# THERMAL CONDUCTIVITY MODELING OF DIELECTRIC OILS-BASED NANOFLUIDS USING THE FINITE ELEMENT METHOD

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**Abstract:**
The enhancement of the thermal conductivity of dielectric oils has a positive effect on the performance of electrical equipment that uses these oils as a cooling medium. Nanofluids (NFs) have inspired high-voltage engineers to use them as alternative fluids in power transformers due to their impressive heat transfer and insulation compared to traditional dielectric oils. The present study is a numerical simulation by COMSOL Multiphysics of the thermal conductivity of NFs based on dielectric oils used in power transformers, to identify the effect of temperature, the concentration of nanoparticles (NPs), type of insulating fluid and NPs on thermal conductivity. The NFs were modeled inside a cube using the finite element method (FEM) by applying a temperature gradient. Several types of NPs were used (SiC, ZnO, $TiO_2$, and $Al_2O_3$) in addition to several volume concentrations (0%, 0.001%, 0.002%, 0.01%, and 0.02%). The results showed a significant improvement in the thermal conductivity of the NFs with increasing concentration since the best results were recorded at an estimated volume concentration of 0.02%, while the lowest results were obtained for samples using a volume concentration estimated at 0.001%. The base fluid (BF) type and NPs play a dominant role in the thermal performance of the NFs, as the vegetable oil-based nanofluid provided the highest thermal conductivity values and silicon carbides (SiC) was the best NPs used in this study. However, a decrease in thermal transfer capacities was observed for all samples with increasing temperature.

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## 1. INTRODUCTION

Electricity is the fundamental basis for the development of the economy and the well-being of societies. The growing demand for electrical energy has increased enormous pressures on the stability of the grid. The electricity grid must have the capacity to meet the enormous demand for energy, and resist reckless working conditions to ensure a safe and stable electricity supply [1]. The development of electrical networks has led to the search for contemporary high-reliability devices to ensure the efficiency of electrical transmission. Insulating materials play an important role in the healthy and reliable operation of power devices such as circuit breakers, switches, capacitors, and transformers, as the lifespan of these devices is related to the condition and properties of these insulating materials [2].

The transformer is one of the most essential elements in electrical networks because it serves as a vital link in the transport and distribution of electrical energy [3]. This electrical component is also reliable in continuous operations with a 30 to 40 year service life it is known to be expensive and has a direct impact on the operation of the

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network any fault in this device leads to network interruptions and consequently significant economic losses [4]. The magnetic circuit and the coils are the primary loss sources in transformers with cooling oils. All of these losses produce heat, which must be transferred away to the external environment without causing the core, winding, or structural components to become too hot, which could damage the insulation. It is well known that the oil's contact with the coils and magnetic core causes the transfer of heat from those to the latter, where the other components of the cooling system discharge heat to the external environment through conduction, convection, and radiation [5,6].

The main function of insulating oils is to provide cooling to protect the core and coils by filling the voids with insulating materials [7] because the internal heat of the transformer, if left, can cause serious danger, and this is no better than oils for transporting it overseas, as the oil easily penetrates between the coils and the heat is transferred. Then, the process of expelling the heat contained in the oil takes place either by natural convection or by forced convection. And to ensure the oil's ability to expel this heat under different operating conditions and over a wide range of temperatures, several characteristics related to viscosity, thermal conductivity, boiling point and evaporation point must be available in oils. The functions of transformer oils are not limited to heat transfer, as they have other roles such as insulation, oxidation prevention and fault detection [4,8].

Mineral oils (MO) are among the most used insulating oils in high-voltage equipment due to their good performance, but they have disadvantages related to the environmental aspect, as they are very toxic, have a short lifespan, and are a non-renewable resource. In response to these issues, vegetable oil (VO) has been introduced as alternatives to MO, as they are an environmentally friendly renewable resource and have a high flash point. However, researchers seek to improve the heat transfer capabilities of these insulating fluids by adding NPs [9,10], The term NFs was introduced to improve the properties of fluids by researchers in 1995 [11]. It has been proven that NFs have great potential to improve the thermal conductivity of coolants used in transformers, thanks to the solid NPs which modify the properties of these insulating oils and thus absorb more heat in high voltage equipment, which reduces heat loss and improve transformer performance [12,13].

NFs are a mixture of single or multiple nanoparticles of nanometric dimensions suspended in a specific percentage in a dielectric fluid [14]. NFs have emerged as very promising solutions for use as alternative fluids in electrical equipment due to their exceptional thermal and dielectric performances. The application of nanotechnology to increase device properties is a major research topic as nanofluids have attracted interest in various engineering applications such as high voltage engineering, automotive, solar power equipment, medicine, mechanics, etc [14,1].

The study of the mechanisms of increasing thermal conductivity is of great importance for increasing the performance and capabilities of devices. Transformer failures resulting from high temperatures constitute 12.66% of the total causes of transformer failure [1]. NFs have been proposed as potential alternatives to cooling oils used in transformers. Many researchers and research groups have focused on the thermophysical properties of NFs, including thermal conductivity, which is of great importance in cooling systems [6,7].

Many studies have been carried out on the mechanisms and methods to improve the thermal conductivity and electrical insulation of transformer insulating oils using NFs by adopting several techniques and investigating auxiliary factors to increase the thermal properties and electrical. Numerous theoretical, numerical, and experimental works have been published on the thermal conductivity and electrical insulation of NFs [2].

Much research has focused on improving the thermal conductivity of NFs by studying and modeling the factors affecting this thermal conductivity, in addition to understanding the potential mechanisms behind this improvement [15]. This study presents numerical modeling of thermal conductivity of NFs by developing a model in COMSOL Multiphysics software, to highlight the role of factors affecting the thermal conductivity of NFs through numerical simulation by adding NPs to dielectric oils used in transformers of power at different volume concentrations and different types. The simulation results were compared for all samples used in the study, and these results provided a numerical approach to improving the properties of transformer oils through the application of nanotechnology for the possibility of applying Insulating nanofluids as alternatives to traditional oils.

## 2. FACTORS INFLUENCING THE THERMAL CONDUCTIVITY OF NFs BASED ON DIELECTRIC OILS

Thermal conductivity is one of the most important thermophysical properties responsible for efficient heat transfer [16]. The thermal conductivity range of dielectric oils used in power transformers is between 0.10 and 0.16 $Wm^{-1}K^{-1}$ [17]. To increase the thermal properties of these insulating oils, the researchers added different types, shapes, and amounts of NPs to form NFs [18]. NFs are a new generation of dielectric fluids used in high-voltage transformers [7,19]. They show a promising improvement in the heat transfer properties. Thanks to a better thermal conductivity of the solid particles than that of basic fluids as well as to the high specific surface of the NPs [20]. NFs are governed by a number of factors including Acidity (PH), Aggregation, NPs Concentration, NPs Shape, NPs Size, Surfactants, Thermal Conductivity Measurement Techniques, Effect of Temperature, Types of Fluid basis, and Types of NPs (Fig. 1). These factors contribute significantly to the thermal ability of dielectric materials [21,22].

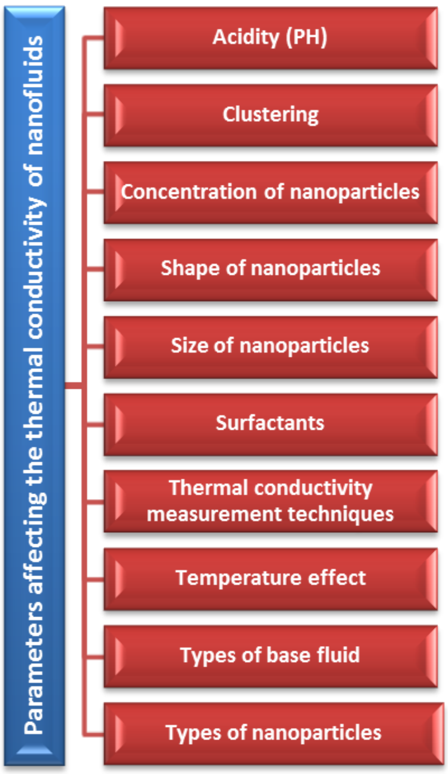


**Fig. 1.** Factors influencing the thermal conductivity of NFs

## 3. THE MECHANISM OF THERMAL CONDUCTIVITY IN NFs

In the field of heat transfer, NFs have proven their ability to improve the thermal performance of systems [16]. Thermal conductivity is the ability of the material to conduct heat, where the suspension of NPs modifies the thermal properties of dielectric fluids, and therefore greater heat absorption for the insulating fluid, which enhances the performance of high voltage equipment [7]. The researchers simulated and experimentally studied the thermal behavior of NFs to determine the possible mechanisms behind this interesting enhancement. Several mechanisms have been proposed to explain the noticeable increase in the thermal conductivity of NFs (Fig. 2). Such as the Brownian motion effect of NPs [23], Thermophoresis, Aggregation of NPs, Nanolayer at the liquid/particle interface, and the nature of heat transport in NPs [15,24].

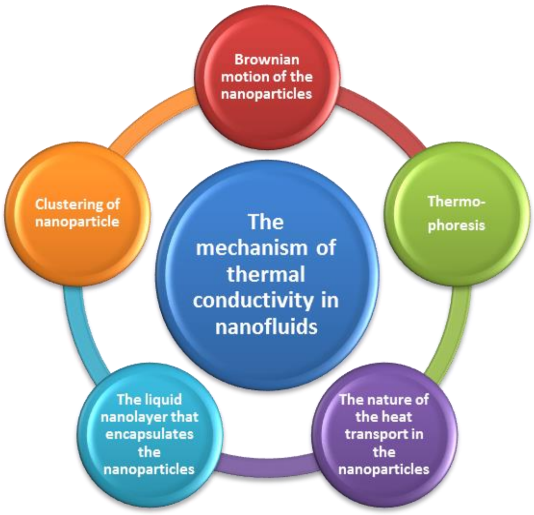


**Fig. 2.** The mechanism of thermal conductivity in NFs

## 4. NUMERICAL MODELING

### 4.1 Description of the Physical Problem

The finite element method is one of the widely used solutions to study problems related to dielectric media of high voltage devices [14]. In this study, a 3D model was developed using the Multiphysics COMSOL software (Fig. 3) to model the thermal conductivity of NFs based on insulating oils and determine the effect of different factors influencing this thermal conductivity (types of BF, types of NPs, temperature, volume concentration). All modeling steps are described in detail in Fig. 4 [25].

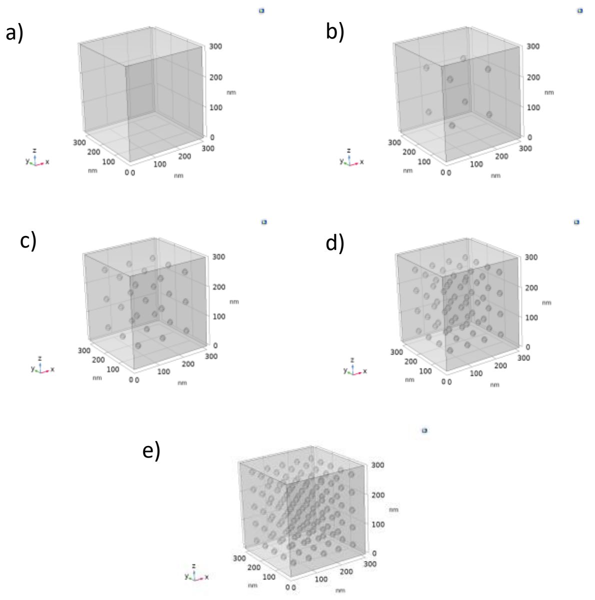


**Fig. 3.** Physical model geometry by COMSOL software for each volume concentration used in the study : (a) 0%; (b) 0.001%; (c) 0.004%; (d) 0.01%; (e) 0.02%

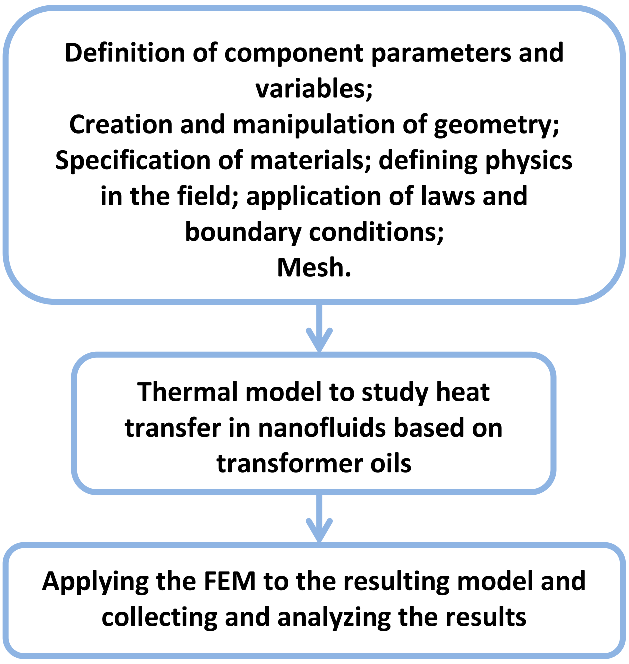


**Fig. 4.** Steps and methodology for approaching the problem studied by the finite element method

### 4.2 Mathematical Equation

The heat transfer module in COMSOL Multiphysics software provides users with interfaces and tools for heat transfer by conduction, convection, and radiation; the mathematical model for heat transfer in solids is based on the following equation [6,25]:

$$\rho C_p \frac{\partial T}{\partial t} - \nabla.(k\nabla T) = Q \quad (1)$$

The mathematical model for heat transfer in fluids is based on the following equation [6,25]:

$$\rho C_p \frac{\partial T}{\partial t} + \rho C_p \, u.\nabla T - \nabla.(k\nabla T) = Q \quad (2)$$

Where are: $\boldsymbol{\rho}$ is the material density (kg/m$^3$), $\boldsymbol{C_p}$ is the heat capacity (J/(kgK)), $\boldsymbol{T}$ is the temperature (k), **u** is the flow rate speed (m/s), $\boldsymbol{k}$ is the thermal conductivity (W/(mK)), $\boldsymbol{t}$ is the time (s) and $\boldsymbol{Q}$ is the heat source.

The temperatures of each liquid insulator vary with loads throughout the day and are a major concern in energy transmission and distribution. The temperature is not evaluated as an average, but as a "hot spot" temperature in the transformer windings. The insulation performance of transformer oil is a key factor for the normal operation of these devices [1]. In order to explore the performance of transformer oil under varying working conditions, the oil was selected in a varying temperature range where the right and left boundary temperature was fixed at 90°C and 20°C and the other walls were constant. According to the boundary conditions, the fluid velocity is zero, and therefore the heat transfer in this model depends on fluid heat conduction and not on fluid heat convection [26]. As well as the modeling of the NFs inside the cube is considered in stationary mode.

Fourier's law gives the conductive heat flux of the NFs, which can be expressed that result from the product of the thermal conductivity and the negative local temperature gradient. In composite materials, the heat flux depends on the value of the thermal conductivity of this mixture, which is given according to the following equation [25]:

$$q = -k_{nf}.\nabla T \quad (3)$$

Where is: $\boldsymbol{q}$ The conductive heat flux (W/m$^2$)

On the other hand, the calculation of the thermal conductivity of the biphasic mixture is approached by different classical relations; among these relations appear the Maxwell, Hamilton-Crosser, and Yu and Choi equations. In our study, we relied on the Maxwell model (4) to determine the thermal conductivity values of NFs; this model is more commonly used to predict the thermal conductivity of a compound material [20,27].

$$k_{nf} = \left[ \frac{2k_{bf} + k_p + (k_p - k_{bf})2\phi}{(2k_{bf} + k_p - (k_p - k_{bf})\phi} \right] k_{bf} \quad (4)$$

Where are: $\boldsymbol{k_{bf}}$ and $\boldsymbol{k_p}$ are the thermal conductivities of BF and NPs, respectively (W/(mK)),

$k_{nf}$ is the thermal conductivity of NFs (W/(mK)), $\phi$ is the volume concentration of NPs.

In this model, the study was limited to using NPs with a spherical shape and a fixed diameter of 10 nm.

### 4.3 Characteristics of the Materials Used

In the model for calculating the thermal conductivity of NFs, the input values are the thermal conductivity (***k***), the density ($\rho$), the viscosity (**μ**), and the heat capacity ($C_p$) for the NPs [28] and the insulating oil (Table 1) [29,30], these thermophysical properties indicated the ability of transformer oils to capture and dissipate heat to the outside environment [3]. In this modeling the square cube is filled with NFs of MO+SiC; VO+SiC; MO+ZnO; VO+ZnO; MO+$Al_2O_3$; VO+$Al_2O_3$; MO+$TiO_2$; VO+$TiO_2$ to determine the role of carrier fluid type and NPs on thermal behavior.

## 5. RESULT AND DISCUSSION

The simulation of a thermal model of the thermal conductivity of NFs is presented in this section using COMSOL Multiphysics, the NPs are stable in the dielectric liquid in addition to fixing the size and shape of the NPs. The modeling is introduced when the cube is filled with the NFs by the application of a temperature gradient (Fig. 5), The temperature of the right and left sides has been fixed at 90°C and 20°C to generate a flux of heat at the level of the cube. The simulation is processed with different volumetric concentrations of NFs samples (0%, 0.001%, 0.002%, 0.01%, and 0.02%).

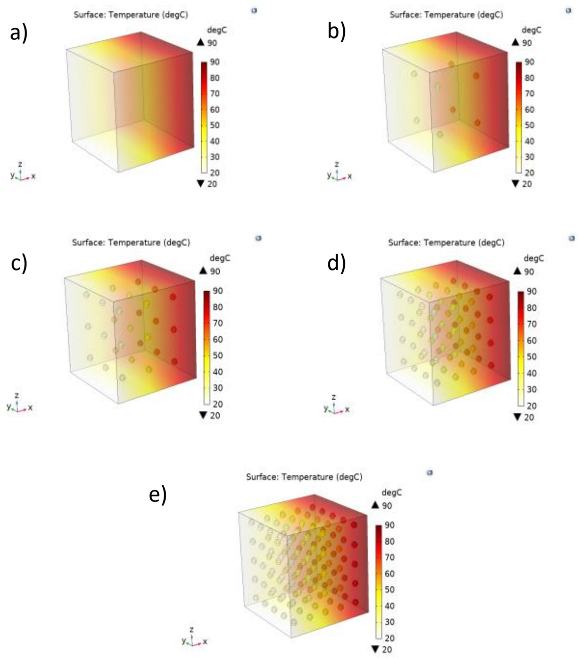


**Fig. 5.** Temperature distribution in a cube filled with NFs: a) 0%; b) 0.001%; c) 0.004%; d) 0.01%; e) 0.02%

**Table 1.** Properties of materials used

| Material | $\rho$ (kg/m³) | $C_p$ (J/(kgK)) | *k* (W/(mK)) | μ (kg/(ms)) |
|---|---|---|---|---|
| Mineral oil (MO) | 1098.72-0.712·T | 807.163+3.58·T | $0.1509\text{-}7.101\cdot10^{-5}\cdot T$ | $0.08467\text{-}0.0004\cdot T+5\cdot10^{-7}\cdot T^2$ |
| Vegetable oil (VO) | 1132-0.7243·*T* | 802.26+3.25·*T* | $0.1953\text{-}7.969\cdot10^{-5}\cdot T$ | $374.08\cdot e^{-0.029T}$ |
| $Al_2O_3$ NPs | 3970 | 765 | 40 | – |
| $TiO_2$ NPs | 4250 | 686.2 | 8.9538 | – |
| ZnO NPs | 5600 | 495 | 80 | – |
| SiC NPs | 3160 | 675 | 490 | – |

### 5.1 Effect of Temperature and Volume Concentration of NPs on the Thermal Conductivity of NFs

The Figs. 6 and 7 gives the results of modeling the thermal conductivity of NFs based on vegetable and mineral oils as a function of temperature; the curves show that the thermal conductivity of all the samples decreases with increasing temperature, the reason for this decrease is that the density of the carrier oil is lower at higher temperatures by its effect on the movement Brownian [6]. For the effect of the volume fraction of NFs, the presence of NPs in transformer oil positively affects heat transfer performance due to the higher thermal conductivity of solid NPs which generates higher heat flux than host fluids, whereas, increasing the concentration results in a greater heat flux thanks to the decrease in the separation distance between the NPs. This allows to improve the thermal conductivity values and thus improves the efficiency of the transformer oil. Fig. 8 and Table 2 show the role of concentration in increasing the heat flux of NFs.

High concentration of NPs leads to agglomeration which reduces the conductivity of NFs. Searching for the optimal concentration of NPs is important for improving the electrical and thermophysical properties of high-voltage devices. The simulation results highlighted the role of volume concentration on increasing thermal conductivity capabilities, as it was noted from the results that the best volume concentration used in the study is 0.02%, and the thermal performance of the NFs decreases with the decrease in the amount of NPs in the insulating fluid, as the lowest value of thermal conductivity was recorded at Concentration estimated at 0.001%.

In high-voltage devices, the temperature rise of transformers is linked to load changes throughout the day, as the increase in transformer temperatures leads to deterioration of the condition of the liquid insulator, which results in a decrease in the life span of the transformer [1]. Through the studied temperature range, it was found that the thermal conductivity capacity of NFs decreases with increasing temperature, as the ideal values of thermal conductivity for samples were recorded at 20 °C, while the lowest values were at 90 °C.

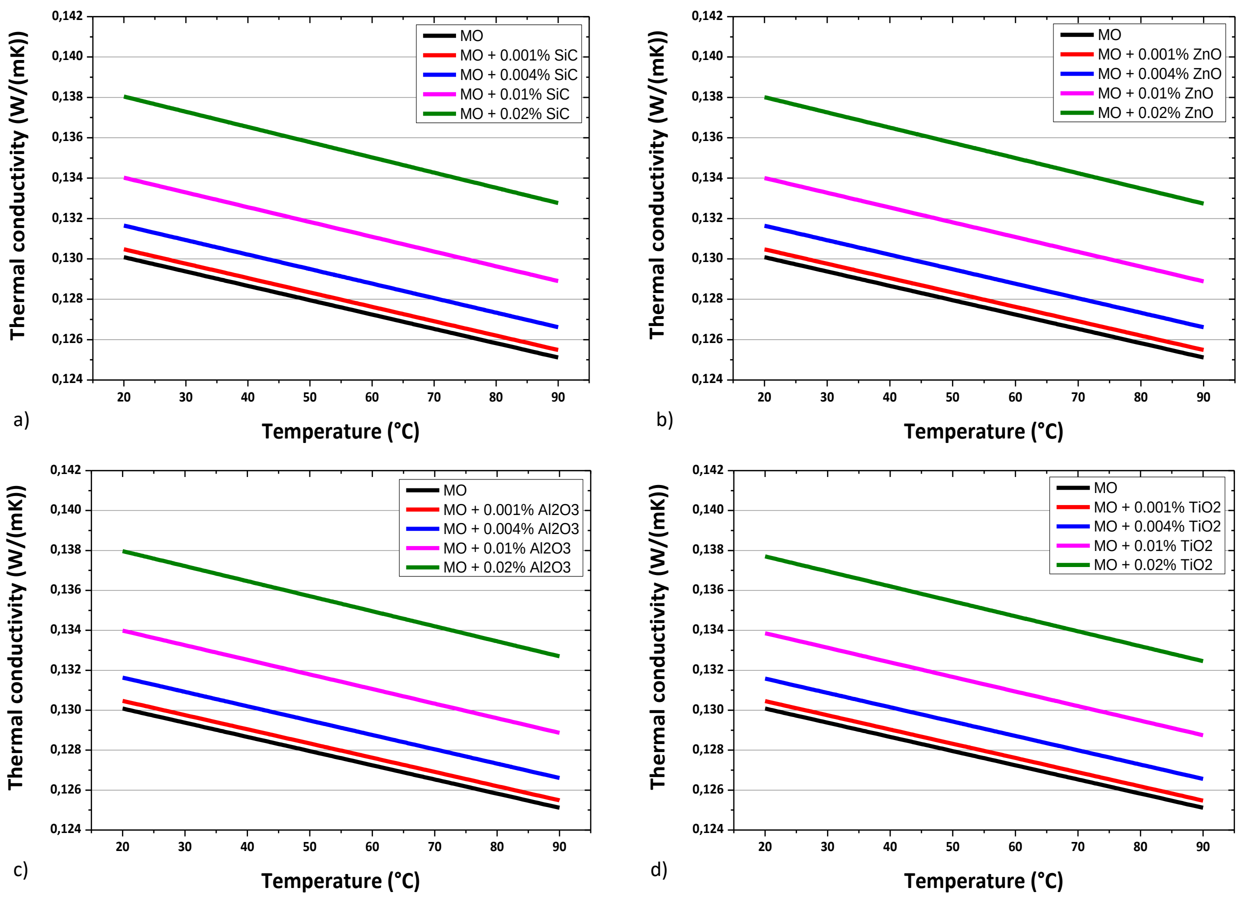


**Fig. 6.** Effect of volume concentration and temperature on the thermal conductivity of NF based on MO: a) MO+SiC; b) MO+ZnO; c) MO+$Al_2O_3$; d) MO+$TiO_2$

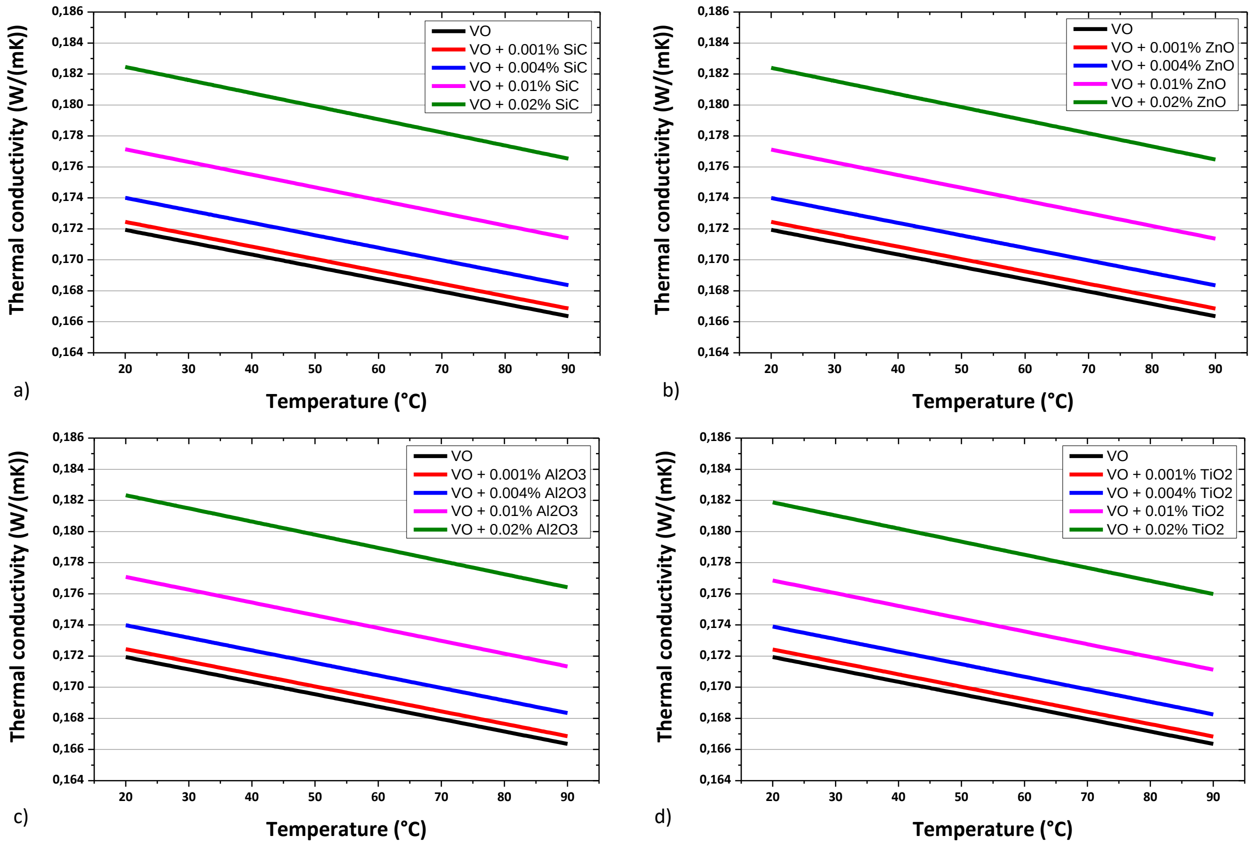


**Fig. 7.** Effect of volume concentration and temperature on the thermal conductivity of NF based on VO: a) VO+SiC; b) VO+ZnO; c) VO+$Al_2O_3$; d) VO+$TiO_2$

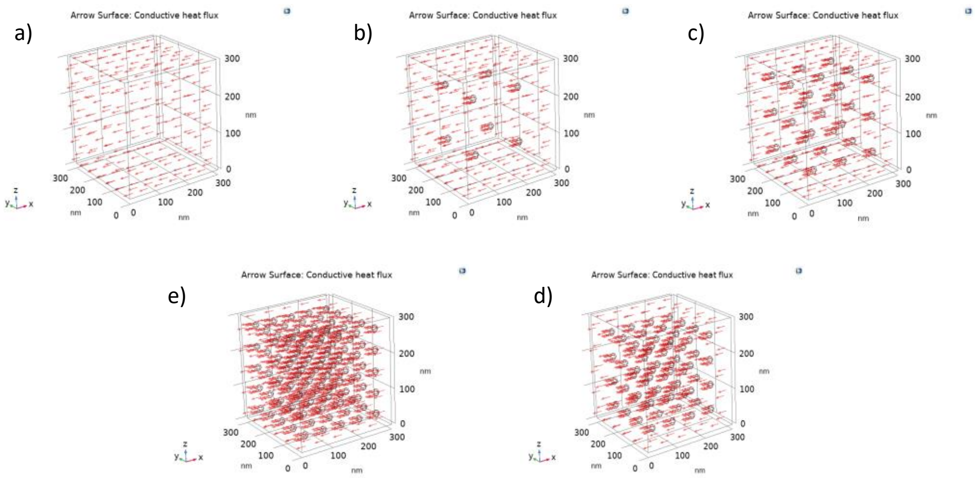


**Fig. 8.** Conductive heat flux of NFs: a) 0%; b) 0.001%; c) 0.004%; d) 0.01%; e) 0.02%

**Table 2.** Total heat flux for nanofluids

| Samples | Volume concentration | | | | |
|---|---|---|---|---|---|
| | **0.02%** | **0.01%** | **0.004%** | **0.001%** | **0%** |
| **Heat flux of MO + $TiO_2$ (W/nm$^2$)** | 0,031549 | 0,030668 | 0,030147 | 0,029888 | 0,029802 |
| **Heat flux of MO + $Al_2O_3$ (W/nm$^2$)** | 0,031609 | 0,030697 | 0,030158 | 0,029891 | |
| **Heat flux of MO + ZnO (W/nm$^2$)** | 0,031617 | 0,030701 | 0,03016 | 0,029891 | |
| **Heat flux of MO + SiC (W/nm$^2$)** | 0,031625 | 0,030705 | 0,030161 | 0,029892 | |
| **Heat flux of VO + $TiO_2$ (W/nm$^2$)** | 0,041784 | 0,040633 | 0,039952 | 0,039613 | 0,039501 |
| **Heat flux of VO + $Al_2O_3$ (W/nm$^2$)** | 0,041888 | 0,040684 | 0,039972 | 0,039618 | |
| **Heat flux of VO + ZnO (W/nm$^2$)** | 0,041904 | 0,040691 | 0,039975 | 0,039619 | |
| **Heat flux of VO + SiC (W/nm$^2$)** | 0,041917 | 0,040698 | 0,039977 | 0,03962 | |

## 5.2 Effect of the Type of BF and NPs on the Thermal Conductivity of NFs

The Fig. 9 illustrated a comparison of the thermal conductivity of NFs among all samples used for modeling at 20 °C. Where the results provided a convergence of thermal conductivity values for all NPs used (SiC, ZnO, $TiO_2$, and $Al_2O_3$), and on the other hand, the carrier fluid played a major role in improving the thermal properties, as NFs based on vegetable oils provided high thermal conductivity values compared to NFs based on mineral oils, and the difference between them was about 5%.

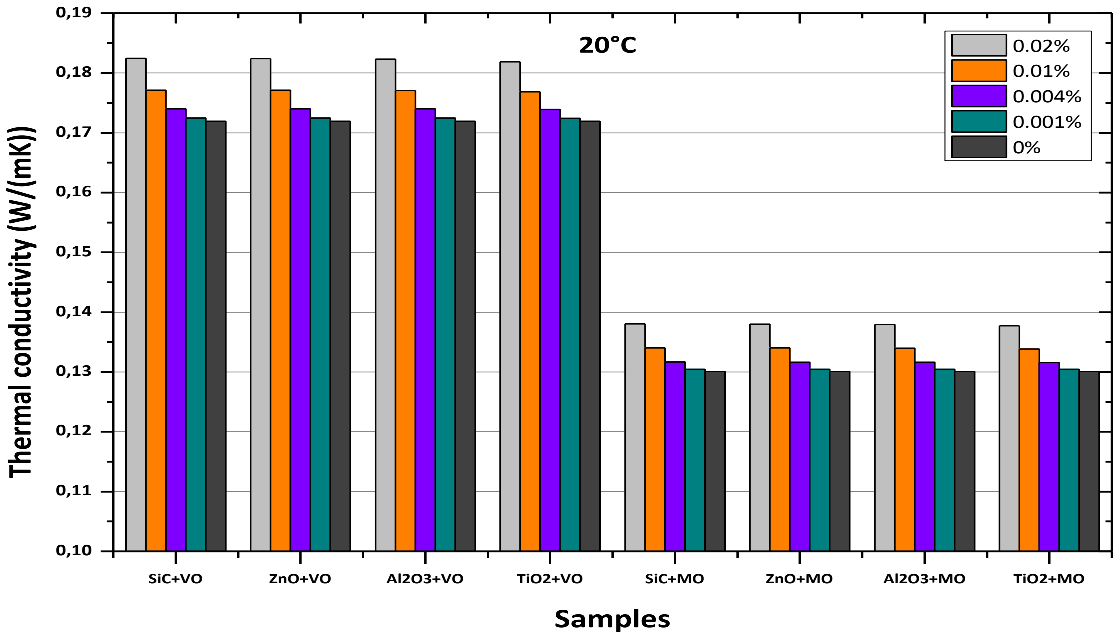


**Fig. 9.** Effect of NPs type and carrier oil on thermal conductivity at 20°C

Environmentally friendly vegetable fluids have been presented as potential alternatives to mineral oils because of their encouraging insulating and thermal qualities. They are naturally extracted from seeds or flowers. They attract many researchers to examine their effectiveness as insulating fluids in high-voltage equipment [1,2], and this has been observed through the results of numerical modeling. All nanofluid samples in which VO were used as base fluids provided higher thermal conductivity results compared to those based on MO, and this highlights the role of the base fluid in influencing the thermal conductivity of NFs.

The properties of NPs vary in terms of thermal conductivity, thermal capacity, density, and electrical conductivity, as these factors greatly affect the thermal performance of NFs. The effectiveness of the types of NPs on influencing the thermal capacity of NFs was studied, where four types of NPs were used separately (SiC, ZnO, $TiO_2$, and $Al_2O_3$). In transformer insulating oil, the best performing nanoparticles were SiC, followed respectively by ZnO, $Al_2O_3$, and $TiO_2$.

## 6. OBSTACLES ASSOCIATED WITH THE APPLICATION OF NANOFLUIDS IN POWER SYSTEMS

NFs have provided useful and positive solutions in various fields of life such as energy, medicine, pharmacy, industry, and others. However, although nanofluids have proven their effectiveness and ability to increase the performance of devices, they have some shortcomings that limit their practical applications (Fig. 10). which can be limited to the following points [31]:

- The small size of NPs and their ability to interact efficiently with the living environment and living organisms pose a serious threat to human health and the environment. The toxicity of NPs depends on the type of NPs, the concentration of the NPs, the time of exposure, and the size and shape of the NPs. It is extremely dangerous to human health and leads to various reactions on the skin and respiratory system and other parts of the human body and causes many diseases. They also cause very serious environmental degradation that affects the air, water, soil, and other living environments [31].

- The instability of NPs in the insulating liquid leads to a deterioration in the thermal properties of this insulating medium, as NPs tend to agglomerate due to their shape, size, concentration, and the attractive forces applied to them [2,31].
- The cost of producing and processing NFs is one of the hindering challenges that lead to restricting the use of NFs as insulating media in power transformers. Less expensive methods for NFs characterization should be sought and made available for commercial applications [2].

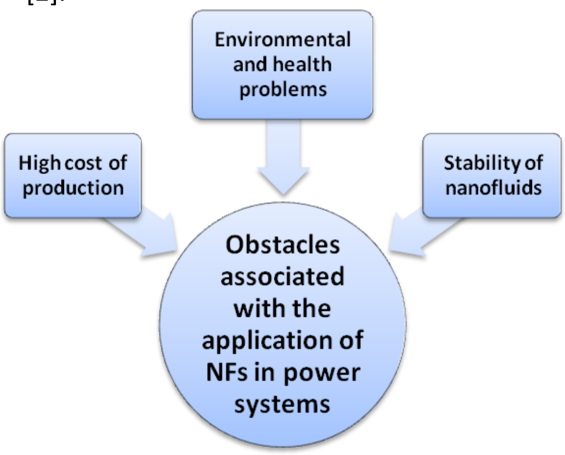


**Fig. 10.** Obstacles associated with the application of NFs in power systems

## 7. CONCLUSION

The finite element method provides a numerical approach to visualize the results of any nanofluid mixture using different types, sizes, and concentrations of NPs to predict suitable samples for any application before conducting field experiments. In this paper, the thermal conductivity of NFs was modeled using the COMSOL Multiphysics software to determine the factors affecting the heat transfer of insulating NFs, where the following results were observed.

- An increase in base fluid temperatures leads to a decrease in the thermal conductivity values of NFs, which affects the thermal performance of transformer oils.
- The type of NPs and BF have a major role in the thermal behavior of NFs, because by changing the type of carrier oil and NPs, the thermal conductivity values change, and we noticed through the results a convergence of the values of thermal conductivity for all samples.
- With the increase in the volume fraction of the NPs, the thermal conductivity performances of all the samples used increase. The results also showed that NFs based on vegetable oils have better thermal conductivity capacities than those based on mineral oils.
- The best thermal conductivity values for the mixture between VO and silicon carbide (SiC) nanoparticles at a volume concentration of 0.02%.
- The lowest thermal conductivity values were also recorded for the mixture between MO and titanium oxide ($TiO_2$) nanoparticles at a volume concentration of 0.001%.
- It is evident from the results that the best NPs used in the study is silicon carbide (SiC) and the best base liquid is VO, in addition to this, the most effective volume concentration is 0.02 %.
- The highest thermal conductivity performance was recorded at 20 °C, while the lowest performance was at 90 °C, and this is what was shown by the 34 samples studied.

The results obtained from numerical simulations confirmed the ability of NFs to improve insulating liquid media used in electrical transformers since positive results were obtained for all samples used in the study. However, some technical obstacles prevent the practical applications of NPs, related to the production cost and the stability of NPs in the cooling medium, in addition to their impact on the environment and human health.

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## Conflicts of Interest

The authors declare no conflict of interest.

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