

The Impact of Temperature Variation on the Dielectric Properties of Prepared Stable Nanofluids and Methyl Ester

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ABSTRACT

Vegetable oils are considered a replacement for mineral oil in the cooling and insulation of power equipment. This could be related to its environmental friendliness and abundance in Nigeria. Palm Kernel (vegetable) oil and TiO₂ nanoparticles were combined to prepare a stable nanofluid. However, the TiO₂ nanoparticle is functionalized with Oleic acid as a surfactant to enhance the stability of the fluid. Modified TiO₂ nanoparticles were also characterized by Fourier Transform infrared (FTIR) spectroscopy to ascertain their functional group. The impact of temperature variation on the dielectric properties of the prepared stable nanofluid samples at 0.1 to 0.6wt% of particles and methyl ester (obtained from palm kernel) was studied. Hence, the parameters used in the samples to be measured were relative permittivity, dielectric loss factor, and viscosity. All samples' relative permittivity and dielectric loss factor were assessed using the Rohde & Schwarz HM8118 Programmable inductive capacitive reactance (LCR) Bridge within a frequency range of 20 to 200 kHz. Viscosity was determined using the RVDV-1 Brookfield digital viscometer. Insulation technology in transformers ensures thermal efficiency, mechanical strength, environmental safety, and long – term reliability. Helps to prevent electrical faults, improves cooling by dissipating heat generated during operation and prevent internal short circuits in the system. The novelty of this study contributes to the academic understanding of thermo – dielectric behavior in bio – based Nanofluids and supports the development of sustainable, high performance insulating materials.

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INTRODUCTION

Dielectric fluids play an important role as insulating and cooling media in electrical equipment such as transformers, capacitors and cables in today's power systems. The dielectric and thermal properties of the insulating fluids used have a significant influence on the efficiency, reliability and lifespan of such equipment (Pang et al, 2020). Mineral oil (MO) has traditionally been the most widely used transformer insulating fluid; however, growing environmental and thermal performance concerns have prompted the investigation of alternative eco-friendly fluids such as methyl ester derived from natural oils (Oommen & Claiborne, 2019). Therefore, MO is not biodegradable and is harmful to the environment. This can have serious consequences for both land and aquatic animals in the event of a spillage (Ishak et al., 2016). And vegetable oils, particularly natural esters, gained popularity as insulating fluids because of their biodegradable nature and eco-friendliness (Jacob, Preetha, and Krishnan 2020). In recent years, nanotechnology has introduced new possibilities for enhancing the dielectric and thermal properties of insulating fluids through the dispersion of nanoparticles, resulting in the development of Nanofluids (Kurimsky et al, 2021). These Nanofluids exhibit improved thermal conductivity, dielectric strength and minimize dielectric loss compared to conventional insulating oils. However, the performance of these fluids is significantly influenced by temperature, which affects dielectric parameters such as relative permittivity, dielectric loss and the viscosity (Adewale et al, 2022).

Many researchers have determined that nanofluids serve as a beneficial alternative to mineral oil for high-power equipment due to their impressive dielectric properties. In a study published by Du et al. in 2015, the impact of Fe₃O₄ nanoparticle size on the electrical characteristics of vegetable oil-based nanofluids was explored. Their findings indicated that incorporating nanoparticles enhances the dielectric breakdown performance of these nanofluids. Furthermore, it has been reported that the dielectric frequency response of oil-paper composite insulation can be improved by utilizing TiO₂ nanoparticles, thereby enhancing the insulation behavior. The research highlighted that the addition of nanoparticles enhances the oil's breakdown strength and relative permittivity (Hwang et al., 2010). While nanofluids offer notable benefits, maintaining their stability continues to pose a significant challenge. Efforts are still underway to create a nanofluid that remains stable throughout the entire lifecycle of the shell (Jacob et al., 2020).

The stability of dispersed nanoparticles has been enhanced by applying surface coatings with various surfactants, including Sodium Dodecyl Benzene Sulphonate (SDBS), Oleic acid, Tween 85, Stearic acid, Span 80, and Propylene glycol (Ghadimi et al., 2013; Dombek et al., 2014). In a different light, Makmud et al. explored the impact of nanoparticles on the dielectric response of natural ester-based nanofluids used for insulation. Their findings highlighted the significant role of oleic acid as an artificial surfactant that enhances the suspension of nanoparticles within oil-based solutions (Makmud et al., 2018). In a related study, Oparanti et al.

investigated the use of palm kernel oil nanofluids for high-voltage insulation. Their research indicated that modifying the surface of the nanoparticles improves their stability when dispersed in methyl ester (Oparanti et al., 2021).

The study, focused on enhancing the stability of TiO₂ nanoparticles by applying oleic acid coating multiple times. This process aimed to produce an optimal stable nanofluid. The coated TiO₂ nanoparticles were then dispersed into methyl ester-based palm kernel oil using a straightforward two-step method, following the approaches of Primo et al. (2016) and Li et al. (2012). The stable nanofluid was analyzed through sedimentation and centrifugation methods (Ali, Teixeira, and Addali, 2018). The vegetable oil samples utilized in this research were not only biodegradable and inexpensive, but also readily available in Nigeria. Furthermore, the non-toxic nature of vegetable oils ensures that they do not harm the environment in the event of spills, aligning with the United Nations' Sustainable Development Goal No. 7 (SDG7). This commitment underscores the importance of seeking affordable, reliable, and sustainable energy solutions for all.

Understanding how temperature variations impact these dielectric properties is therefore vital for ensuring reliable insulation performance under real operating conditions. Temperature-induced variations can alter the molecular structure and charge transport mechanisms within both Nanofluids and methyl esters. As the temperature rises, increase ion mobility and reduced viscosity may lead to enhanced conductivity and dielectric losses (Zhang et al, 2021). Conversely, the presence of well – dispersed nanoparticles can mitigate these effects by trapping charge carriers and stabilizing the dielectric response. Thus, examining the interplay between temperature, nanoparticle concentration, and fluid base composition provide deeper understanding of the suitability of such modified fluids for power transformer applications.

This study investigates the impact of temperature variation on the dielectric properties of prepared stable Nanofluids and methyl ester. By analysing parameters such as dielectric permittivity, loss factor and viscosity across the range of temperatures, the research aims to provide insight in to their behaviour as potential sustainable insulating materials for power equipment. The findings will contribute to the ongoing development of high – performance, biodegradable transformer insulating fluids capable of operating efficiently under varying thermal conditions.

Theoretical Background

Relative Permittivity (ϵ_r)

Relative permittivity (ϵ_r) describes material interaction with an electric field. The dielectric constant indicates how easily a measurable quantity can vary its resistance when an electric field is applied to a liquid dielectric (Tereshchenko, Buesink, and Leferink 2011). Relative permittivity is the fraction of the absolute permittivity (ϵ) to the permittivity of free space (ϵ_0). As such, suitable insulating fluid must have a high value of relative permittivity (Shah and Tahir, 2011).

$$\epsilon_r = \frac{\epsilon}{\epsilon_0} \quad (1)$$

$$\therefore \epsilon = \epsilon_r \epsilon_0 \quad (2)$$

$$\text{and } C = \frac{A\epsilon_0}{d} \quad (3)$$

where C is the capacitance obtained by Rohde & Schwarz Hm8118 programmable LCR BRIDGE, area, $A = \pi r^2 = \frac{d^2}{4}$, the distance d, between the two plates in a test – cell is 2.5mm, and $\epsilon_0 = 8.85 \times 10^{-12}$ f/m.

Relative permittivity's temperature dependence can be estimated empirically or derived from molecular considerations using the followings:

i. Empirical Linear correlation (Arora et al, 2011)

$$\epsilon_r(T) = \epsilon_{r0} = \alpha(T - T_0) \quad (4)$$

Where ϵ_{r0} is permittivity at reference temperature T_0 , α is temperature coefficient of permittivity and T in the temperature.

ii. Debye model for polar dielectrics

$$\epsilon_r = \epsilon_\infty + \frac{\epsilon_s - \epsilon_\infty}{1 + (\omega\tau)^2} \quad (5)$$

Where ϵ_∞ is the optical permittivity at high frequency limit, ϵ_s static permittivity at low frequency limit, $\omega = 2\pi f$ is the angular frequency of the applied field, and τ is relaxation time which affects temperature to an Arrhenius – type relation as:

$$\tau = \tau_0 e^{Ea/kT} \quad (6)$$

Where τ_0 is pre – exponential factor, Ea is the activation energy for dipole relation, k is the Boltzmann constant and T is the absolute temperature.

iii. Curie Weiss Law

Describe how dielectric permittivity varies with temperature. Therefore, for dipole – dipole interaction:

$$\epsilon_r = \frac{C}{T - T_c} \quad (7)$$

T_c is the Curie temperature; C is Curie – Weiss constant and T is the absolute temperature. When $T > T_c$ for paraelectric, thermal agitation dominates and dipoles become randomly oriented, then caused low ϵ_r . For $T = T_c$, ϵ_r reaches the highest value, dielectric is in phase transition. Moreover, materials showed spontaneous polarization as $T < T_c$ for ferroelectric materials.

Dielectric Polarization

Polarization of dielectric is the orientation of electric charges by an applied electric field by taking algebraic sum of induced dipole moments. Dielectric polarization depends strongly on temperature, because temperature controls molecular motion, dipole alignment, charge mobility and relaxation processes. Mathematically,

$$P = \epsilon_0 \chi_e E \quad (8)$$

Where χ_e is the electric susceptibility and E is applied electric field. Dielectric polarization mechanisms are; electronic (P_e), ionic (P_i), orientational/dipolar (P_o) and space charge/interfacial (P_{sc}) polarizations.

Electronic Polarization

Electronic polarization P_e , arises from displacement of the electron cloud relative to the nucleus by an applied electric field for a static body. The effect of temperature is weak due to larger electron binding energies, is nearly temperature – independent. Therefore,

$$P_e = N\alpha_e E \quad (9)$$

Where N is the number of polarizable atoms per unit volume (m^{-3}), α_e is the electronic polarizability ($C.m^2/V$) and E is applied electric field (V/m). Electronic polarization is occurred due to higher frequency, at ultraviolet region.

Ionic Polarization

Ionic polarization occurs in ionic solid due to relative displacement of positive and negative ions and is slightly decrease with increasing temperature. Because, thermal expansion increases interionic ionic space and reducing restoring forces.

The displacement is independent of temperature.

$$\alpha_i = \frac{e^2}{\omega_0^2} \left(\frac{1}{m} + \frac{1}{M} \right) \quad (10)$$

Where e is the charge of an electron, ω_o is the angular frequency, m is the mass of the positive ion, M is the mass of the negative ion.

Orientation Polarization

Orientation polarization: this is the main polarization mechanism in liquid. This occurs in polar molecules with permanent dipole moment even in the absence of an electric field. When this material is kept in an electric field the molecules align themselves along the field direction resulting in a dipole moment in the field direction. Application of field makes positive portion align along field direction and negative portion align opposite to field direction. Orientation polarization P_o is given by

$$P_o = \frac{N\mu^2 E}{3K_B T} = N\alpha_o E \quad (11)$$

$$\text{Where } \alpha_o = \frac{\mu^2}{3K_B T} \quad (12)$$

Space Charge Polarization

Space charge polarization; the heterogeneous dielectrics, for example partially crystalline insulating materials, have positive and negative ions as free charge carriers. Without an external field, the dielectric is in neutral condition and the positive and negative charges neutralize each other. However, under the effect of an external electric field, the charge carriers in the dielectric move towards opposite polarity electrode surface, giving rise to a macroscopic dipole. In this case on removing the applied electric field, the dielectric returns to its original neutral state. Dielectrics having this type of polarization mechanism are also described as nonpolar, that is, these do not build a dipole without an external field. The boundary surface polarization is commonly present in heterogeneous insulating materials, such as impregnated paper insulations, hard-pressed boards, and taped insulations used in electrical machines and even at voids in solid homogeneous dielectrics. Such materials normally have a low value of ϵ_r .

The total polarization $P = NE\alpha$. The space charge polarization is very small and can be neglected.

$$P = NE\alpha = NE \left[\alpha_e + \alpha_i + \alpha_o = 4\pi\epsilon_o R^3 + \frac{e^2}{\omega_o^2} \left(\frac{1}{m} + \frac{1}{M} \right) + \frac{\mu^2}{3K_B T} \right] \quad (13)$$

Where R is the radius of the atom, e is (Arora et al., 2011).

Dielectric Loss

Dielectric loss is well-defined as

$$\tan\delta = \frac{\epsilon''}{\epsilon'} = \frac{1}{\omega RC} \quad (12)$$

Where δ is the angle between the charging and active currents, called the loss angle. The loss ($\tan\delta$) processes the inadequacy of dielectric constituents. Dielectric loss is influenced by both frequency and temperature. When the temperature rises, the mobility of ions increases, further enhancing conduction through the polarization process. Loss increases with higher temperatures. Viscosity refers to how much a fluid resists flow. Dynamic viscosity specifically measures this resistance when an external force is applied. The viscosity of insulating fluids plays a significant role in heat transfer and is highly dependent on temperature (Abdelmalik 2012). When the insulating fluid gets heated, its molecules start to vibrate around their average position, resulting in an increase in their kinetic energy. This rise in average kinetic energy is linked to a decrease in the frictional force within the layers of the insulating fluids (Umar et al., 2018). Temperature in transformers tends to rise continuously due to power losses originating from their windings and magnetic circuits (Khaparde et al., 2004). As a result, insulating fluids are crucial in dissipating this heat within liquid-filled power equipment. They help lower the temperature of the components to suitable levels, ensuring the reliable operation of oil-filled power systems (Mohamad et al., 2017).

In the meantime, the correlation between viscosities and temperature is analyzed using an Arrhenius plot, which can be expressed as follows:

$$\eta = A \exp(E_a / kT) \quad (13)$$

A is the pre-exponential term (Pa s), Viscosity (Pa s), T is the temperature in kelvin (K), k is Boltzmann constant (eV/K), and E_a is the activation energy (eV/mol) determined from the slope of a graph plotting $\ln(\eta)$ versus $1/T$ (Umar et al., 2018). Activation is the energy required to stop the mobility of charge carriers contained in fluid. Hence, suitable insulating fluid has higher activation energy.

MATERIALS AND METHODS

Preparation of Samples

The preparation of the nanofluids involved a two-step method, where coated nanoparticles were dispersed into fatty acid methyl ester (FAME) and stirred at 800 rpm for a duration of 2 hours (Jacob et al., 2020). This approach is favored for its affordability and the practical ease it offers during preparation (Primo et al. 2016). Prior to taking measurements, the suspended particles were separated from the sediments. Therefore, the Prepared samples by different concentration (wt%) and highly purified methyl ester are shown in Figure 1.



Figure 1: Prepared ME and Nanofluids with Eight-Times Coated TiO₂ Nanoparticles

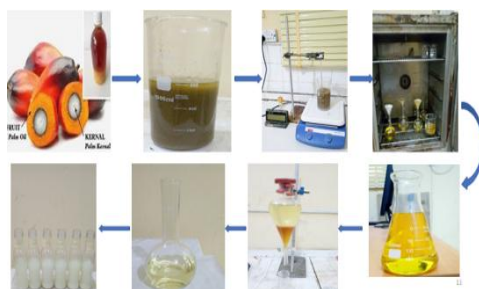


Figure 2: Preparation of Samples

Titanium dioxide (TiO_2) nanoparticles were coated by oleic acid as surfactant for compatibility. Research on nanofluid made from palm kernel oil for high – voltage insulation was done by Oparanti *et al.* They used oleic acid as surfactant and prepared a nanofluids in a range of 0.1 to 0.6wt% for a single coating. They were concluded that Surface modification of the nanoparticles help to improve the stability of dispersed nanoparticles into ME (Oparanti *et al.*, 2021). In this study, the TiO_2 nanoparticles were coated 1 to 10th times. The sedimentation method reveals that nanofluids prepared by eight times coating TiO_2 nanoparticle has the highest stability. As a result, the samples were prepared with the same range as Oparanti *et al.* in order to investigate the dielectric properties, how they affect the temperature variation and how multiples coating can affect the dielectric properties of prepared insulating fluids.

FT-IR Spectroscopy

The functional groups were analyzed using FTIR spectroscopy, utilizing the Carry 630 FTIR Spectrometer for

the infrared absorption measurements. During the analysis, the sample holder and cap of the spectrometer were meticulously cleaned with methanol and acetone to eliminate any contaminants. The cap was secured, and a background scan was performed. A droplet of the sample was then placed onto the measurement cell of the spectrometer. The sample underwent scanning with infrared light across a frequency range of 4000 cm^{-1} - 650 cm^{-1} , enabling the acquisition of spectra that identify the functional groups present in the samples.

Measurement of Viscosity

The dynamic viscosity of all prepared samples was assessed using a Brookfield RVDV-1 digital viscometer agreeing to ASTM D445 at different temperatures ranging from 30°C to 80°C. The temperature variation of the samples was assessed using a water bath placed on a controlled thermostatic hot plate, as illustrated in Figure 3 below.



Figure 3: Viscosity Measurement Setup

Relative Permittivity and Loss Factor

The relative permittivity and loss factor of the prepared samples were measured in accordance with the International Electrochemical Commission (IEC 60247-2004), utilizing the Rohde & Schwarz HM8118 Programmable LCR BRIDGE. The setup involved two parallel plates, each with a diameter

of 30mm and a gap of 2.5mm between them. All electrodes were fully immersed in the samples. Dielectric constant and loss were assessed across a range of frequencies, from 20 Hz to 200 kHz, at different temperatures from 30 to 80°C as shown in Figure 3 below



Figure 4: Relative Permittivity and Loss Measurement set - at Different Temperatures

RESULTS AND DISCUSSION

Description of Samples

Nanofluids were prepared by dispersing eight-time coated TiO₂ nanoparticles into highly purified ester oil, with weight percentages ranging from 0.1% to 0.6%. After allowing the

sediment particles to settle, the concentration of the suspended nanoparticles was estimated. In Table 1, you will find the codes and descriptions for all the samples used in this study.

Table 1: Sample Codes for Identification of the Dielectric Test and Amounts of Nanoparticles

Code	Description	Percentage of suspended nanoparticles (g/l)
ME	Methyl ester	0.00
ECNF _{0.04}	Eight times coated nanofluid at 0.1wt%	0.04
ECNF _{0.07}	Eight times coated nanofluid at 0.2wt%	0.07
ECNF _{0.11}	Eight times coated nanofluid at 0.3wt%	0.11
ECNF _{0.15}	Eight times coated nanofluid at 0.4wt%	0.15
ECNF _{0.18}	Eight times coated nanofluid at 0.5wt%	0.18
ECNF _{0.22}	Eight times coated nanofluid at 0.6wt%	0.22

Fourier Transform Infra-Red Results

FTIR characterization focused on analyzing the infrared absorption and vibrations created by various functional groups, which helped to uncover the chemical structure of the samples (Liao et al., 2008). Figures 4 and 5 provide a visual representation of the FTIR measurements for both the pristine TiO₂ and the treated TiO₂. In Figure 5, the spectral band at 3235 cm⁻¹ corresponds to the symmetric and asymmetric stretching modes of the hydroxyl group (T-OH) (Praveen et al., 2014; Abifarin et al., 2019). Additionally, the distortion vibration of the Ti-OH bending mode is noted around 1636

cm⁻¹ (Chougala et al., 2017), the analysis reveals two distinct peaks linked to the O–H bending modes of both the adsorbed water and hydroxyl groups present on the TiO₂ surface. According to Chougala et al. (2017), the spectral band between 1000 cm⁻¹ and 400 cm⁻¹ corresponds to the Ti-O stretching and the Ti-O-Ti associating stretching modes. Additionally, the peak observed at 650 cm⁻¹ is indicative of anatase titania, which serves to confirm that the titanium oxide nanoparticles being utilized are specifically of the anatase type (Lu et al., 2012).

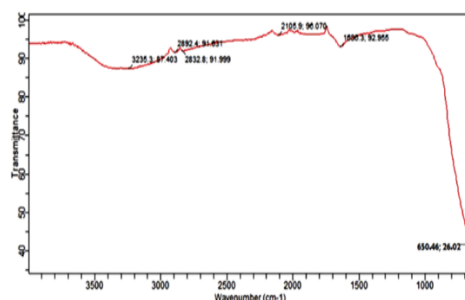


Figure 5: FTIR Spectra of Pure TiO₂

Figure 6 illustrates that TiO₂ nanoparticles coated with oleic acid exhibit a distinct peak for the –CH₂ group at 2926 cm⁻¹. This peak is not observed in the uncoated TiO₂, confirming the presence of oleic acid on the nanoparticles' surface as a result of the coating process. The peak detected at 1461 cm⁻¹ indicates the presence of carboxylate, highlighting the combined effects of oleic acid along with the surfaces of the

nanoparticles through various physical and chemical interactions. The carboxylate peak displayed in Figure 6 suggests that a reaction occurred between the carboxylic acid group (–COOH) of oleic acid and the hydroxyl (–OH) group of TiO₂ nanoparticles. These findings are consistent with those reported by Zou et al. (2011).

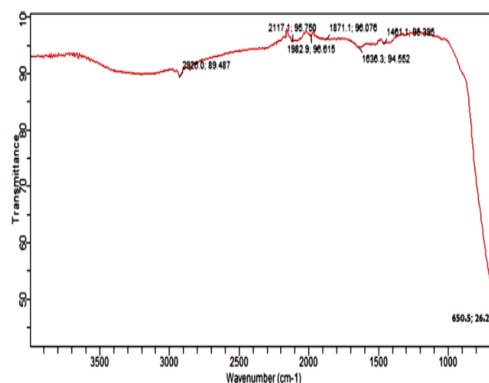


Figure 6: FTIR Spectra of Oleic Acid-Coated TiO₂

Viscosity Measurement Test

Furthermore, the figure showed that the samples' viscosity decreased as the temperature changed. Every molecule experiences a rise in its thermal or kinetic energy as the temperature increases. The cohesive energy of the molecules

reduces the resistive force among the layers of liquid molecules. This, in turn, increases molecular mobility and lowers viscosity (Abdelmalik 2012). The findings indicated that the coating has no impact on viscosity.

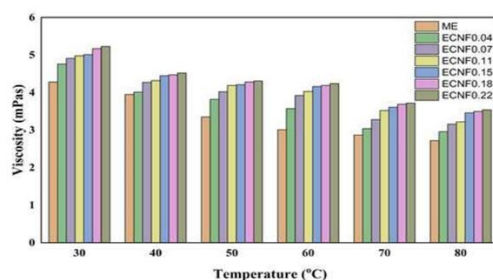


Figure 7: Variations of Viscosity with Temperature of Samples

An Arrhenius plot was obtained from the viscosity values with temperature (see Figure 7). The activation energy for each sample was calculated using the slope of the Arrhenius plots, which are summarized in Table 2. The activation energy of all samples rises as the temperature increases, leading to the dissociation of molecules. This process restricts the enhanced mobility of the ions present in the fluids, ultimately hindering conduction by diminishing ion mobility. An

excellent insulating fluid must consume more activation energy, be a non-conductor, and have low viscosity to flow heat away. The higher activation energy rate suggests that additional energy is needed to decrease the viscosity of insulating fluids. Eventually, activation energy will generally increase with concentration by reducing the charge mobility (Makmud *et al.*, 2018 and Oparanti *et al.*, 2021).

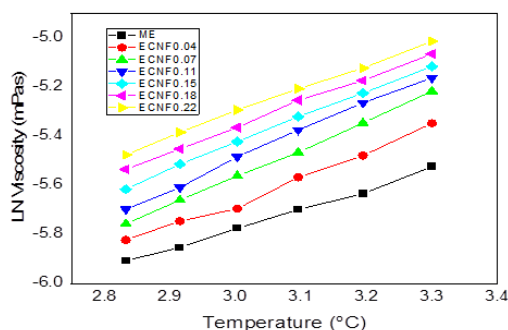


Figure 8: Arrhenius Plot for the Viscosity of Samples

Table 2: The Activation Energy of Samples

Samples	Activation energy (eV/mol)
ME	0.07
ECNF _{0.04}	0.08
ECNF _{0.07}	0.09
ECNF _{0.11}	0.10
ECNF _{0.15}	0.12
ECNF _{0.18}	0.13
ECNF _{0.22}	0.14

Permittivity with Temperature

The dielectric permittivity of prepared samples was evaluated at different temperatures ranging from 30°C - 80°C at 10°C intervals, as shown in Figure 8. The dielectric constant across all samples exhibits a consistent trend, decreasing as the temperature rises. Notably, the dielectric permittivity values for ME are lower compared to the other sample which is 3.21 at 30°C and drop to 1.81 at 80°C. This is similar to the result obtained by (Ishak *et al.*, 2016). The results found that the dielectric permittivity of canola oil is 2.005 at 30°C and it drops to 1.863 at 90°C. Sure! Here's the rewritten text: As

temperature increases, thermal agitation makes dipoles reorient faster and reducing the relaxation time. Consequently, the dielectric permittivity tends to decrease due to increased molecular disorder that caused weaker interaction among the molecules (Shah and Tahir, 2011). The rise in temperature also increases the kinetic energy of the molecules of the insulating fluids, causing the molecules to vibrate randomly and collide elastically. Then, the dipole moment is reduced, and the dielectric permittivity is lowered

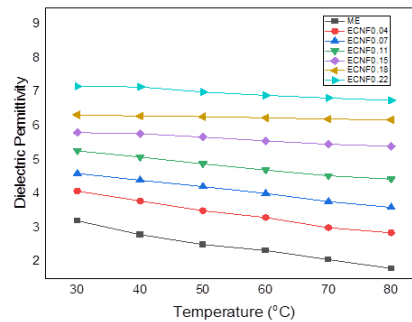


Figure 9: Permittivity as a Function of the Temperature of Samples

Dielectric Loss with Temperature

Figure 10 illustrates how dielectric loss changes with temperature. It shows that as the temperature rises, there is a steady increase in dielectric loss. This increase can be linked

to the enhanced average kinetic energy of the molecules in the nanofluids, which leads to quicker vibrations of the charges around their average positions. As a result, this vibration boosts the conduction of ions present in the fluids.

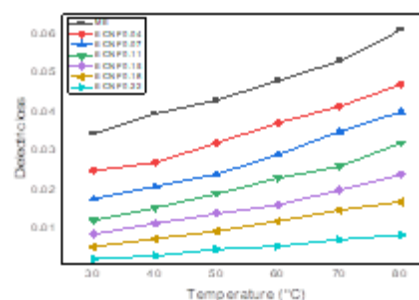


Figure 10: Permittivity as a Function of the Temperature of Samples

CONCLUSION

After thoroughly investigating and analyzing the results, it is clear that temperature has a significant impact on the dielectric properties of all samples. Among them, ECNF_{0.22} stands out as the most effective nanofluid for cooling and insulating oil-filled power equipment. This is primarily due to its low dissipation factor and high permittivity, which can be attributed to the increased concentration of nanoparticles. In contrast, ME displayed the least favorable dielectric properties, lacking nanoparticles entirely. Furthermore, increasing the concentration of nanoparticles in vegetable oils leads to enhanced dielectric properties, aligning with findings from previous studies. The research also determined that TiO₂ nanoparticles coated eight times represented the optimal coating method, yielding stable nanofluids for three months without any signs of sedimentation.

REFERENCES

- Ab Ghani, S. N. (2018). Methods for Improving the Workability of Natural Ester Insulating Oils in Power Transformer Applications: A Review. *Electric Power Systems Research* 163, 655–67.
- Abdelmalik, A. A. (2012). The Feasibility of Using a Vegetable Oil-Based Fluid as Electrical Insulating Oil.
- Ali, N. J. (2018). A Review on Nanofluids: Fabrication, Stability, and Thermophysical Properties. *Journal of Nanomaterials*.
- Chougala, L. M. (2017). A Simple Approach on Synthesis of TiO₂ Nanoparticles and Its Application in Dye Sensitized Solar Cells.

Dombek, G. Z. (2014). The Study of Thermal Properties of Mineral Oil and Synthetic Ester Modified by Nanoparticles TiO₂ and C 60. *IEEE*, Pp. 1–4.

Ghadimi, A. a. (2013). The Influence of Surfactant and Ultrasonic Processing on Improvement of Stability, Thermal Conductivity and Viscosity of Titania Nanofluid. *Experimental Thermal and Fluid Science* 51, 1–9.

Hamid, M. H. (2016). Dielectric Properties of Natural Ester Oils Used for Transformer Application under Temperature Variation. *IEEE International Conference on Power and Energy (PECon)*. Melaka, Malaysia: IEEE, Pp. 54–57.

Hwang, J. G. (2010). Effects of Nanoparticle Charging on Streamer Development in Transformer Oil-Based Nanofluids. *Journal of Applied Physics* 107(1):014310.

Ishak, N. N. (2016). High Voltage Characteristics of Kraft Paper Insulator with Effect of Palm Oil and Coconut Oil. *IET*, Pp. 1–8.

Jacob, J. P. (2020). Review on Natural Ester and Nanofluids as an Environmental Friendly Alternative to Transformer Mineral Oil. *IET Nanodielectrics* 3(2), 33–43.

Jamail, N. M. (2017). Insulation Characteristic Analysis of Coconut Oil and Palm Oil as Liquid Insulating Material. *International Journal of Simulation: Systems, Science and Technology* 41(49), 1–6.

- Khaled, U. a. (2019). Statistical Investigation of AC Dielectric Strength of Natural Ester Oil-Based Fe₃O₄, Al₂O₃, and SiO₂ Nano-Fluids. *IEEE Access* 7, 594–601.
- Khaparde, S. a. (2004). *Transformer Engineering: Design and Practice*. Taylor & Francis Limited.
- Li, J. Z. (2012). Preparation of a Vegetable Oil-Based Nanofluid and Investigation of Its Breakdown and Dielectric Properties. *IEEE Electrical Insulation Magazine* 28(5), 43–50.
- Liao, R.-j. C.-j. (2008). Thermal Aging Micro-Scale Analysis of Power Transformer Pressboard. *IEEE Transactions on Dielectrics and Electrical Insulation* 15(5), 1281–87.
- Lu, H. Y. (2012). Effects of Hydrothermal Temperature on Formation and Decoloration Characteristics of Anatase TiO₂ Nanoparticles. *Science China Technological Sciences* 55(4), 894–902.
- Lu, X. X. (2008). Nanocomposites of Poly (L-Lactide) and Surface-Grafted TiO₂ Nanoparticles: Synthesis and Characterization. *European Polymer Journal* 44(8), 2476–81.
- Makmud, M. Z. (2018). Influence of Conductive and Semi-Conductive Nanoparticles on the Dielectric Response of Natural Ester-Based Nanofluid Insulation. *Energies* 11(2), 333.
- Makmud, M. Z. (2019). Partial discharge in nanofluid insulation material with conductive and semiconductive nanoparticles. *Materials*, 12(5), 816.
- Mohamad, M. S. (2017). AC Breakdown Voltage and Viscosity of Palm Fatty Acid Ester (PFAE) Oil-Based Nanofluids. *Journal of Electrical Engineering and Technology* 12(6), 2333–41.
- Oparanti, S. A. (2021). AC Breakdown Analysis of Synthesized Nanofluids for Transformer Insulation. In Review. doi: <https://doi.org/10.21203/rs.3.rs-453749/v1>
- Praveen, P. G. (2014). ‘Structural, Optical and Morphological Analyses of Pristine Titanium Di-Oxide Nanoparticles–Synthesized via Sol–Gel Route. *Spectrochimica Acta Part A: Molecular and Biomolecular Spectroscopy* 117, 622–29.
- Primo, V. A. (2016). Applicability of Nanodielectric Fluids to the Improvement of Transformer Insulation Properties. in Vol. 1. *IEEE*, Pp. 76–79.
- Shah, Z. H. (2011). Dielectric Properties of Vegetable Oils. *Journal of Scientific Research* 3(3): doi: <https://doi.org/10.3329/jsr.v3i3.7049..481-92>
- Tereshchenko, O. V. (2011). An Overview of the Techniques for Measuring the Dielectric Properties of Materials. XXXth URSI General Assembly and Scientific Symposium. Istanbul: *IEEE*, Pp. 1–4.
- Umar, S. A. (2018). Synthesis and Characterization of a Potential Bio-Based Dielectric Fluid from Neem Oil Seed. *Industrial Crops and Products* 115:117–23. doi: <https://doi.org/10.1016/j.indcrop.2018.02.009>
- Zou, P. J.-X.-T.-J. (2011). Dielectric Properties and Electrodynamical Process of Natural Ester-Based Insulating Nanofluid. *Modern Physics Letters B* 25(25), 2021–31.

