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Nanofluids Technology for Improved Electrical Power Transformer Efficiency: An Experimental and Numerical Investigation

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تكنولوجيا الموائع النانوية لتحسين كفاءة محولات الطاقة الكهربائية: دراسة تجريبية وعددية

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ABSTRACT

An experimental and numerical study has been conducted to investigate how incorporating nanoparticles into transformer oil affects thermal behavior. This study aims to evaluate the impact of nanofluids on the efficiency and performance of electrical power transformers. Distribution electrical transformers must meet a number of essential criteria, including electrical insulation, safety concerns, and economic considerations. A numerical method was adopted using the ANSYS Fluent tool to model the actual test results and explain how nanoparticles affect thermal properties. It is advantageous because it outperforms mineral oils and makes a specific contribution to insulation and thermal gains. Therefore, it is possible to enhance the efficiency and life of transformers by improving certain qualities of transformer oil. The formation of hybrid nanofluids (CuO + Al2O3 + TiO2 + oil) with various concentrations (0.2%, 0.4%, and 0.6% w/v) and the creation of nanofluids (Fe3O4 + oil) with comparable concentrations will be the two main axes of the investigation. The findings demonstrated that nanofluids (Fe3O4) improve insulating efficiency and thermal conductivity while cooling the transformer at 0.6% w/v. With the addition of hybrid nanofluids (CuO, Al2O3, and TiO2), the dielectric increases directly with little to no change in the other parameters.

Keyword: Electrical power transformer, Heat transfer coefficient, Nanofluids, Transformer Oil, Thermal conductivity.

الملخص

تم إجراء دراسة تجريبية وعددية لمعرفة مدى تأثير دمج الجسيمات النانوية في زيت المحولات على السلوك الحراري. تهدف هذه الدراسة إلى تقييم تأثير الموائع النانوية على كفاءة وأداء محولات الطاقة الكهربائية. يجب أن تستوفي محولات التوزيع الكهربائية عددًا من المعايير الأساسية، بما في ذلك العزل الكهربائي، ومخاوف السلامة، تم استخدام برنامج ANSYS Fluent لنمذجة نتائج الاختبار الفعلية والاعتبارات الاقتصادية. حيث تم إجراء دراسة عددية باستخدام أداة وشرح كيفية تأثير الجسيمات النانوية على الخواص الحرارية. حيث إنه مفيد لأنه يتفوق على الزيوت المعدنية ويساهم بشكل خاص في العزل والمكاسب الحرارية. ولذلك فمن الممكن تعزيز كفاءة وعمر المحولات من خلال تحسين صفات معينة لزيت المحولات. إن تكوين الموائع النانوية الهجينة مع (CuO + Al2O3 + TiO2) النفط بتركيزات مختلفة (0.2%، 0.4%، و0.6% وزن/حجم) وإنشاء الموائع النانوية + Fe3O4) الزيت بتركيزات مماثلة سيكونان المحورين الرئيسيين للتحقيق. أظهرت النتائج أن السوائل النانوية (Fe3O4) تعمل على تحسين كفاءة العزل والتوصيل الحراري مع تبريد المحول بنسبة 0.6% وزن/حجم. مع إضافة السوائل النانوية الهجينة(CuO ، Al2O3، و(TiO2، يزداد العزل الكهربائي مباشرة مع تغيير بسيط أو عدم حدوث أي تغيير في المعلمات الأخرى.

الكلمات المفتاحية:، محولات القدرة الكهربائية، معامل انتقال الحرارة، الموائع النانوية، زيت المحولات، التوصيل الحراري

1. Introduction

Distribution electrical transformers have a shelf life and may operate for up to 50 years. The only item that needs to be checked regularly is the transformer oil. Which lengthens the transformer's lifespan and improves its efficiency; as a result, this study will concentrate on this factor due to its critical significance. Modern electrical power network transformers are among the most crucial components due to their high cost and lengthy lifespan. In addition, it is vital to consider economic development and optimal exploitation. It must be knowledgeable about potential issues and how to fix them [1][2].

The main purposes of electrical transformer oil include heat transmission, electrical insulation, oil circuit breakers, transformers, capacitors, reactors, insulators, bushings, and other electrical equipment diagnostics [3][4] Since nanotechnology allows for an improvement in the thermal properties as well as the creation of superior replacements for currently used oils [5] it was crucial to conduct real-world studies to ascertain how transformer oil was affected by nanotechnology. Therefore, over the past ten years, much research has been done on the term "Nanofluids," which is now widely used in the dielectric industry [6].

Due to their remarkable and distinctive characteristics, nanofluids have grown in popularity over the past few years. Even though there have lately been a few review papers on the thermal properties of nanofluids, it appears that some also covered the thermal, physical, and electrical aspects [7][8]. Research has focused on developing new transformer oil that can perform better than the current one. A novel class of insulating Nanofluids has been proposed by combining transformer oil with nanoparticles. Yu-zhen et al. [9] examined the morphology of Titanium oxide ($TiO2$) nanoparticles. The single-crystalline structure of the nanoparticles is demonstrated by $TiO2$'s consistent particle size distribution and average diameter of 6 nm when distributed in the fluid.

Research and studies are carried out to evaluate the extent of the alteration and whether it is positive or negative each time this nanomaterial is coupled with a specific type of oil transformer, and the findings are recorded. Metals (Cu, Ag, and Au), nitride ceramics (AlN, SiN), oxide ceramics (CuO), carbide ceramics (Sic, Tic), semiconductors (Sic), carbon nanotubes, and composite materials can all be used to make nanoparticles for usage in nanofluids. This composite material is made up of alloy nanoparticles (AL70 Cu 30) or nanoparticle core-polymer shell composites, as well as non-metallic, metallic, and other nanoparticle-containing substances, brand-new materials and systems, some of which are "doped" with molecules at the solid-liquid interface and may also exhibit useful properties.

V. Segal et al.[10] conducted the first study on the modification of Iron oxide (Fe_3O_4) nanoparticles. They found that its dielectric strength characteristic leads to exceptional dielectric breakdown output voltages (two times higher than mineral oil). To move electricity from one electrical system to another, drive transformers of two distinct sorts are used throughout. Transformers with and without oil are offered. Nonetheless, oil-filled transformers are the most common type used in electrical distribution networks[2].The oil's twin roles as an insulator and a cooling agent, protecting the core and winding, make the transformer perfect for outdoor usage.

This paper provides comprehensive information on these materials and their potential uses and insight into the insulating and thermal properties of transformer oil-based Nanofluids. In the current study, several Nanofluids are made by mixing nanoparticles with transformer oil. Then the resulting fluids' electrical, chemical and thermal properties are investigated experimentally and numerically. To predict the results that would be observed, it was necessary to carry out a numerical study in one of the CFD programs using control equations and equations for thermal and physical properties. This study used the ANSYS Fluent tool, version 2016.1, to mimic the actual test results and explain how nanoparticles affect thermal properties. After simulating the transformer with pure transformer oil initially, the solution is carried out using nanofluids (Fe_3O_4+Oil) with different concentrations of 0.2%, 0.4%, and 0.6% w/v and repeated using transformer oil-based hybrid nanofluids (CuO+oil, Al_2O_3+oil, TiO_2+oil) with volume fractions of 0.2%, 0.4%, and 0.6%.

2. Transformer Cooling Methods

The "transformer cooling" process involves distributing heat from the transformer to a safe level. Heat is mainly created through power loss. Although utility usage partially disperses heat, insulation failure will occur due to the transformer's increased temperature. Hence, transformers require a cooling system. The method of cooling transformers can be categorized. Cooling is used for dry-type and oil-immersion transformers [11][12]. In this investigation, nanofluids will be used to cool the transformer. In addition to being able to transfer heat and serve as electrical insulators, the oils used in transformers occasionally run the risk of becoming explosive or flammable [13]. In order to provide the ideal circumstances for running the transformer under loads, it is crucial to consider the physical properties of this fluid and potential upgrades. Insulation and heat transfer efficiency are the two most significant improvements to consider[14].

Since they were discovered, it has been feasible to use nanoparticles in various industries, including developing Nanofluids for transformer oils to improve specific oil properties[15]. Many tests and studies were conducted on numerous nanoparticle types to find out how they affected thermal conductivity and to pinpoint particular variants that possessed this property. Two different preparation methods can be used to prepare the nanofluid in a single step or in two steps. Since it is believed to be more compatible with oil, less expensive, and quicker to complete, the two-step method is one of the procedures used to create nanofluid[16][17]. To create nanoparticles, several techniques can be used to manufacture metal oxides, including Al2O3, Fe3O4, TiO2, CuO, and others[18], [19] in the second phase, the formation of the nanofluid, the choice of the nanoparticles must take into account essential properties such as thermal conductivity, dielectric, and permittivity. Each element of the nanoparticles is determined by the needs into which they are divided. One of the two approaches is typically utilized to prepare the nanofluid employing a conductor, semiconductor, and insulator[20] . The two-step method is generally employed for mixing nanoparticles in the base fluid using high shear mixing, ball milling, ultrasonic or magnetic stirring [21]. Al2O3, CuO, and TiO2 materials have been found to increase voltage breakdown at specific concentrations, according to several studies[22]. Moreover, at specific concentrations, the two-step method's Fe3O4 nanoparticles improve heat transfer [23].

3. Problem explanation

This article uses a 400 KVA transformer, a regular part of the Iraqi electrical grid, as a case study. **Figure 1** shows both the interior and exterior of this transformer. Three copper coils joined by a steel core comprise the transformer's (coils and core assembly) structure. All of these parts are submerged in transformer oil, which is contained in a container inside the transformer and has fins to enhance heat transfer. Heat is transferred from the core and coils to the outside through the external wall by the transformer oil, acting as an electrical insulator and a cooling liquid. This heat must be radiated in order to maintain the oil at a reasonable temperature. **Table 1** shows the properties of pure oil and Nanofluids at 25 degrees Celsius.

(a)

(b)

Figure (1): (a) Exterior and (b) Interior Images of 400 KVA Transformers.

Table (1): Pure oil and Nanofluids properties at 25 ^{o}C**.**

	μ (Kg /m.s)	Cp (J / Kg.K)	k (W /m. K)	Density (Kg /m^3)
Pure oil	0.0125	2000	0.108	890
Fe3O4	0.0009	718.44	1,631	5170
CuO	0.0175	535.6	32.9	6 315
TiO2	0.00115 (Li et al. 2009)	686	8.96	4250
Al2O3	5x10^{-7} (Ali et al. 2022)	675	490	3160

4. Experimental setup

The experiments are conducted in the laboratory of Diyala Company for Electrical Industries, Diyala, Iraq. This study employed a method to evaluate the amount of heat generated in a power transformer based on the characteristics of the transformer oil, both with and without the addition of hybrid nanofluids. The qualities of the transformer oil were analyzed in the experimental investigation [24]. The experiments were done after preparing the process of the hybrid nanofluids as Titanium oxide TiO2 (20 nm), Iron oxide Fe3O4 (20 nm), and Aluminum trioxide Al2O3 (20 nm)) at 0.2, 0.4 and 0.6 % concentrations, in addition of preparing nanofluid Copper oxide CuO (40 nm). Using a two-step process, oil was combined with iron tetraoxide, and (titanium oxide, copper oxide, and aluminium trioxide).

The experiments include: -

a) Nanoparticles were mixed with transformer oil using the mass-to-volume (nanoparticle/volume of oil) method to make nanofluids. Many different weights were then added to a particular volume of oil to achieve varied concentrations.

b) Nanoparticles and oil were blended using an ultrasonic device by adding the necessary amount of oil and a specific mass of nanoparticles and then running the device for 30 minutes. To prevent particle sedimentation, testing the sample soon after mixing is preferable.

c) Sample collection: To ensure more reliable test findings, the manufactured nanofluid is placed in special opaque samples that do not permit light to enter. These samples are then tightly sealed off from the outside world.

d) Sample size: The sample size shouldn't be less than one litter, depending on how many tests it will be put through. The quantity of the sample increases with the number of tests.

e) Testing samples: Due to the sensitivity of this type of test, which is impacted by even the simplest conditions, as well as the possibility of findings varying from one device to another or more, samples must be tested at the exact location and time.

Breakdown voltage, flash point, thermal conductivity, and pour point tests were performed in this research and the results were reported per their findings. The samples were examined individually under the same circumstances. The dielectric strength or voltage breakdown was tested in the breakdown device (BDV), where the electrodes were submerged in oil with a gap of 2.5 mm between them. Five tests were conducted on a single sample, and the results' average was calculated. The lowest temperature at which the gaseous component is released to produce a combustible mixture is the second test (flash point). This property is crucial to prevent the oil from igniting, which might result in fires and explosions. The third test (Pure Point), the lowest temperature at which the oil starts to freeze and obstructs the thermal exchange process, should be conducted in freezing climates [25].

5. Mathematical and Numerical models.

The transformer generates heat as a result of the electrical impedance. By means of natural convection, oil absorbs this heat and transmits it to the outside walls. The heat is subsequently transferred from the outside walls to the surrounding air via convection and fin-based radiation. The continuity, momentum, and energy equations for the transformer oil in three dimensions, steadiness, and incompressibility are [26]–[31]

$$\nabla V = 0 \quad (1)$$

$$\rho(V.\nabla V) = -\nabla P + \nabla.\left(\nabla \mu_j \nabla V_j\right) + F \quad (2)$$

$$\rho c_{p(}V.\nabla T) = k\nabla^2 T \quad (3)$$

The properties of nanofluid are a mixture of the properties of the fundamental fluid and the spatial concentration-dependent properties of the nanoparticles. For example, the features of nanofluids (oil + Fe3O4) can be calculated using the relationships below.

The volume fraction (Φ),

$$\phi = \frac{m_n/\rho_n}{m_n/\rho_n + m_{bf}/\rho_{bf}} \quad (4)$$

The density,

$$\rho_{nf} = \phi \cdot \rho_n + (1-\phi) \cdot \rho_{bf} \quad (5)$$

The specific heat of the pure nanofluid,

$$C_{p,nf} = \frac{\phi \cdot (\rho_n C_{p,n}) + (1-\phi) \cdot (\rho_{bf} C_{p,bf})}{\rho_{nf}} \quad (6)$$

Dynamic viscosity of the pure nanofluid,

$$\mu_{nf} = \frac{\mu_{bf}}{1 - 34.87 \left(\frac{d_p}{d_{bf}}\right)^{-0.3} \phi^{1.03}} \quad (7)$$

The thermal conductivity of the pure nanofluid

$$\frac{k_{nf}}{k_{bf}} = \frac{k_p + 2k_{bf} - 2\phi(k_{bf} - k_p)}{k_p + 2k_{bf} + \phi(k_{bf} - k_p)} + \frac{\rho_p \phi C_{p\,bf}}{2k_{bf}} \sqrt{\frac{2\kappa_B T}{3\pi d_p \mu_{bf}}} \quad (8)$$

The following equations are used for the hybrid nanofluid (oil+ Al2O3+TiO2+CuO) properties.

The volume fraction (Φ)

$$\Phi = \frac{V_{hp}}{V_{hp} + V_{oil}} \quad (9)$$

Density can be calculated for all volume concentrations by.

$$\rho_{hb,nf} = \Phi_{np1}\rho_{np1} + \Phi_{np2}\rho_{np2} + (1 - \Phi_{np1} - \Phi_{np2})\rho_{oil} \quad (10)$$

The viscosity of hybrid nanofluid is calculated by.

$$\mu_{hb,nf} = \left(1 + 2.5(\Phi_{np1} + \Phi_{np2})\right)\mu_{oil} \quad (11)$$

The specific heat of the hybrid nanofluid is calculated by.

$$\rho_{hb,nf} Cp_{hb,nf} = \Phi_{np1}\rho_{np1} Cp_{np1} + \Phi_{np2}\rho_{np2} Cp_{np2}(1 - \Phi_{np1} - \Phi_{np2})\rho_{oil} Cp_{oil} \quad (12)$$

The thermal conductivity of hybrid nanofluid is presented by.

$$\frac{k_{hb,nf}}{k_{oil}} = \left[\frac{Cp_{hb,nf}}{Cp_{oil}}\right]^{-0.023} \left[\frac{\rho_{hb,nf}}{\rho_{oil}}\right]^{1.358} \left[\frac{\mu_{oil}}{\mu_{hb,nf}}\right]^{0.126} \quad (13)$$

sing a CFD program like Ansys software is the greatest method for forecasting fluid flow patterns and heat transfer mechanics in complicated shapes and bodies. The link between the Grashof (Gr) and Prandtl (Pr) numbers and the natural heat transfer by convection can be used to derive the Nusselt number (Nu), which represents the percentage of convection to conduction heat transfer. Numerical analysis and simulation of pure oil fluid are computed after obtaining the values of Gr and Pr from the equation.

$$Nu = C \times [Gr \times Pr]^n \tag{14}$$

$$Gr = \frac{g\beta(T_s - T_\infty)D^3}{\nu^2} \tag{15}$$

$$Pr = \frac{\mu \times Cp}{K} \tag{16}$$

Overall heat transfer coefficient (h) can be defined by Nusselt number (Nu).

$$h = \frac{Nu \times K}{H} \tag{17}$$

where, Nu : Nusselt No, K: thermal conductivity of fluid ($W/m.K$) and H is the height of core and windings (m).

The boundary condition for solving the equations above is no slip velocity on any wall. Data on the electrical losses in coils and cores converted to heat production are used to calculate the values of a constant heat generation source term applied to coils and cores. The precise heat loss produced in actual transformers is used to determine this source term first. Both natural convection and radiation are exposed to the fins' surfaces and the complete transformer's exterior walls. The average and maximum temperatures of the oil and the heat transfer rate are determined by numerically solving the temperature distributions from the aforementioned model. The solution is done by nanofluid (Fe3O4+Oil) with different concentrations of 0.2%, 0.4%0.6% w/v and repeated using transformer oil-based hybrid Nanofluids (CuO, Al2O3, TiO2+oil) with volume fractions of 2%, 4%and 6% after simulating the transformer with pure transformer oil initially.

As illustrated in **Figure 2**, a quarter of the transformer can be employed as a computational model to represent the entire transformer in order to simplify the numerical solution and benefit from geometrical symmetry. This is due to the fact that it is challenging and time- and memory-intensive to numerically simulate the whole transformer seen in Figureure 1. The equations are numerically solved using the finite volume method, and the segregated solver then transforms the results into an algebraic form. The greatest fluid temperature and heat transfer coefficient are then established after measuring the temperature variation in the oil. Several different size meshes represented the computational domain. Eight mesh sizes were employed to study mesh independence, and the findings for oil mean temperature for the various meshes used are presented in **Figure 3** for an ambient temperature of 25 ^{o}C. The grids will be utilized for all numerical solutions until there are 134563 cell components, as any additional increase will not significantly affect the result.

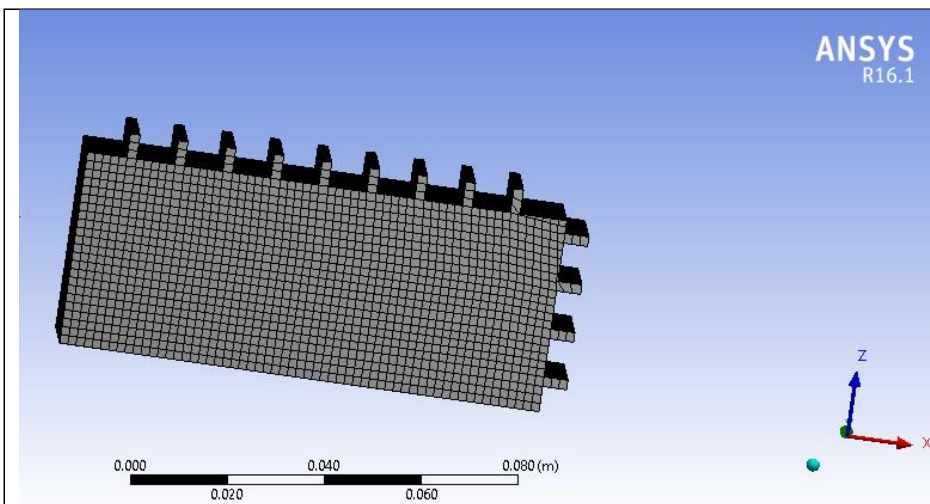


Figure (2): Mesh used for the computational model.

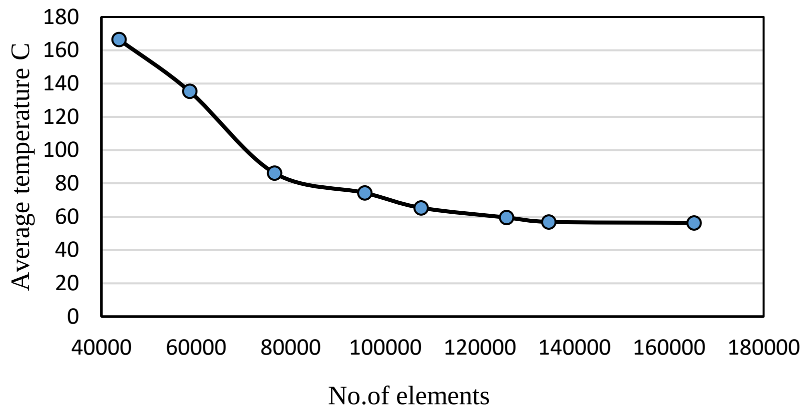
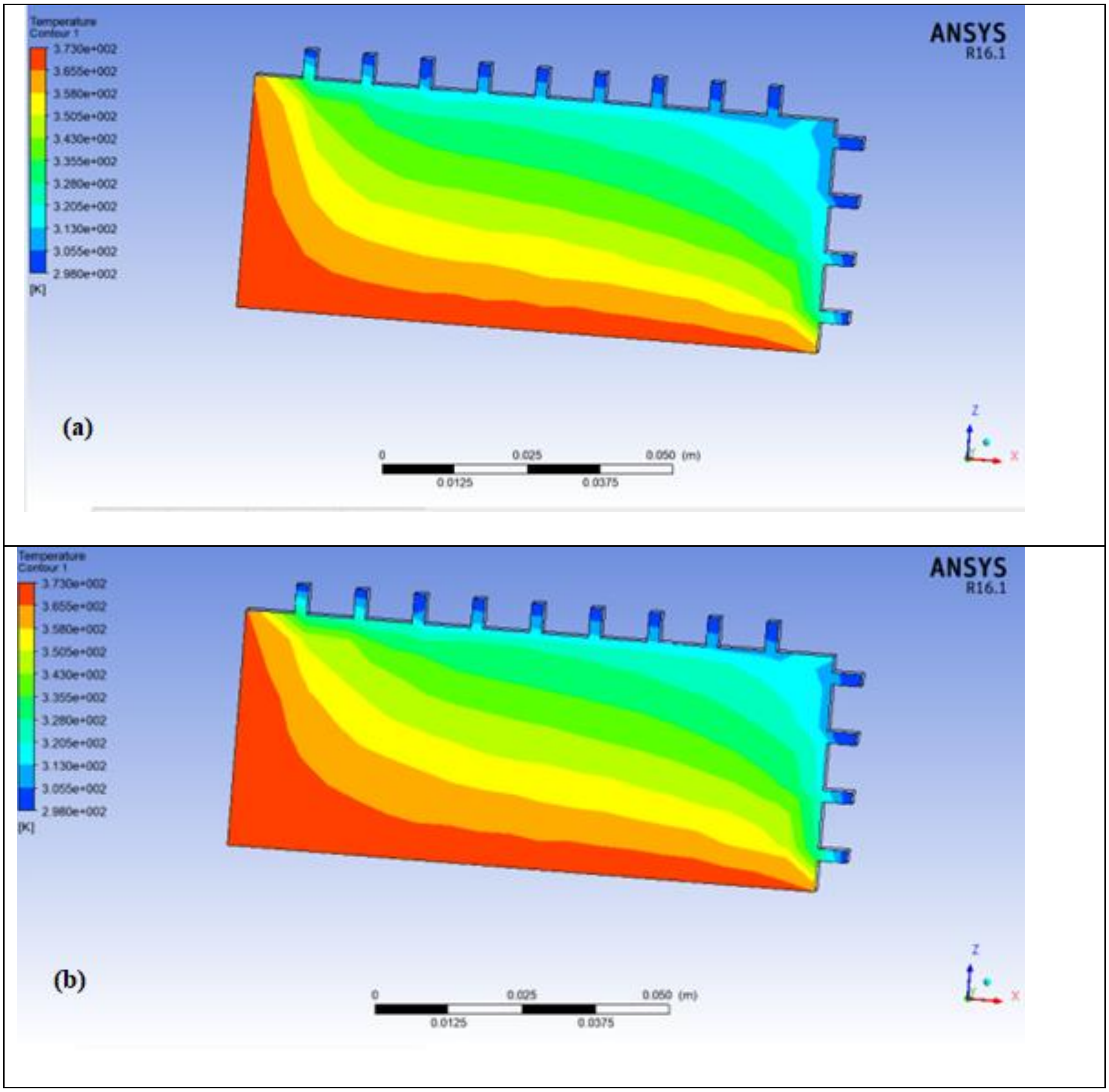


Figure (3): Temperature distribution at different mesh sizes.

6. Results and discussion

Numerical discoveries using ANSYS Fluent V. 2016.1 include pure oil, nanofluids (Fe3O4+oil), and hybrid nanofluids (CuO, Al2O3, and TiO2+oil).To investigate their impact on the heat transmission from the coils and core to the surrounding air, the nanofluid particles are diluted in three-phase power transformer oil at different concentrations of 0.2%, 0.4%, and 0.6%. When heat is produced internally, the temperature of the transformer rises; therefore, the oil and additives will enable it to be cooled. The graphs below demonstrate how various fluids behave when lowering the transformer's temperature. **Figure 4 (a)-(c)** depicts the temperature distribution in the transformer's x-z plain when hybrid nanofluids (CuO, Al2O3, TiO2+oil, and oil+Fe3O4) are added at 0.2% concentrations to pure oil. It is clear that the temperature changes, reaching its highest points near the surfaces of the core and winding and its lowest points at the fins of the transformer. As a result, the heat generated by the transformer's core and winding can be dispersed into the surrounding environment.


Temperature
Contour 1
3.730e+002
3.655e+002
3.580e+002
3.505e+002
3.430e+002
3.355e+002
3.280e+002
3.205e+002
3.130e+002
3.055e+002
2.980e+002
[K]
ANSYS
R16.1
(a)
0
0.025
0.050 (m)
0.0125
0.0375
Z
X
Temperature
Contour 1
3.730e+002
3.655e+002
3.580e+002
3.505e+002
3.430e+002
3.355e+002
3.280e+002
3.205e+002
3.130e+002
3.055e+002
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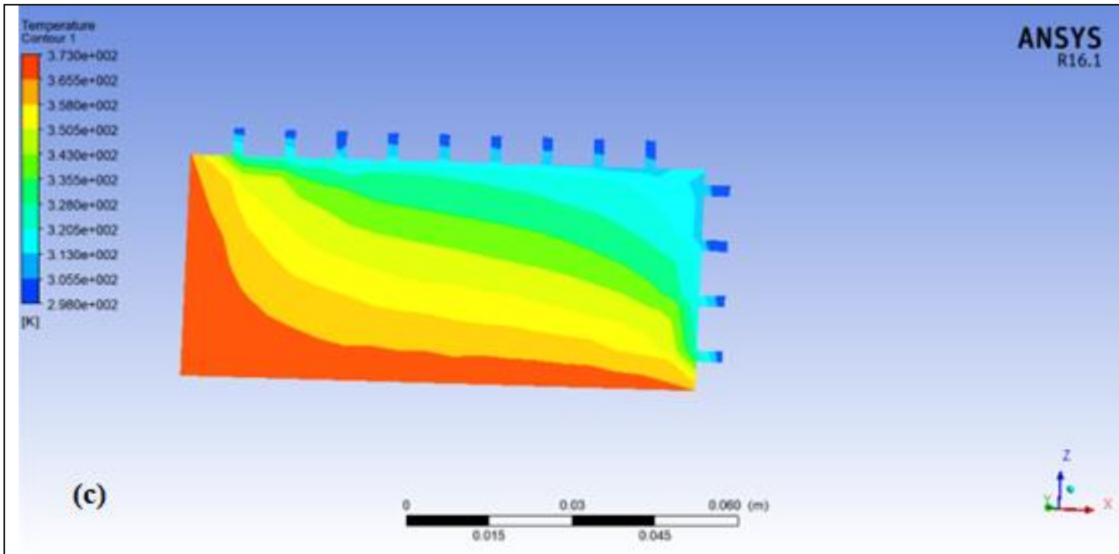

Figure (4): The Temperature distribution in the cut-plain of the transformer with 0.2 % concentrations of Nanofluids corresponding with pure oil, (a)pure oil,(b) Nanofluids (Fe3O4+ oil) and (c) Hybrid Nanofluids(CuO+oil, Al2O3+oil, TiO2+oil)

Figure 5 compares the dielectric breakdown voltage of pure oil and nanofluids with concentrations of 0.2-0.6% of nanofluids; the dielectric breakdown voltage of pure oil is compatible with 0.2% Fe3O4 nanofluids. The dielectric breakdown voltages for 0.6 % of hybrid Nanofluids have the most significant effects compared to other findings. When nanoparticle agglomeration occurs at more significant nanoparticle concentrations, the breakdown voltage starts to fall.

The comparison between the pure oil and the hybrid nanofluid (Al2O3+TiO2+CuO+Oil) at the three concentrations is shown in **Figure 6**. The findings indicated that the use of a mixture of nanomaterials improved the dielectric breakdown. And the concentration has a direct correlation with that improvement. The hybrid nanofluid (Al2O3+TiO2+CuO+Oil) at a concentration (0.6 w/v), which increased the potential breakdown value from 24 KV to 53 KV, produced the best results.

Figure 7 demonstrates how nanofluids' concentration affects transformer fluid's flammability. Serious safety concerns have lately been highlighted due to its flammability. Transformer explosions are a typical occurrence; however, because of oil leaks, they can be dangerous to put out and run the risk of spreading. A fluid's "flash point" is the lowest temperature at which its surface emits an amount of vapor sufficient to produce an ignitable combination in the air. The flame point is the temperature at which vapors burn continuously. When heated past the flash point, oil can support a fire for five seconds at its lowest temperature, but as it warms up, it ignites. The flash point is one factor taken into account when deciding if a fire hazard is likely. As a result, when nanofluid concentrations (0.6%) increase, the flash point of an oil and Nanofluid mixture drops by 20 ^{o}C.

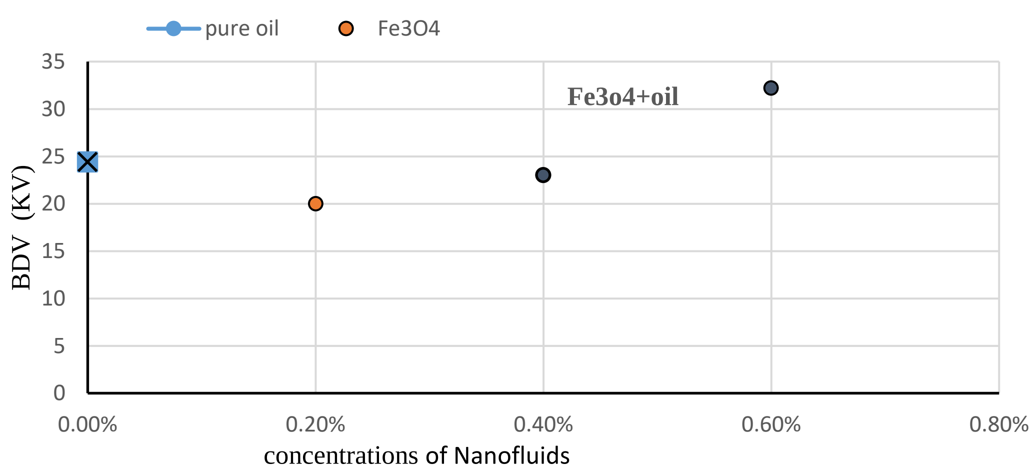

Figure (5): Pure oil and Nanofluids' dielectric breakdown voltage (BDV) characteristics with 0.2–0.6% concentrations of Nanofluids.

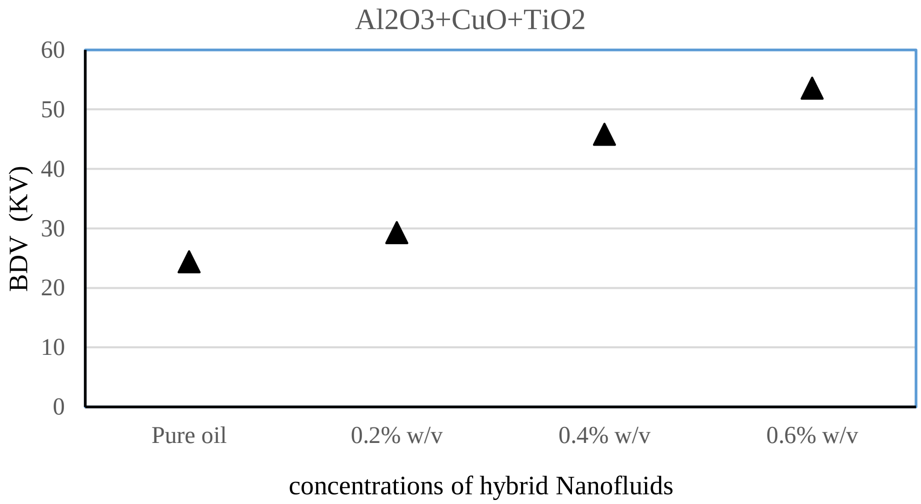

Figure (6): Pure oil and hybrid Nanofluids' dielectric breakdown voltage (BDV) characteristics with 0.2–0.6% concentrations.

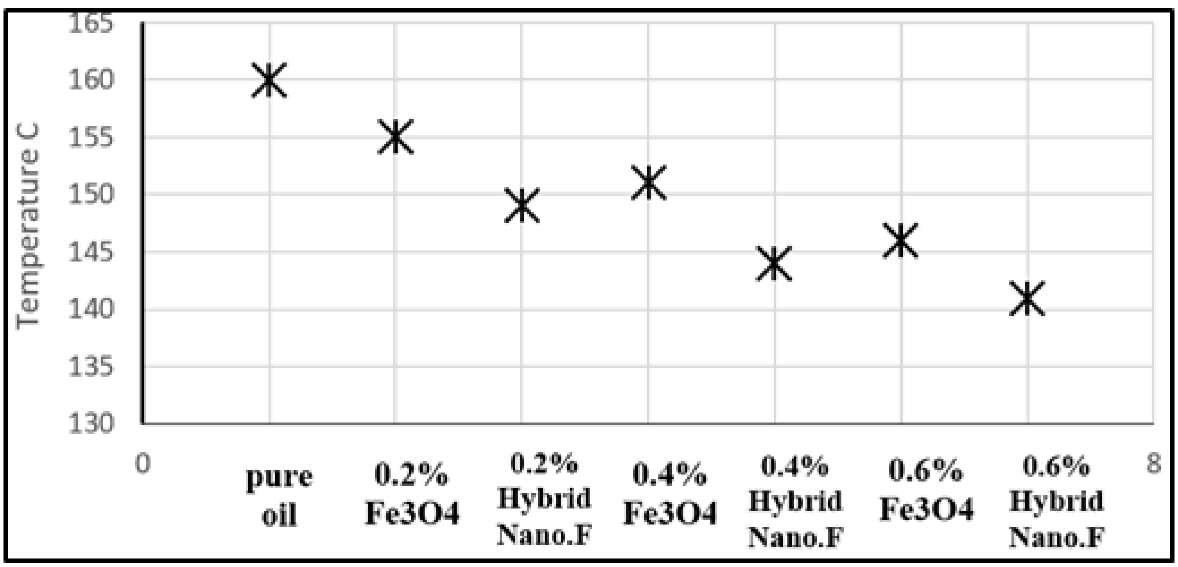

Figure (7): Pure oil and hybrid Nanofluids' flash point with 0.2–0.6% concentrations of Nanofluids

6. Conclusion

In this study, which computationally examines the thermal features of oil transformers and uses a transformer oil-based nanofluid as a cooling medium in place of pure oil, the effects of adding nanoparticles to the transformer oil on its thermal behavior are explored. The findings allow for the following observations:

- The oil's dielectric and thermal insulating properties are enhanced when hybrid nanotechnology is used. Nonetheless, the temperature remains within the permissible range and the insulation is directly inversely proportional to the number of nanoparticles in the oil.
- Nanofluids have improved heat transfer within the transformer, resulting in a noticeable reduction in temperature. The heat transmission from the "winding and core" to the transformer tank was boosted by using nano-Fe_3O_4+oil, which improved the oil's heat conductivity. With a maximum cooling boost of roughly 5%, heat transmission and, as a result, transformer cooling rise with increasing nanoparticle concentration in oil.
- Particularly at 0.6% concentration of hybrid Nanofluids, transformer oil-based Nanofluids have better dielectric breakdown voltage characteristics than mineral oils.
- The results demonstrated that adding nanoparticles to transformer oils lowers the flash point by causing impurities to multiply and release more gases. The hybrid nanofluid had the lowest performance at a concentration of 0.6% w/v, which is considered a bad property even if the solution is still within the allowable limit. Moreover, the relationship between this temperature and the quantity and concentration of nanoparticles in the oil is inverse.

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Nomenclature

A	Area (m^2)	T	Temperature (K)
C	Specific heat (J/(kg K))	nf	Nanofluids
F	Natural convection Source term	hb	hybrid Nanofluids
Gr	Grashof number	bf	Base fluid (oil)
H	height of core and windings (m)	μ	Dynamic viscosity (m^2/s)
h	Overall heat transfer coefficient W/(m^2.K)	Φ	volume fraction
k	Thermal conductivity (W/m K)	ρ	Density (Kg/m^3)
Pr	Prandtl number	V	Velocity (m/s)
Nu	Nusselt number	ρ_{nf}	Density of nano fluid (Kg/m^3)
Al2O3	Aluminum trioxide	$C_{p,nf}$	specific heat of the pure nanofluid
CuO	Copper oxide	μ_{nf}	Dynamic viscosity of the pure nanofluid
TiO2	Titanium oxide	$\mu_{\mathrm{hb,nf}}$	viscosity of hybrid nanofluid
Fe3O4	Iron oxide		

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Availability of data and materials

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