. Many studies have been conducted on dielectric properties of vegetable oils used in household consumption such as peanut, palm oil [10], rapeseed, sunflower [11], olive, castor [12]. Price inflation will therefore be a given insofar as there will be a risk of conflicts with households. A biodegradable and inedible oil suggested as a substitute to mineral oil in transformers is that from the calabash seed scientifically known as *lagenaria siceraria*. It is a creeping plant that produces large spherical fruits commonly found in central Africa region. The centre is filled with seeds that has oil. The seeds are harvested, cold pressed and filtered to obtain clear oil. The dried fruits are used to make various traditional objects, including kitchen utensils (containers, gourds, cases), floats or musical instruments (kora, maracas, sanza, sitar among others). Among the traditional uses, let us quote the manufacture of penis cases among certain tribes of New Guinea or Africa, the brewing and transportation of traditional beers, as well as the preparation of mate. In many countries, calabashes are used for artisanal purposes. Countries that cultivate gourds, such as Cameroon, have great advantages in that they have virgin land that facilitates the cultivation of these products in large quantities. In Cameroon, calabashes are more used to make kitchen objects and ornaments.

Very few studies have been devoted to calabash oil. Olatunde et al [13], have studied this oil as an industrial application, especially for transformers use. But only, they limited themselves much more to the determination of the physicochemical properties from which they concluded that this oil would be a substitute to transformer oil. As far as the dielectric parameters are concerned, only the dielectric strength was evaluated. However, the dielectric characteristics such as permittivity, conductivity and loss angle are also essential for the selection of transformer oil. The resistivity, for example, is one of the important parameters to guarantee the quality of the transformer oil and to increase the efficiency of the transformer operation [14].

The objective of this work is to assess the dielectric properties of calabash seed oil as substitute of mineral oil in power transformers. Thus, the permittivity, dissipation factor, and the conductivity of the calabash oil were examined. The results were compared to those obtained in previous works. To simulate working conditions as well as critical situations in transformers, the temperature was varied between -30 and 60 °C along with variations of the frequency.

II. MATERIAL AND METHOD

A. Sample preparation

The calabashes were harvested in the West region of Cameroon; the fruits are picked after ripening and the seeds are extracted. Then, they are cleaned, rid of the remains of gangues and of some residual skins. Afterwards, it's proceed to a heat treatment stage, prior to the oil extraction phase, which consists in drying the seeds, which will facilitate shelling. The first step in processing these seeds is therefore dehulling to separate the seeds from the pods. This can be done by hand or with the help of a huller. After removing the tegument that surrounds the seeds, they are a little heated and then crushed and reduced to a paste between the wheels of a mill. The paste obtained is then pressed; the oil is filtered at several levels and heated to 70°C to eliminate the esters (waste and water molecules).

B. Dielectric properties to be measured

The dielectric properties to be measured are: relative permittivity, loss factor or loss angle and conductivity.

➢ *Relative permittivity or dielectric constant*

Under the effect of an electric field, a displacement of the charges composing the dielectric fluid is observed causing a polarization mechanism. The dielectric response of a material is modeled by the following equation (1) where ε represents the absolute complex dielectric constant, ε' the real part representing the dielectric constant and ε" the imaginary part representing the dielectric losses [15]:

$$\varepsilon = \varepsilon' - j\varepsilon'' \quad (1)$$

The absolute permittivity ε is the product of the relative permittivity ε_r and the vacuum permittivity ε_0 ($\varepsilon_0 = 8.85.\ 10^{-12}$ F/m):

$$\varepsilon = \varepsilon_r . \varepsilon_0 \quad (2)$$

In the case of a perfect dielectric, ε_r is the quotient of the capacitance C_x between two electrodes, assumed to be embedded in this dielectric (oil-filled capacitor), by the capacitance C_v of the same electrode configuration in vacuum. The relative permittivity is given then by:

$$\varepsilon_r = \frac{C_x}{C_v} \quad (3)$$

The permittivity of mineral oil is about 2.2 and that of vegetable oils about 3.1, the dissolution and dissociation of impurities will be greater in vegetable oils than in mineral oils. [16].

➢ *The dissipation factor*

The dissipation factor is a measure of the dielectric losses in an electrically insulating fluid in an alternating electric field and the energy dissipated as heat. The dissipation factor or loss factor (tgδ) is directly related to the resistivity and permittivity in AC voltage. The representation of these losses by an equivalent diagram of capacitor C and resistor R in parallel allows to write:

$$tg\delta = \frac{1}{R.C} \quad (4)$$

➢ *Conductivity/resistivity*

Moreover, to be electrically insulating, a liquid must conduct as little electric current as possible when a voltage is applied to it. Its conductivity σ must therefore be as low as possible or conversely its resistivity ρ (Ω.m) must be as high as possible (ρ=1/σ). The conductivity of an insulating liquid is due to the presence of free charges. Under the effect of an electric field, these charges move causing conduction current. The higher the temperature, the lower the viscosity of the liquid and the greater the mobility of the ions [17].

C. Experimental set up

The goal of this investigation is to assess the dielectric properties of the calabash seeds oil. The device used for dielectric spectroscopy is a frequency response analyzer Novocontrol BDS20. The experimental setup is shown in *Fig.1*. The measuring cell was placed in a temperature-controlled chamber that enabled temperature variations. A sample of the investigated liquid with a volume of 50 ml was applied to the prepared electrode cell. The available frequency range of the device is from 3μHz to 10 MHz with a maximum applied voltage of 1 V. The measurement limit in tgδ is approximately $3\text{x}10^{-5}$ for measurements in the range between 10Hz - 100 kHz and for a capacitance between 50pF – 2nF. The dielectric parameters were evaluated with respect to their changes in the AC field with frequencies from 50 MHz to 100 kHz and temperatures from -35 °C to 60 °C. After each measurement, the test fluid is changed, the electrode system is cleaned of waste oil and then placed in a dryer for about 1 hour to complete eliminate water particles.

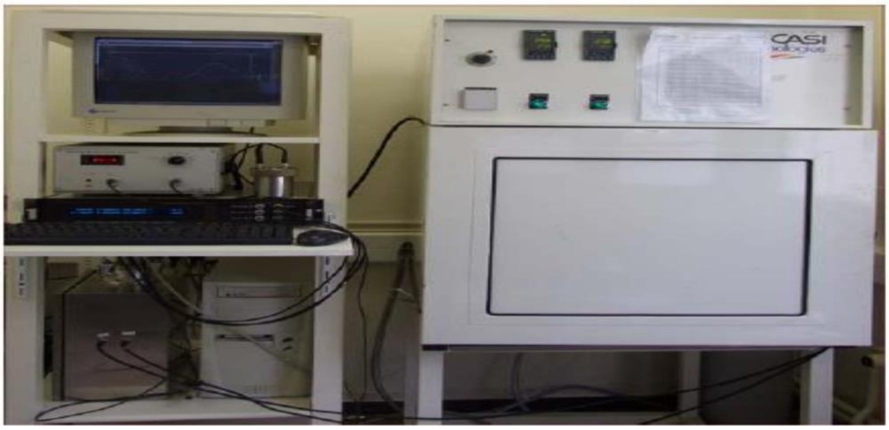

Fig. 1: Devices for measuring the dielectric properties and conditioning of oil

D. Principle of the measurements

The principle here is that of dielectric spectroscopy. Dielectric spectroscopy (DS) also called impedance spectroscopy, is widely used to study the response of a sample subjected to an applied electric field, fixed or variable frequency [18]. Dielectric spectroscopy is the most reliable frequency analysis tool to highlight the relaxation and conduction phenomena that occur at the microscopic scale in an insulating polymer. DS is a universal and powerful tool to study soft matter, whose principle is to determine the complex permittivity as a function of the frequency of the soft matter [19].

The principle of impedance spectroscopy is therefore based on the application of a sinusoidal voltage and the analysis of the amplitude and phase shift of the current response of the material. DS can be used in very low frequency ranges (µHz), what is useful to know is the state of the different interfaces existing between insulation components, up to very high frequencies (THz) [20]. It provides information about the molecular dynamics as well as important material parameters such as the static dielectric permittivity (ε) and the DC electrical conductivity [21].

III. RESULTS AND DISCUSSION

A. Study of the permittivity

- *Dielectric spectrum*

Fig. 2 below show a typical spectrum of the real ε' and imaginary ε″ parts of complex permittivity of calabash seeds oil over a wide range of frequencies (10^{-3}-10^{7} Hz) at room temperature 20°C. The real part of the permittivity presents very slight frequency dependence in the considered frequency range.On the other hand, the imaginary part displaysa more frequency-dependent behavior.

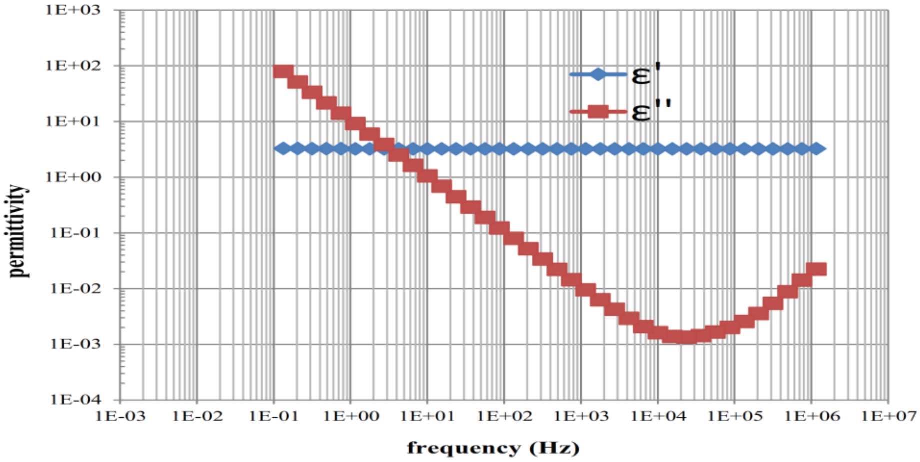

Fig. 2: Spectrum of the real ε' and imaginary ε″ parts of permittivity of calabash seeds oil.

- *Frequency spectrum of the permittivity of calabash oil for different temperatures*

Fig. 3 display frequency dependence of the real part of complex permittivity of calabash oil at temperatures from -35°C to 60 °C with step 5 °C. The dielectric spectroscopy allows to obtain results over a wide frequency range. Within the studied frequency range, the permittivity decreases with increasing temperature and frequency. *Fig. 3* shows that in the ultra-low frequency area, a very fast decrease in the real permittivity component value is observed for negative temperatures. In the area from about 1 HZ to about $3x10^{5}$ Hz, depending on the temperature, the rate of reduction slows down. The decreasing value of the dielectric constant is explained by the fact that, when the temperature increases, the interaction between the molecules weakens. It can be assumed that as the temperature increases, the viscosity of the oil decreases. The increase in temperature also leads to an increase in the kinetic energy of the moving segments leading to a greater chance of movement and therefore, decreases the orientation of the dipole, which results in a lower dielectric constant [14]. The higher the permittivity, which in fact represents the dielectric constant, the better the oil. Indeed, for a low dielectric constant, the electrical stresses of industrial systems are higher. The results obtained show that the permittivity of calabash seeds oil behaves like mineral oil in that it decreases with increasing temperature and frequency [22].

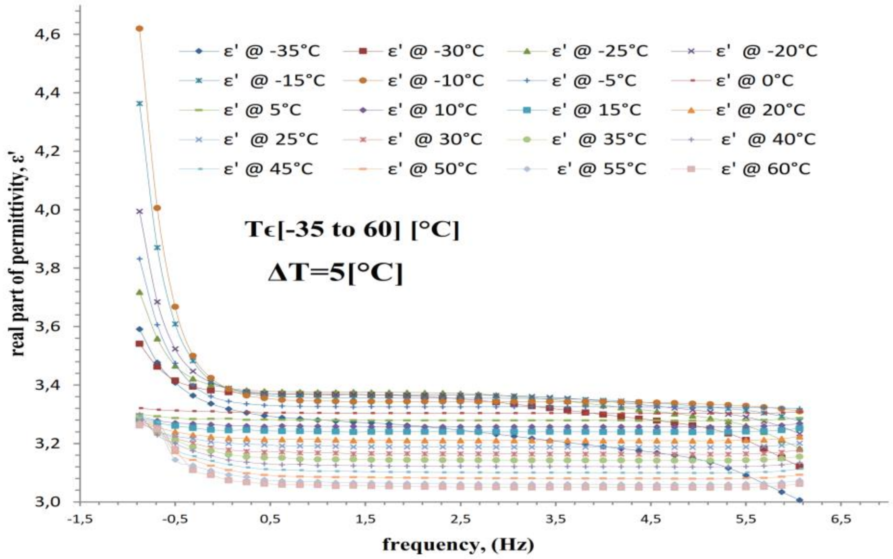

Fig. 3: Frequency dependence of the real part of complex permittivity of calabash oil for different temperatures

B. *Study of dielectric losses (tgδ)*

- *Influence of the frequency*

The dissipation factor or dielectric loss (tgδ) measures the inefficiency of insulating materials. Frequency dependence of tgδ in calabash seed oil from calabash at room temperature 20 ° C is shown in Fig. 4 and Fig. 5. When the variations of the ratio ε″/ε'=tgδ as a function of frequency are plotted in logarithmic coordinates, highlighting the tangents at the different slopes, two linear branches of slope -1 (for f <1 kHz) and +1 (f>10kHz) are obtained. The intersection of these two branches forms a minimum at frequencies of the order of 10^4 Hz. At low frequencies, the relationship in 1/f is specific to conduction losses. With increasing frequencies above approximately f = 100 Hz, the values of tgδ decrease. Figure 5 also shows that the increase in measurement temperature causes the increase of losses particularly at low frequencies. This effect is due to the acceleration with an increase in temperature of the relaxation processes of the insulating oil dipoles.

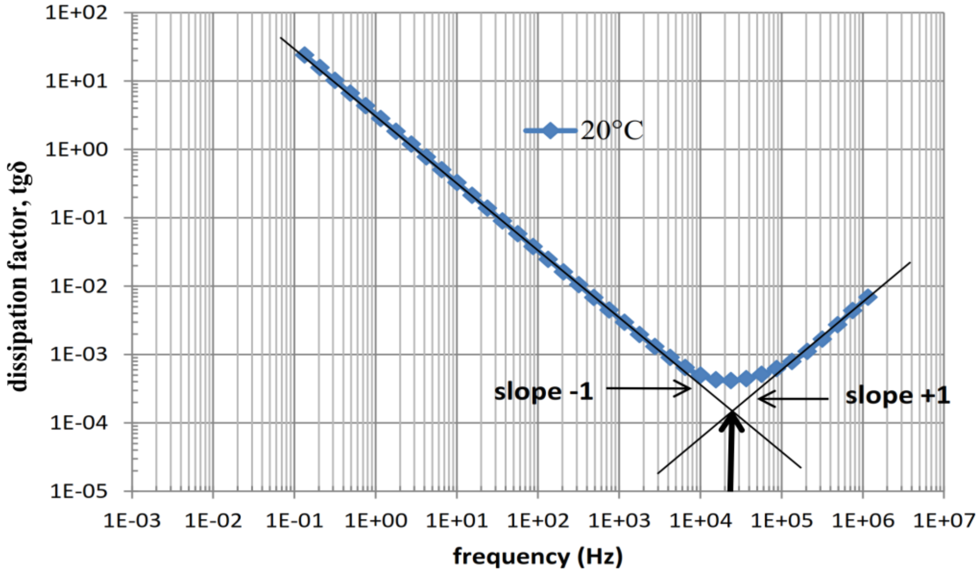

Fig. 4: Frequency dependence of tgδ in calabash seed oil from calabash at 20 °C

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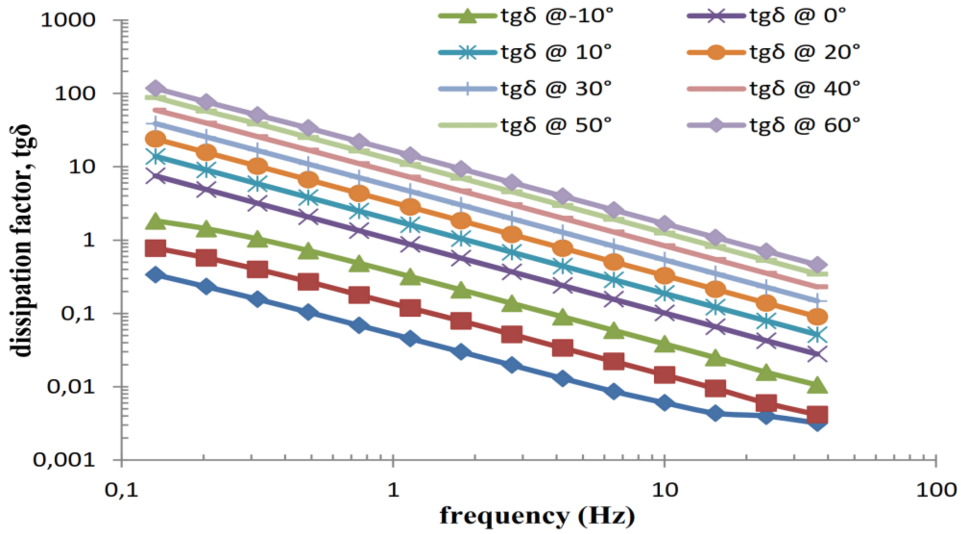

Fig. 5: Frequency dependence of tgδ of calabash oil with temperature

- *Influence of temperature*

In the high-frequency range, the losses, which increase with frequency, are certainly representative of losses by dipole relaxation [23]. For a given frequency, an increase in temperature should induce a decrease in losses, contrary to the case of conduction losses. The influence of temperature on the dielectric spectra of calabash oil, presented in Figure 6 below, confirms this analysis. The curves at -10 °C and -20 °C show a more complex variation this because the conduction losses become very small. In the high frequency range (for frequencies higher than 10^4 Hz), the losses can be caused by dipolar relaxation.

With increasing frequencies above approximately f = 10 MHz, the values of tgδ decrease and reach a minimum as shown in *Fig.6*. The values of tgδ at a minimum are relatively slightly dependent on temperature. In the frequency range above the minimum the values of tgδ start to rise. This statement is verified by the fact that increasing the temperature leads to a decrease in losses (*Fig. 6* and *Fig. 7*). For a dipolar relaxation phenomenon, tgδ is proportional to τω (τ being the relaxation time of the liquid dipoles) [23]. Thus, at a given frequency, an increase in temperature leads to variations of the loss angle as observe experimentally (*Fig. 7)*. However, for T>35°C, tgδ becomes almost independent of T. This can only be explained by the fact that, at these temperatures, the frequency range in which tgδ is proportional to f becomes very limited due to the very high conductivity of the liquid, and that the accuracy on the measurement of tgδ decreases sharply when approaching the intrinsic limits of the system.

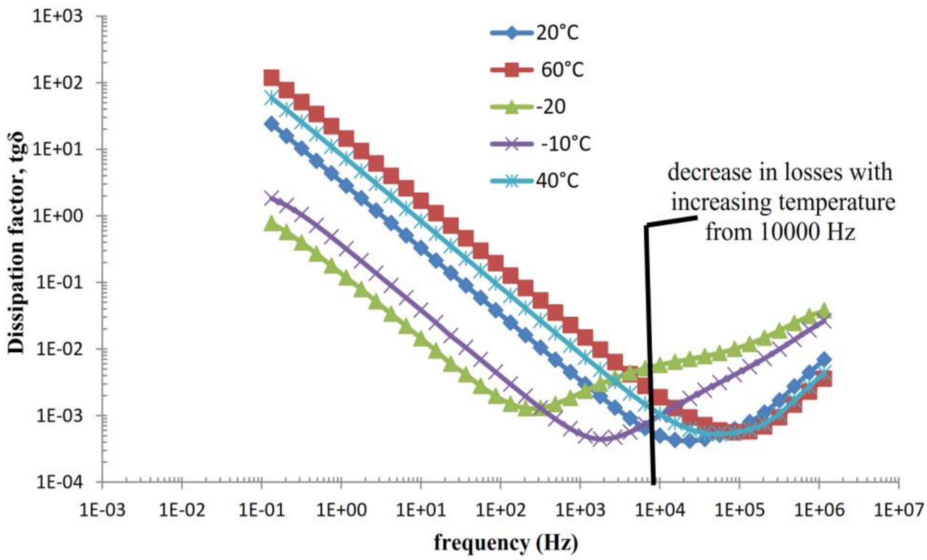

Fig. 6: Frequency dependence of tgδ in calabash oil for different temperatures

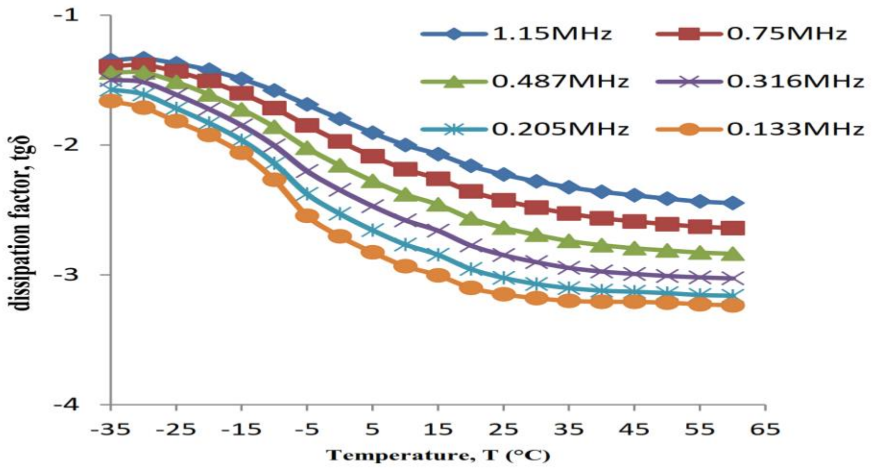

Fig. 7: Variations of tgδ with temperature for frequencies from 0.133 to 1.15 MHz

➢ *Comparison with mineral oil*

Measurements made in mineral oil by [3] show a similar pattern of the frequency spectrum of losses. At room temperature, 20°C it can be concluded that in the low frequency range, the conduction losses, in mineral oil are lower than those in calabash oil. This may be due to the fact that the common mineral oil measured belongs to the group of naphthenic oils, the major part of which consists of cycloalkanes [24]. Cycloalkanes are less polar than triglycerides and fatty acids in vegetable oils [25]. Vegetable oils are composed mainly of esters. The mobility of esters is higher than that of cycloalkanes, so the viscosity of vegetable oils is also lower.

At higher frequencies, due to the insufficient sensitivity of the measuring apparatus, it is difficult to specify the values of the losses by dipolar relaxation, even at high temperatures. These very high losses in calabash oil may be due to a high viscosity. This is a disadvantage for calabash oil. This oil has dielectric losses at 20°C and 56 Hz for about 5.86×10^{-02}.At 25°C and for the same frequency, the dielectric losses increase to $tg\delta = 7.55 \times 10^{-02}$.

C. Study of the conductivity

➢ *Influence of frequency*

Fig. 8 shows the frequency spectrum of the conductivity (σ) calculated by the spectrometer. For low frequencies (f<1kHz), the conductivity remains constant. At higher frequencies, following the process of polarization, an atypical increase in the conductivity curve can be seen (Figure 8). One remark is that the conductivity of the liquid can be reliably measured by the spectrometer at low frequencies.

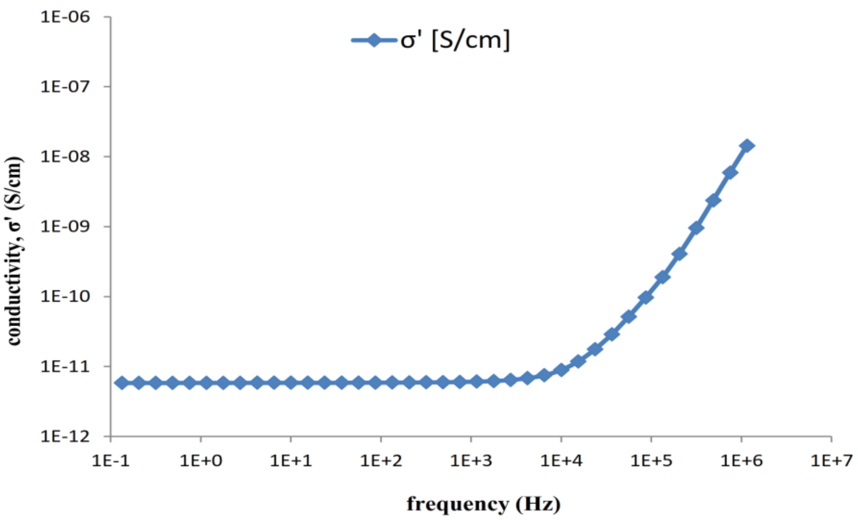

Fig. 8: Conductivity of lagenaria siceraria oil at 20°C

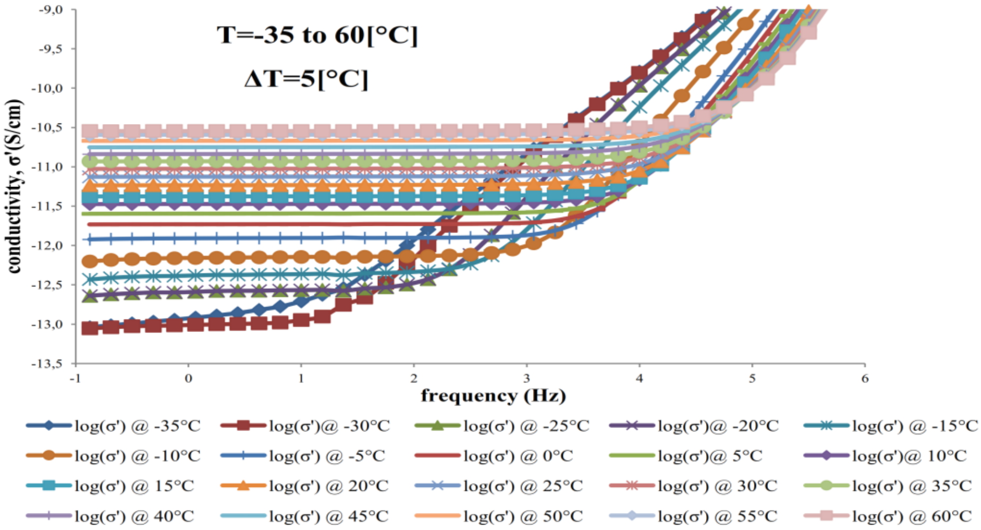

Fig. 9: Conductivity spectrum of lagenaria siceraria oil for different temperatures

The range of frequencies where tgδ is proportional to 1/f depends on the temperature. Indeed, since the conductivity of a liquid can only increase with temperature, the higher the temperature, the higher this frequency ranges. This is due to the fact that with increasing thermal stress, new charge carriers responsible for conductivity appear [24]. As is generally known, low temperature inhibitors improve the oxidation stability of transformer oil. Previous work [22, 26] has established that with increasing temperature, the relaxation processes become faster. Therefore, it can be said that the decrease in resistivity reflects the high content of free ions and ion forming particles. It also indicates a high concentration of conductive contaminants.

For high temperatures therefore, the conductivity is higher and consequently the resistivity is lower. The oil of lagenaria siceraria shows at 20°C and 56 Hz a conductivity equal to 5.88 x 10-12S.cm-1i.e. a resistivity of 1.7 x1013Ω.m. At 25°C and for the same frequency, we have σ=7.52 x 10-12 S.cm-1 i.e. ρ=1.33 x 1013 Ω.m.

Compared to mineral oil, which has a DC resistivity of about 4.36 x 1011 at 20°C [22], calabash oil is rather well placed.

IV. CONCLUSION

The dielectric loss measurements were performed over a wide range of frequencies (dielectric spectroscopy), whereas the previous measurements were all performed at the fixed frequency of 50 (or 60) Hz. This allowed to highlight the characteristic frequency ranges in which conduction or polarization losses are predominant. It was also found that the dielectric constant can be easily determined by low frequency dielectric spectroscopy.

Compared to mineral transformer oil, vegetable oil from lagenaria siceraria has a higher conductivity at high temperatures, and higher dielectric losses at low frequencies. This would be a major obstacle for some applications (e.g. impregnation of cables or capacitors), but not in the case of a transformer where dielectric losses are negligible compared to magnetic losses (iron losses) or Joule effect losses (copper losses) [3]. In addition, the vegetable oil of lagenaria siceraria has a better dielectric constant (3.19 at 25°C) than mineral oil (2.2 at 25°C). calabash oil could replace mineral oil except for some quality control requirements of the oil as it is used; a safe solution would be to conduct a study to find a suitable blend that will allow calabash oil to have properties as close as possible to those of mineral oil, with fire resistance and biodegradability similar to those of pure vegetable oils.

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