# NUMERICAL MODELING OF THE THERMOPHYSICAL PERFORMANCE OF MINERAL OIL-BASED DIELECTRIC NANOFLUIDS TO IMPROVE THE COOLING IN POWER TRANSFORMERS

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*Searching for ways to improve the thermophysical properties of insulating oils used in power transformers is crucial to increasing heat transfer efficiency and keeping this effective device in the electrical network as long as possible. Nanotechnology has provided promising solutions for high-voltage engineers to use in enhancing the thermal properties of dielectric fluids through the thoughtful incorporation of nanoparticles. This study presents a numerical modeling of the thermophysical properties of dielectric nanofluids based on the finite element method. To shed light on the role of nanoparticles in improving the thermal performance of mineral oils, three types of conductive, semiconducting and insulating nanoparticles were used separately in the dielectric fluid (SiC, $TiO_2$, and $Al_2O_3$) and at different volume concentrations (0 vol%, 0.25 vol%, 0.44 vol%, 0.62 vol%, 1.1 vol%). Furthermore, the physical properties were measured over a large temperature range of 20 °C to 80 °C The results showed an increase in the value of thermal conductivity, viscosity, and density of the insulating fluid when NPs were added, where the effect was more evident with the integration of larger quantities of nanoparticles. This increase was suppressed by the change in temperature. The improved thermal conductivity contributes to enhancing the cooling capacity, but the high viscosity and density of the nanofluids lead to a decrease in pressure and an increase in pumping requirements. On the contrary, a reduction in the specific heat capacity of mineral oil was observed at addition of nanoparticles, which can negatively affect the thermal performance.*

Key words*: Dielectric nanofluids, finite element method, heat transfer, Insulating oils, mineral oil, numerical modeling, nanoparticles, Power transformers, thermophysical performance*

## 1. Introduction

Electricity is undoubtedly the basic pillar of life [1]. The rapid expansion of the world population has increased the demand for electrical energy, which has put enormous pressure on the power system [2, 3]. The power grid needs to adapt in all these challenges resulting from the increase in loads to ensure a safe and stable supply. This will require equipment with high capabilities and reliability [4]. Since the vital element of the power system is the transformer, the future needs in terms of enhancing its efficiency have become an inevitable necessity [5]. The unsatisfactory performance of the liquid cooling system is the main factor that limits the efficiency of transformers [6]. In recent decades, nanotechnology has provided promising solutions to improve the performance of insulating fluids used in high-voltage equipment. This has led to the production of high-tech materials, among which are dielectric oil-based nanofluids [7].

Transformers are static machines that convert energy from one level to another without changing frequency [8, 9], and are a vital link in power transmission and distribution processes [3]. The performance of a transformer depends entirely on its relatively low operating temperature. This condition is met if the heat exchange generated in the transformer is efficient [10]. Heat is generated mainly by losses that usually arise in the coils and magnetic core of the transformer (copper losses and iron losses) [11]. This heat spreads throughout the transformer and is dissipated to the external environment by the dielectric oil. The accumulation of heat inside the transformer without efficient dissipation leads to thermal aging of the oil paper insulation, which has serious consequences [12, 13]. The operational life of a transformer is usually 35 to 40 years. It has been reported that the life of a transformer can be reduced by up to 18 years due to problems with dielectric fluids [14, 15]. Therefore, it is of utmost importance to increase the heat transfer efficiency to preserve the insulating oil and improve the life of the transformer [16].

Studies have revealed that the heat transfer capabilities of dielectric oils used in transformers can be modified by implanting nanoparticles (NPs) into these insulating materials [7]. The result of this studied addition of NPs into transformer oils was the formation of dielectric nanofluids (DNFs) [4, 5]. Nanotechnology has helped researchers to enhance the heat transfer performance of dielectric fluids used in electrical appliances [7]. The main feature for evaluating the function and performance of any heat transfer fluid is the thermophysical properties (TPHPs) such as thermal conductivity, viscosity, specific heat, and density [17]. mineral oils (MO) is traditionally used in transformers as an insulating medium due to its good thermal and dielectric capabilities, but its operation under high loads may lead to the deterioration of its properties. The proper operation of transformers depends on the efficiency of the cooling function and the dielectric strength of the used insulating fluid. Therefore, it is of utmost importance to study the TPHPs of transformer oils and find ways to improve them or find a better alternative [18]. The improved TPHPs of DNFs enable highly efficient heat transfer processes [14]. This would solve many of the problems associated with high-voltage equipment that relies on oil as an insulating and cooling medium [19].

The TPHPs of DNFs have been investigated in several experimental studies. Although experimental measurements are a reliable means of determining the TPHPs of nanofluids (NFs), their synthesis and characterization can be costly and technically challenging. The use of models and simulation studies helps to address the challenges. Simulation software provide the ability to predict the TPHPs of different types of NFs by using several theoretical models. These models help in estimating the values of parameters such as thermal conductivity, viscosity, specific heat, and density to give an idea of the properties of any mixture of DNFs before conducting its experimental preparation [20]. Most similar research in the field has focused on evaluating the TPHPs of NFs experimentally. This paper differs from the works published in previous literature in that it presents a numerical study of the TPHPs of DNFs used in power transformers. The purpose is to develop a three-dimensional model using the finite element method (FEM) based on the COMSOL Multiphysics software to evaluate the thermal performance of NFs based on MO by adding different types and quantities of NPs and measuring its properties related to thermal conductivity, viscosity, specific heat, and density. This numerical contribution provided positive results, as the use of nanotechnology led to enhancing the TPHPs of insulating oils, which can contribute to improving the cooling capacity of transformers during their operation.

## 2. Dielectric nanofluids

The need for high reliability and efficiency insulating oil has forced researchers to produce advanced materials with improved technologies [7, 21]. The first transformer oil developed was MO. Mineral oil is one of the most widely used insulating oils in high-voltage equipment due to its satisfactory performance that has served the industry for several decades [3]. Silicone oils were developed in the early 1970s. However, they are now limited to special applications. Since the early 1990s, natural and synthetic esters have gained great interest due to their biodegradable nature and suitable insulating properties [19, 22]. The latest development is the enhancement of transformer oils by applying nanotechnology [7], by implanting NPs of different types, shapes, and sizes in insulating oils to form DNFs [23]. The concept of NFs was introduced at the ASME International Mechanical Engineering Congress and Exposition by Choi et al in 1995 where they demonstrated the possibility of enhancing the thermal conductivity of conventional heat transfer fluids by suspending metallic NPs in the fluid [24]. The term a nanofluid refers to a colloidal fluid consisting of NPs of at least one dimension with a thickness of less than 100 nm homogeneously dispersed in a base fluid [23, 25]. The fluid is designed to enhance the thermal properties of the base fluid [3]. Initially, research focused on applications with conventional heat transfer fluids such as water, ethylene glycol, and engines oils, which demonstrated that NFs provide better heat transfer performance than conventional fluids [26]. In 1998, Segal et al. made the first application of NPs to transformer insulating oils. They studied the pulse and AC breakdown strength of MO enhanced with magnetic NPs ($Fe_3O_4$). The results showed an improvement in the pulse and AC breakdown voltage of the NFs compared to pure MO [27]. Since then, a large number of research papers have been published in the field of DNFs. In fact, Insulating NFs are the most studied research topic regarding nanotechnology applications in electrical transformers [7]. The improved thermal and electrical properties of DNFs have led to their being considered as the next generation of liquid-insulating materials on which high-voltage equipment will be based [23].

## 3. Thermophysical properties of dielectric nanofluids

To predict the heat transfer behavior of NFs, knowledge of their TPHPs is of utmost importance [28]. Improved thermophysical properties such as thermal conductivity, viscosity, specific heat, and density of heat transfer fluids enable highly efficient heat transfer processes more specifically for dielectric fluid applications used in electrical devices. It can be observed that increasing the thermal conductivity and specific heat of DNFs while reducing the density and viscosity is the ultimate goal of enhancing the efficiency of these liquid dielectric media [17]. Conventional insulating fluids such as mineral oils, synthetic oil, and organic oil have inherently modest heat transfer rates, which makes their performance limited for high-voltage applications that require highly efficient heat transfer fluids in the face of increasing energy demands [29, 30]. Although convection is the main mechanism of heat transfer when the liquid is the cooling medium, NPs are incorporated into the basic fluids to enhance the contribution of TPHPs [5]. The improvement in the TPHPs of DNFs is limited by a large number of factors including NPs concentration, NPs type, NPs shape and size, base fluid type, temperature, additives, agglomeration, pH, measurement techniques, and preparation methods [31, 4]. Since the proposal of NFs as cooling fluids in high-voltage devices, researchers have focused on demonstrating these trends and have tried to determine how to achieve a significant improvement in the TPHPs without harming the dielectric properties or any other basic property of the dielectric fluid [4, 5, 32].

## 4. Numerical modeling

### 4.1. Formulation of the problem and conditions

COMSOL Multiphysics is a software widely used worldwide for modeling problems related to high-voltage engineering, as it enables researchers to test, develop, and validate their ideas in a smooth manner due to its flexibility and ability to combine multiple physics [4, 33]. In this work, a three-dimensional model was developed using the FEM (Fig. 1) to simulate heat transfer in DNFs and to study the effectiveness of NPs in influencing the thermophysical properties (thermal conductivity, viscosity, heat capacity, density) of insulating oils used in power transformers by applying different types and concentrations. The physical problem consists of a cylindrical tank filled with NFs so that the NPs are stable in a homogeneous manner in the insulating fluid. A temperature gradient is applied to the upper and lower surfaces and the simulation process is performed on the resulting model.

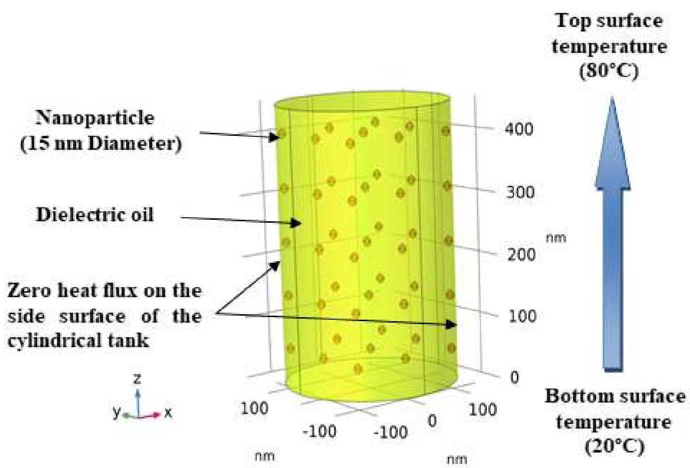



**Figure 1. Geometry of the problem studied**

**The boundary conditions for the numerical study of the thermophysical performance of dielectric nanofluids are set as follows:**

- Three types of NPs were used in this study conductive, semiconducting, and insulating (SiC, $TiO_2$, and $Al_2O_3$) with spherical shapes and a fixed diameter of 15 nm. Their TPHPs are given in Tab. 1.
- It was decided to disperse the NPs in the insulating liquid with different volume concentrations of 0 vol% to 1.1 vol%.

**Table 1. Thermophysical properties of nanoparticles**

| Materials | $k_{np}$ [W.m$^{-1}$K$^{-1}$] | $(C_p)_{np}$ [J.kg$^{-1}$K$^{-1}$] | $\rho_{np}$ [kg.m$^{-3}$] | Reference |
|---|---|---|---|---|
| Insulating NPs (**$Al_2O_3$**) | 40 | 765 | 3970 | [34] |
| Semiconducting NPs (**$TiO_2$**) | 8.9538 | 686.2 | 4250 | [35] |
| Conductive NPs (**SiC**) | 490 | 675 | 3160 | [36] |

- The volume percentage of nanomaterial toward base fluid volume was calculated through Eq. (1) [37]. Fig. 2 presents the geometry of the problem at hand after applying different concentrations of NPs in the base fluid (0 vol%, 0.25 vol%, 0.44 vol%, 0.62 vol%, 1.1 vol%).

$$\phi = \frac{V_{np}}{V_{np} + V_{bf}} \times 100 \qquad (1)$$

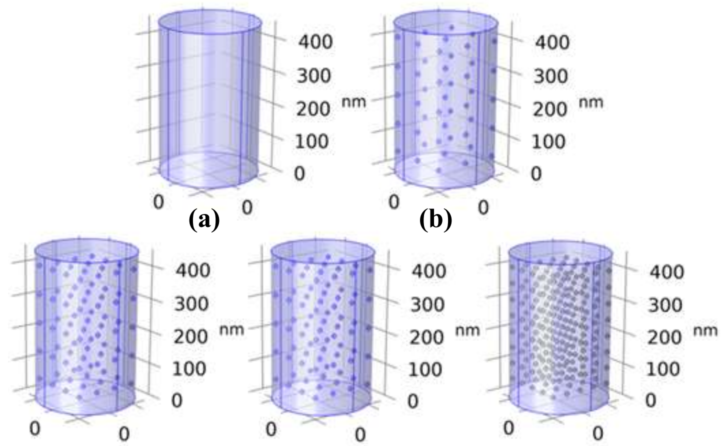



**Figure 2. Geometry of model after applying different concentrations of nanoparticles in the dielectric fluid: (a) MO + 0 vol% NPs; (b) MO + 0.25 vol% NPs; (c) MO + 0.44 vol% NPs; (d) MO + 0.62 vol% NPs; (e) MO + 1.1 vol% NPs**

- Heat is generated in the magnetic core and coils due to changing loads throughout the day [7, 20]. All this heat is transferred to the external environment via insulating oil by natural convection [36]. In order to evaluate the cooling efficiency of DNFs for different operating conditions, The lower and upper limits of the cylindrical tank were set at two temperatures of 20°C and 80°C, such that the heat flux was within the Z-axis, as shown in Fig. 3 and the temperature of the side surface of the tank was considered constant.
- The Time-Dependent study is used in this research considering the DNFs velocity equal to zero.
- On the other hand, in this study, MO of petroleum origin were used as a base fluid, which are among the most widely used insulating oils in transformers because they have excellent performance that serves the industry [3]. The physical properties of these oils as a function of temperature are presented by the following Eq [4]:

$$k_{bf} = 0.1509–7.101\times10^{-5}\times T \tag{2}$$

$$\mu_{bf} = 0.08467–0.0004\times T+5\times10^{-7}\times T^2 \tag{3}$$

$$(C_p)_{bf} = 807.163+3.58\times T \tag{4}$$

$$\rho_{bf} = 1098.72–0.712\times T \tag{5}$$

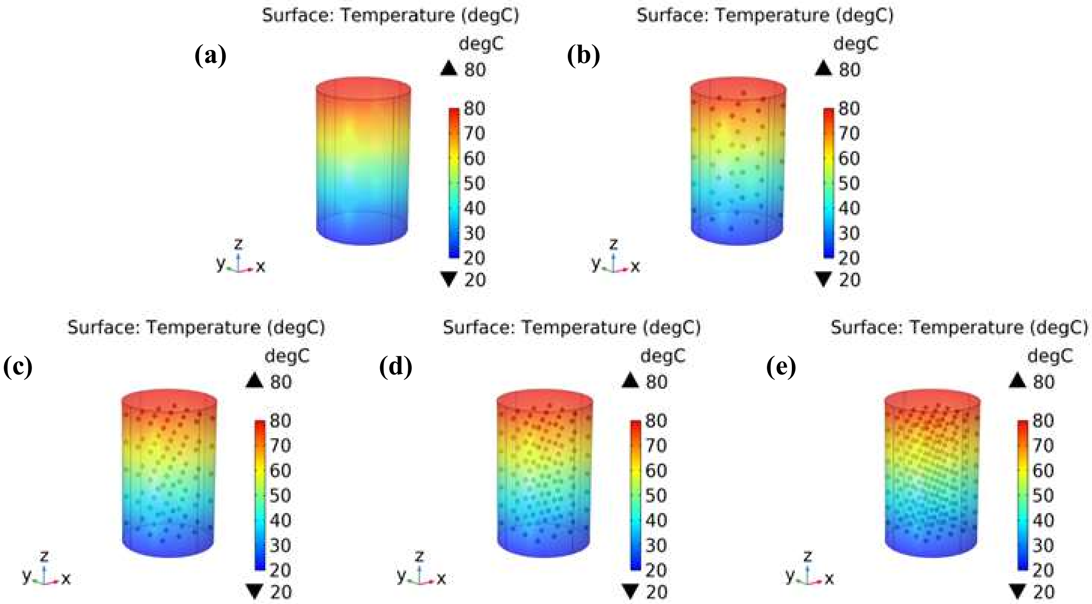



**Figure 3. The studied model after applying a temperature gradient: (a) MO + 0 vol% NPs; (b) MO + 0.25 vol% NPs; (c) MO + 0.44 vol% NPs; (d) MO + 0.62 vol% NPs; (e) MO + 1.1 vol% NPs**

### 4.2. Governing equations

To solve this problem, the heat transfer interface in solids and liquids in addition to the laminar flow (spf) interface as a field of study. So that the governing equations for energy (Fourier's law) (6), conservation of mass (7), and conservation of momentums (8) were obtained as follows:

Energy Eq:

$$\rho C_p \frac{\partial T}{\partial t} + \rho C_p \mathrm{u}.\nabla T – \nabla.(k\nabla T) = Q \tag{6}$$

Continuity Eq:

$$\rho\nabla.\mathrm{u} = 0 \tag{7}$$

Momentum Eq:

$$\rho\frac{\partial \mathrm{u}}{\partial t} + \rho(\mathrm{u}.\nabla)\mathrm{u} = \nabla.[-p\mathrm{I} + K] + F \tag{8}$$

Where: K equals $\mu(\nabla u+(\nabla u)^T)$ for incompressible Newtonian flow

For the calculation of the thermophysical parameters of DNFs (thermal conductivity, viscosity, density, specific heat), Classical equations widely used in the literature were relied upon to predict the properties of two-phase mixtures [34], which can be presented as follows:

- Model (Eq. 9) [38] was relied upon to determine the thermal conductivity of DNFs.

$$k_{nf} = [\frac{k_{np} - \left(\frac{3}{\Psi} - 1\right)\phi\left(k_{bf} - k_{np}\right) + \left(\frac{3}{\Psi} - 1\right)k_{bf}}{k_{np} - \phi\left(k_{np} - k_{bf}\right) + (\frac{3}{\Psi} - 1)k_{bf}}] \times k_{bf} \tag{9}$$

- The viscosity of DNFs is determined by the model (Eq.10) [39].

$$\mu_{nf} = (1 + 2.5\phi + 6.2\phi^2).\,\mu_{bf} \tag{10}$$

- Model (Eq. 11) [40] was used to determine the specific heat of DNFs.

$$(C_P)_{nf} = \frac{(1-\phi)\left(\rho C_p\right)_{bf} + \phi\left(\rho C_p\right)_{np}}{(1-\phi)\rho_{bf} + \phi\rho_{np}} \tag{11}$$

- Model (Eq. 12) [41] was used to determine the density of DNFs.

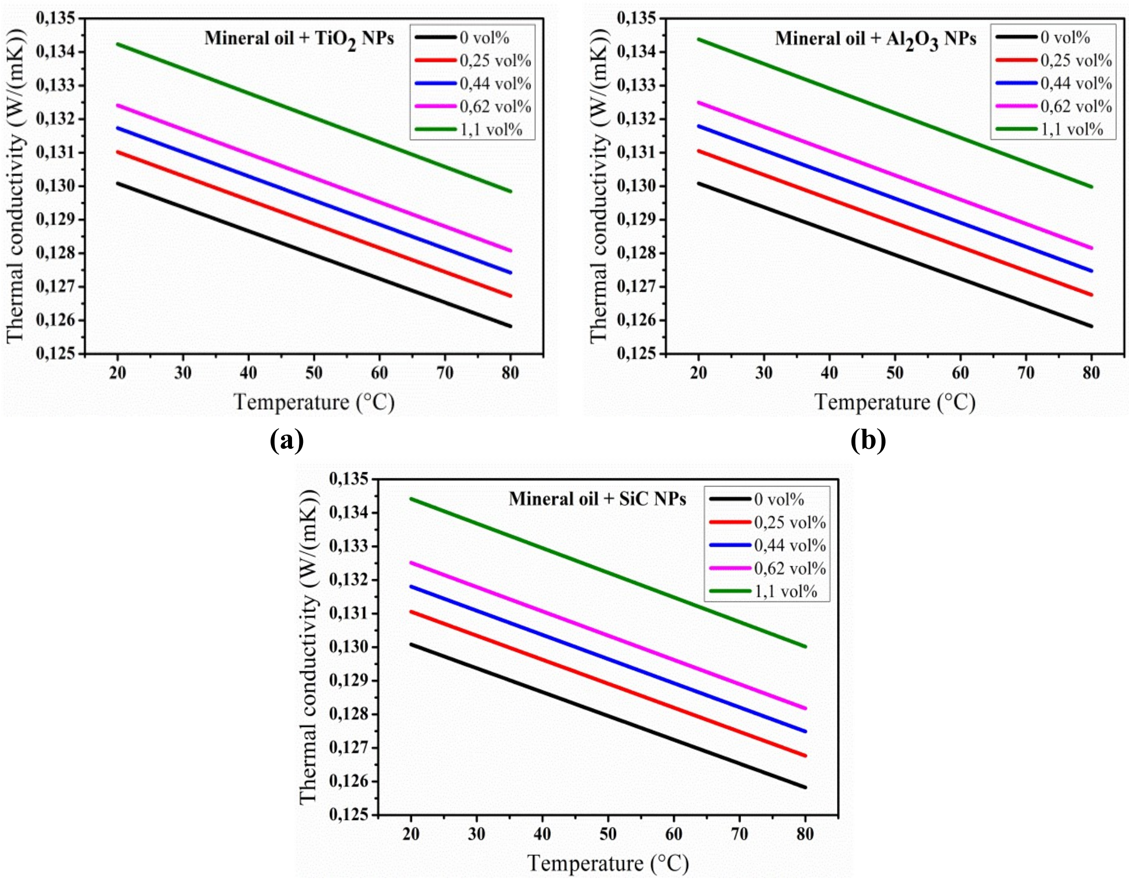
$$\rho_{nf} = \phi\rho_{np} + (1-\phi)\rho_{bf} \tag{12}$$

## 5. Results and discussion

The results of numerical simulations of the thermophysical properties of insulating oils reinforced with NPs are presented in this section. The NPs were fixed in the base fluid in a homogeneous manner so that they were stable. In addition, the experiment was conducted for each sample taking into account the boundary conditions (the temperature of the lower and upper surfaces at 20 °C and 80 °C. The velocity of the dielectric nanofluids is zero).

### 5.1. Thermal conductivity

Figure 4 shows the results of numerical modeling of the thermal conductivity of the DNFs and MO as a function of temperature. The addition of NPs to the dielectric fluid improved the thermal conductivity values of all DNFs samples used in the study. The results showed a slight difference in the thermal conductivity values of the DNFs when changing the type of NPs. The conductive nanoparticles (SiC) provided the highest efficiency in terms of increasing the thermal performance of the dielectric nanofluids, followed by the insulating nanoparticles ($Al_2O_3$) and then the semiconductor nanoparticles ($TiO_2$). This can be attributed to the different thermal conductivity values of each type of NPs used [5]. Unfortunately, with increasing temperature, the thermal conductivity efficiency decreases, which was observed in all samples used in the study. The increase in transformer temperature due to the increase in loads accelerates the aging of the insulating materials and reduces the efficiency of dissipating the accumulated heat [4]. In light of this, the nanoparticles failed to enhance the thermal performance of the dielectric fluid under the increased loads resulting from the reckless operation of the transformer.




**(a)** **(b)**

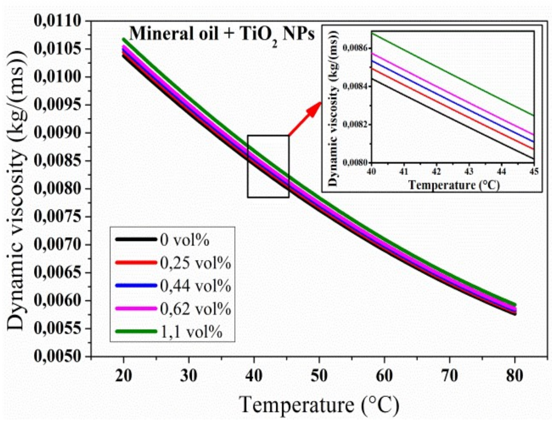
**(c)**

**Figure 4. Thermal conductivity of pure dielectric oil and dielectric nanofluids: (a) MO + $TiO_2$ NPs; (b) MO + $Al_2O_3$ NPs; (c) MO + SiC NPs**

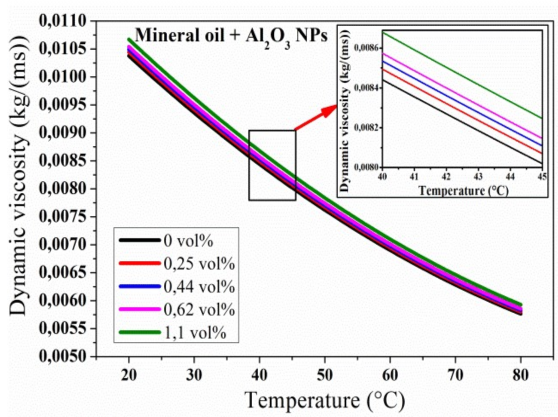
On the other hand, the volume concentration of NPs played an effective role in influencing the thermal conductivity of the DNFs, where the highest values recorded were at a volume concentration of 1.1 vol%, followed, respectively, by 0.62 vol%, 0.44 vol%, 0.25 vol%, and 0 vol%. Increasing the amount of NPs in the mineral oil leads to improving the thermal conductivity, thanks to the solid NPs with high thermal conductivity compared to the insulating liquid [5]. Improving the thermal conductivity helps to enhance the efficiency of the transformers and increase the operational life of this vital device used in the electrical network.

### 5.2. Viscosity

Figure 5 displays the change in viscosity of dielectric nanofluid and mineral oil for different values of temperature and volume concentration of NPs, The results of the study showed a significant increase in the viscosity of DNFs with the addition of larger amounts of nanoparticles. The highest values were recorded at a volume concentration of 1.1 vol%, followed, respectively, by 0.62 vol%, 0.44 vol%, 0.25 vol%, and 0 vol%. The increase in viscosity of the insulating fluid leads to a decrease in pressure and therefore more pumping power requirements[17], which makes it difficult to dissipate heat quickly and contributes to the formation of hot spots. This increase in viscosity was suppressed with temperature changes. When the temperature increases, the viscosity of the nanofluid decreases due to the decrease in intermolecular forces between the oil molecules [3], On the other hand, it was observed that there was no effect of the type of NPs (SiC, $TiO_2$, and $Al_2O_3$) on the viscosity of DNFs, which was reflected in the results of the study. The viscosity stability of the dielectric oil is one of the most important criteria for selecting transformer oil. In general, the use of low-viscosity insulating fluid in transformers contributes to enhancing the cooling efficiency.




**(a)**

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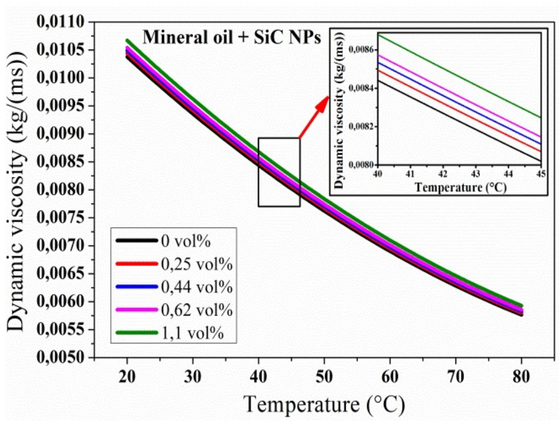
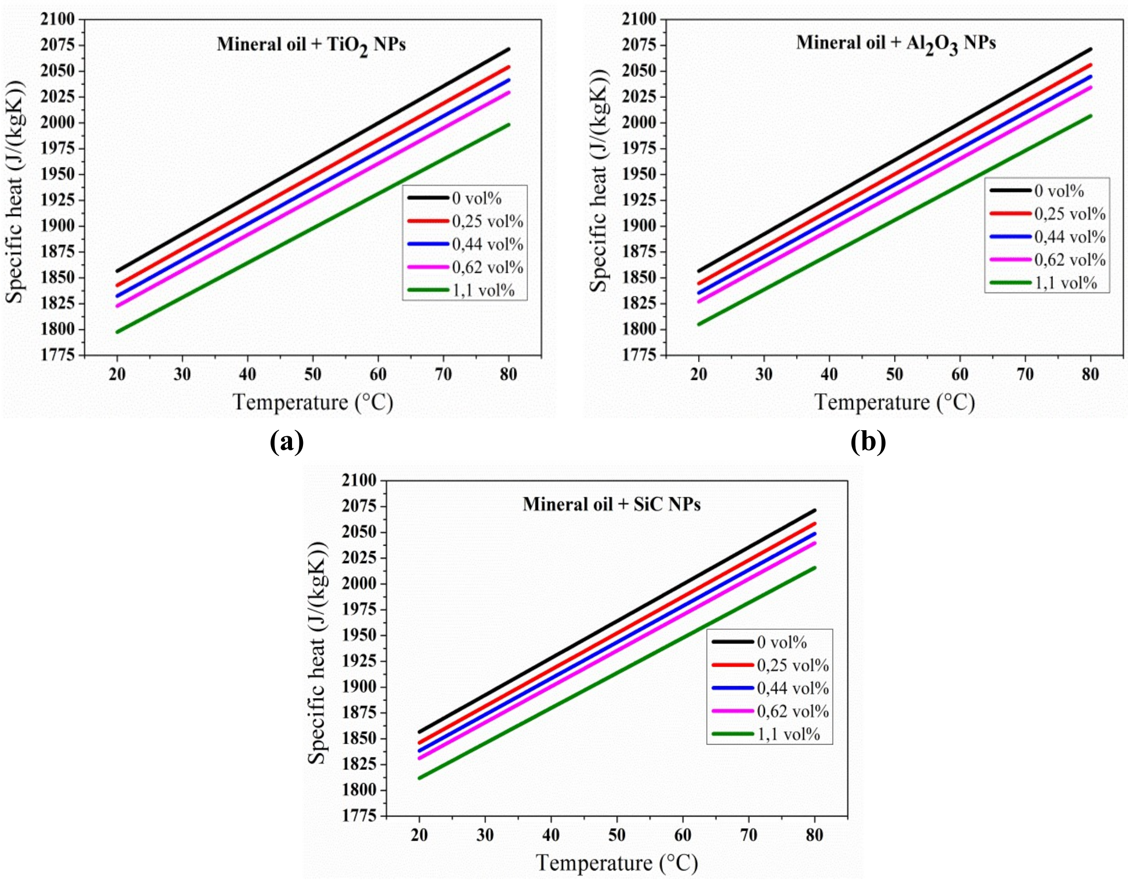



**(c)**

**Figure 5. Viscosity of pure dielectric oil and dielectric nanofluids: (a) MO + $TiO_2$ NPs; (b) MO + $Al_2O_3$ NPs; (c) MO + SiC NPs**

**5.3. Specific heat**

Figure 6 illustrate the variation of specific heat as a function of insulating and nanoparticle-enhanced dielectric fluid's temperature and volume concentration. The results showed that adding NPs to the insulating fluid negatively affects the specific heat, as the percentage of nanoparticles in the base fluid increases, the specific heat decreases due to the high value of the specific heat of the mineral oil compared to NPs. The highest results were recorded at a volume concentration of 0 vol%, followed, by 0.25 vol%, 0.44 vol%, 0.62 vol%, and 1.1 vol%, respectively. However, with increasing temperature, the specific heat was positively affected, which could help in enhancing the cooling efficiency under the harsh operating conditions of transformers. On the other hand, a difference in the specific heat of the DNFs was observed by changing the type of NPs. conductive nanoparticles (SiC) provided the best enhancement efficiency, followed by insulating nanoparticles ($Al_2O_3$) and then semiconductor nanoparticles ($TiO_2$). Specific heat plays a crucial role in determining the cooling capacity of the insulating liquid. The higher its value, the better the heat transfer efficiency [17], the decrease in the thermal capacity of the insulating liquid when adding NPs is one of the most important drawbacks of DNFs.




(c)

**Figure 6. Specific heat of pure dielectric oil and dielectric nanofluids: (a) MO + $TiO_2$ NPs; (b) MO + $Al_2O_3$ NPs; (c) MO + SiC NPs**

### 5.4. Density

Figure 7 gives the change in density of the dielectric nanofluid as a function of temperature and volume concentration. The results show a change in the density of the dielectric fluid when increasing the volume concentration of NPs, where the highest values were at 1.1 vol%, followed, respectively, by 0.62 vol%, then 0.44 vol%, then 0.25 vol%, and then 0 vol%. In addition, the simulation results highlighted the role of the type of NPs in determining the density performance of the DNFs. The semiconductor nanoparticles of titanium oxide ($TiO_2$) presented the highest density values for the nanofluid, followed by the dielectric nanoparticles of aluminum oxide ($Al_2O_3$), and then the conductive nanoparticles of silicon carbide (SiC). The increase in temperature led to a decrease in the density values for all samples used in the study. In general, the insulating fluid used in transformers must have a relatively low density to conduct heat well. Adding high-density solid nanoparticles to the insulating liquid negatively affects the heat transfer efficiency, which results in a decrease in the pumping capacity and an increase in the amount of energy consumption [42].

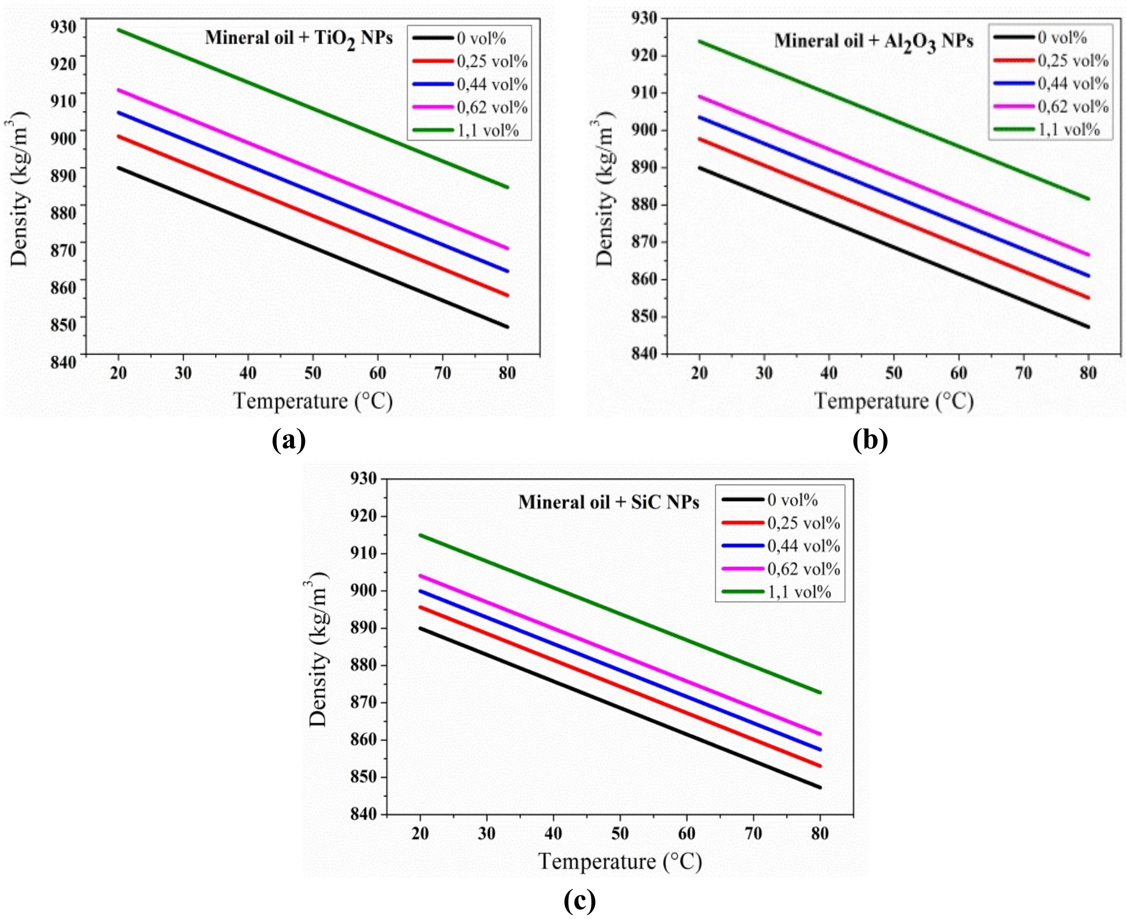



**Figure 7. Density of pure dielectric oil and dielectric nanofluids: (a) MO + $TiO_2$ NPs; (b) MO + $Al_2O_3$ NPs; (c) MO + SiC NPs**

## 6. Validation

The finite element method provides a numerical approach that can give an idea of the results of any nanofluid mixture before conducting field experiments. In this section, we validate the numerical modeling by comparing the calculated results with those obtained from experimental measurements. This numerical simulation has been relied on nanoparticles of metal oxides (SiC, $TiO_2$, and $Al_2O_3$), which is among the most used nanoparticles in dielectric nanofluids due to their high stability, and the volume concentration range recommended in the literature (volume fraction below 1%) to avoid the consequences of excess viscosity [5], in addition to mineral oil of petroleum origin as a basic fluid. Despite the incompatibility of the characteristics of the nanoparticles adopted in numerical modeling (NPs loading, type and size of the NPs, the type of base liquid) with experimental measurements [22, 37, 43], the comparison was made with the literature available to confirm the results of the numerical simulations qualitatively where the comparison showed a convergence in the values of the thermophysical parameters.

Tables 2, 3, 4 and 5 show a comparison of the results of numerical modeling of the thermophysical properties of dielectric nanofluids with those obtained by experimental measurements at 60 °C.

**Table 2. Comparison of numerical modeling results of thermal conductivity in dielectric nanofluids with experimentally measured values at 60 °C**

| Method | Base fluids | NPs parameters | NPs material | NPs loading | Thermal conductivity $k$ [W.m$^{-1}$K$^{-1}$] |
|---|---|---|---|---|---|
| Numerical modeling | Mineral oil | – | – | 0 vol% | 0.12721 |
| | | Spherical shapes Size → 15nm | $TiO_2$ | 0.25 vol% | 0.12814 |
| | | | | 0.62 vol% | 0.12950 |
| | | | | 1.1 vol% | 0.13129 |
| | | | $Al_2O_3$ | 0.25 vol% | 0.12817 |
| | | | | 0.62 vol% | 0.12958 |
| | | | | 1.1 vol% | 0.13143 |
| | | | SiC | 0.25 vol% | 0.12818 |
| | | | | 0.62 vol% | 0.12960 |
| | | | | 1.1 vol% | 0.13146 |
| Experimental | Transformer oil, ref. [37] | – | – | 0 vol % | 0.10626 |
| | | Size → 3-5 nm | $TiO_2$ | 0.002 vol % | 0.10816 |
| | | | | 0.008 vol % | 0.11013 |
| | | | | 0.012 vol % | 0.11043 |
| | Coconut oil, ref. [37] | – | – | 0 vol % | 0.15211 |
| | | Size → 3-5 nm | $TiO_2$ | 0.002 vol % | 0.15237 |
| | | | | 0.008 vol % | 0.15309 |
| | | | | 0.012 vol % | 0.15349 |
| | Soybean oil, ref. [22] | – | – | 0 wt% | 0.51182 |
| | | Spherical shapes Size → $Al_2O_3$ <13 nm $TiO_2$ <21 nm | $Al_2O_3$-$TiO_2$ | 0.2 wt% | 0.52719 |
| | | | | 0.4 wt% | 0.52905 |
| | | | | 0.6 wt% | 0.54395 |
| | Palm oil, ref. [22] | – | – | 0 wt% | 0.45454 |
| | | Spherical shapes Size → $Al_2O_3$ <13 nm $TiO_2$ <21 nm | $Al_2O_3$-$TiO_2$ | 0.2 wt% | 0.53909 |
| | | | | 0.4 wt% | 0.58136 |
| | | | | 0.6 wt% | 0.62636 |
| | Natural ester oil, ref. [43] | – | – | 0 % w/w | 0,12398 |
| | | Size → 50 nm | SiC | 0.004 % w/w | 0,18872 |
| | | Size → 21 nm | $TiO_2$ | 0.004 % w/w | 0,15257 |

**Table 3. Comparison of numerical modeling results of specific heat in insulating nanofluids with experimentally measured values at 60 °C**

| Method | Base fluids | NPs parameters | NPs material | NPs loading | Specific heat $C_p$ [J.kg$^{-1}$K$^{-1}$] |
|---|---|---|---|---|---|
| Numerical modeling | Mineral oil | – | – | 0 vol% | 2001.0981 |
| | | Spherical shapes Size → 15nm | $TiO_2$ | 0.25 vol% | 1984.6226 |
| | | | | 0.62 vol% | 1961.4263 |
| | | | | 1.1 vol% | 1932.2984 |
| | | | $Al_2O_3$ | 0.25 vol% | 1986.5680 |
| | | | | 0.62 vol% | 1966.1423 |
| | | | | 1.1 vol% | 1940.4259 |
| | | | SiC | 0.25 vol% | 1988.6011 |
| | | | | 0.62 vol% | 1971.0181 |
| | | | | 1.1 vol% | 1948.7103 |
| **Method** | **Base fluids** | **NPs parameters** | **NPs material** | **NPs loading** | **Volumetric heat capacity [× 10$^3$ J.m$^{-3}$K$^{-1}$]** |
| Experimental, ref. [37] | Transformer oil | – | – | 0 vol % | 1359.4252 |
| | | Size → 3-5 nm | $TiO_2$ | 0.002 vol % | 1389.3096 |
| | | | | 0.004 vol % | 1399.8843 |
| | | | | 0.012 vol % | 1409.5395 |
| | Coconut oil | Size → 3-5 nm | $TiO_2$ | 0.004 vol % | 1859.5778 |
| | | | | 0.012 vol % | 1869.6042 |

**Table 4. Comparison of numerical modeling results of dynamic viscosity in dielectric nanofluids with experimentally measured values at 60 °C**

| Method | Base fluids | NPs parameters | NPs material | NPs loading | Dynamic viscosity $\mu$ [kg.m$^{-1}$s$^{-1}$] |
|---|---|---|---|---|---|
| **Numerical modeling** | Mineral oil | – | – | 0 vol% | 0.00689 |
| | | Spherical shapes<br>Size → 15 nm | $TiO_2$ | 0.25 vol% | 0.00694 |
| | | | | 0.62 vol% | 0.00700 |
| | | | | 1.1 vol% | 0.00709 |
| | | | $Al_2O_3$ | 0.25 vol% | 0.00694 |
| | | | | 0.62 vol% | 0.00700 |
| | | | | 1.1 vol% | 0.00709 |
| | | | SiC | 0.25 vol% | 0.00694 |
| | | | | 0.62 vol% | 0.00700 |
| | | | | 1.1 vol% | 0.00709 |
| **Experimental, ref. [22]** | Soybean oil | – | – | 0 wt% | 0.01810 |
| | | Spherical shapes<br>Size →<br>$Al_2O_3$ <13 nm<br>$TiO_2$ <21 nm | $Al_2O_3$-$TiO_2$ | 0.2 wt% | 0.01761 |
| | | | | 0.4 wt% | 0.02006 |
| | | | | 0.6 wt% | 0.01945 |
| | Palm oil | – | – | 0 wt% | 0.01739 |
| | | Spherical shapes<br>Size →<br>$Al_2O_3$ <13 nm<br>$TiO_2$ <21 nm | $Al_2O_3$-$TiO_2$ | 0.2 wt% | 0.01814 |
| | | | | 0.4 wt% | 0.01927 |
| | | | | 0.6 wt% | 0.02077 |
| | Coconut oil | – | – | 0 wt% | 0.01248 |
| | | Spherical shapes<br>Size →<br>$Al_2O_3$ <13 nm<br>$TiO_2$ <21 nm | $Al_2O_3$-$TiO_2$ | 0.2 wt% | 0.01323 |
| | | | | 0.4 wt% | 0.01373 |
| | | | | 0.6 wt% | 0.01456 |

**Table 5. Comparison of numerical modeling results of the density in dielectric nanofluids with experimentally measured values at 60 °C**

| Method | Base fluids | NPs parameters | NPs material | NPs loading | Density $\rho$ [kg.m$^{-3}$] |
|---|---|---|---|---|---|
| **Numerical modeling** | Mineral oil | – | – | 0 vol% | 861.2504 |
| | | Spherical shapes<br>Size →15nm | $TiO_2$ | 0.25 vol% | 869.8219 |
| | | | | 0.62 vol% | 882.3595 |
| | | | | 1.1 vol% | 898.6246 |
| | | | $Al_2O_3$ | 0.25 vol% | 869.1219 |
| | | | | 0.62 vol% | 880.6236 |
| | | | | 1.1 vol% | 895.5448 |
| | | | SiC | 0.25 vol% | 867.0969 |
| | | | | 0.62 vol% | 875.6015 |
| | | | | 1.1 vol% | 886.6347 |
| **Experimental, ref. [22]** | Soybean oil | – | – | 0 wt% | 892.4809 |
| | | Spherical shapes<br>Size →<br>$Al_2O_3$ <13 nm<br>$TiO_2$ <21 nm | $Al_2O_3$-$TiO_2$ | 0.2 wt% | 894.5594 |
| | | | | 0.4 wt% | 895.5987 |
| | | | | 0.6 wt% | 896.4301 |
| | Palm oil | – | – | 0 wt% | 884.3548 |
| | | Spherical shapes<br>Size →<br>$Al_2O_3$ <13 nm<br>$TiO_2$ <21 nm | $Al_2O_3$-$TiO_2$ | 0.4 wt% | 883.4216 |
| | | | | 0.6 wt% | 888.5023 |
| | Coconut oil | – | – | 0 wt% | 892.4363 |
| | | Spherical shapes<br>Size →<br>$Al_2O_3$ <13 nm<br>$TiO_2$ <21 nm | $Al_2O_3$-$TiO_2$ | 0.2 wt% | 892.7423 |
| | | | | 0.6 wt% | 895.7014 |

Comparison of numerical modeling results with experimental measurements showed almost convergence in the values of thermophysical properties of the insulating nanofluid (thermal conductivity, viscosity, specific heat, and density) despite the different parameters of the nanoparticles and the base fluid. The experimental results of the vegetable oil-based nanofluid samples presented higher values of thermophysical properties compared to the numerical modeling results of the mineral oil-based nanofluid.

In light of that, the mechanisms underlying the change in the heat transfer capabilities of NFs are of great importance in understanding thermal behavior. the researchers simulated and experimentally studied the thermal behavior of dielectric nanofluids to identify the possible mechanisms behind this interesting enhancement. The mechanisms of heat transfer in NFs have been explained according to five main theories, which are the Brownian movement of NPs in liquids that are caused by the heat, conductive bridges due to aggregation of NPs in the liquid, behavior of the interface between the particles and the liquid (the nanolayer at the liquid/particle interface), Thermophoretic effect, and ballistic phonon transport [4, 5, 32]. understanding the mechanisms and behavior of dielectric nanofluids will help overcome the challenges and accelerate their practical application.

## 7. Obstacles and challenges associated with dielectric nanofluids

Over the past two decades, since the emergence of the possibility of applying nanofluids in transformer oils. The thermoelectric capabilities of dielectric nanofluids have been confirmed [5], where the thoughtful incorporation of NPs with unique properties into the insulating fluids has led to an increase in their performance [1]. Despite all these positive results achieved in the field, there are still some obstacles and challenges associated with practical applications. Some of the shortcomings and challenges of DNFs are presented as follows:

- High production and processing cost [1].
- Poor stability of dielectric nanofluids [1].
- Toxic effect of NPs on the environment and living organisms [4].
- Enhancing compatibility between the base fluid and NPs through modifications of interface properties [32].
- Lack of consensus on the quantities, types, shapes and sizes of NPs suitable for application in dielectric fluid [18].
- DNFs compatibility relationship with other components of the transformer [19].
- Conflict with low specific heat [17].
- Overcoming high viscosity and density [17].
- Reducing pressure drop resulting from the presence of NPs in the dielectric fluid and the associated pumping power requirements [32].
- Changes in transformer design while using NFs as dielectric medium [19].
- Limitations and inaccuracy of currently available theoretical models for predicting the values of thermal and electrical properties of DNFs [19].
- Develop accurate theoretical models valid for all types of DNFs taking into account all variables (NPs concentration, NPs type, NPs shape and size, base fluid type, temperature, additives, agglomeration).
- Development of simulation models for DNFs taking into account as many variables as possible.

- The effectiveness of insulating NFs and their evolution over time under exposure to different electrical, thermal, chemical, and mechanical stresses [5].
- Production and development of environmentally friendly dielectric nanofluids [21].
- Knowing the ability of DNFs to support high temperatures, magnetic fields, humidity, and potential stresses that the insulating fluid is subjected to during the reckless operation of the transformer [5].

**8. Conclusion**

In this work, a thermal model was developed using the FEM to predict the role of NPs in influencing the TPHPs of insulating oils used in power transformers and to study the factors affecting of both thermal conductivity, viscosity, specific heat, and density. The results obtained from numerical modeling confirmed the ability of NPs to improve the thermophysical properties of MO, providing a set of data that can be used in future experiments for nanofluid applications in high-voltage devices, which can be summarized in the following points:

- An increase in the amount of NPs in MO leads to an increase in the values of both thermal conductivity, viscosity, and density. It was noted from the results that the best values were recorded at a volume concentration of 1.1 vol%, followed by 0.62 vol%, 0.44 vol%,0.25 vol%, and 0 vol%, respectively.
- On the contrary, increasing the volume concentration had a negative effect on the specific heat of the DNFs, as a decrease in the specific heat of the insulating fluid was observed when NPs were added. The highest specific heat values were recorded at a volume concentration of 0 vol% (mineral oil) followed, respectively, by 0.25 vol%, 0.44 vol%, 0.62 vol%, and 1.1 vol%.
- The type of NPs has a prominent role in determining the thermal properties of NFs, as variation was observed in the TPHPs of the DNFs samples used in the study depending on the type of NPs.
- The conductive nanoparticles (SiC) were the most efficient in terms of increasing the thermal conductivity and specific heat values of the DNFs, followed respectively by insulating nanoparticles $Al_2O_3$, then semiconducting nanoparticles $TiO_2$.
- Regarding the effect of the type of nanoparticles (SiC, $TiO_2$, and $Al_2O_3$) on the viscosity of the DNFs, it was observed through the results of digital modeling that there is stability in the viscosity values when changing the type of NPs in the insulating fluid (the type of NPs does not affect the viscosity of the DNFs).
- Titanium oxide ($TiO_2$) semiconductor nanoparticles presented the highest density values for the DNFs followed respectively by Aluminum oxide ($Al_2O_3$) dielectric nanoparticles, and then silicon carbide nanoparticles (SiC) conductive nanoparticles.
- An increase in temperature affects the properties of DNFs in a negative way, as it was observed from the results of a decrease in the values of both thermal conductivity, viscosity and density of the DNFs with increasing temperature.
- On the contrary, the specific heat improved when the temperature increased.
- The best values of thermal conductivity, viscosity and density of the DNFs were recorded at 20 °C, while the lowest values were recorded at 80 °C.
- The highest specific heat values were at a temperature of 80 °C, while the lowest was of specific heat recorded at 20°C.

In general, the results presented a variation in the values of the TPHPs of the dielectric oil when NPs were added, as the volume concentration, type of NPs, and temperature played an effective role in influencing the properties of the DNFs. The thermal conductivity value of the MO was improved when NPs were added, which contributes to improving the cooling capacity. In addition, the increase in viscosity and density leads to a decrease in pressure and an increase in friction, and thus higher pumping requirements. On the other hand, the specific heat of the MO decreased when NPs were added, which negatively affects the cooling properties of the liquid insulating media used in power transformers.

The real application of dielectric nanofluids in electrical transformers requires in-depth knowledge of the types, shapes, sizes and concentrations of suitable nanoparticles to achieve a practical insight into the ideal balance between the thermophysical (thermal conductivity, viscosity, heat capacity, density) properties of insulating oils and to determine the nanofluid blend that would enhance the maximum possible parameters.

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**Nomenclature**

| | | | |
|---|---|---|---|
| ***Latin symbols*** | | $\rho$ | Density [kg.m$^{-3}$] |
| $C_p$ | Specific heat [J.kg$^{-1}$K$^{-1}$] | $\phi$ | Volume concentration [-] |
| $F$ | Volume force vector [N.m$^{-3}$] | ***Subscripts*** | |
| I | Identity matrix [-] | bf | Base fluid |
| $k$ | Thermal conductivity [W.m$^{-1}$K$^{-1}$] | nf | Nanoflids |
| $K$ | Stress tensor [N.m$^{-2}$] | np | Nanoparticle |
| $p$ | Pressure [Pa] | ***Abbreviations*** | |
| $Q$ | Heat source [W.m$^{-2}$] | DNFs | Dielectric nanofluids |
| $t$ | Time [s] | FEM | Finite element method |
| $T$ | Temperature [K] | MO | Mineral oils |
| u | Flow velocity [m.s$^{-1}$] | NFs | Nanofluids |
| $V$ | Volume [m$^3$] | NPs | Nanoparticles |
| ***Greek symbols*** | | spf | Single-phase fluid |
| $\mu$ | Dynamic viscosity [kg.m$^{-1}$s$^{-1}$] | TPHPs | Thermophysical properties |
| $\Psi$ | Sphericity ($\Psi$ = 1 for spherical particles) [-] | ASME | American Society of Mechanical Engineers |

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