EVALUATION OF THERMAL CONDUCTIVITY USING NANOFLUIDS TO IMPROVE THE COOLING OF HIGH VOLTAGE TRANSFORMERS

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This paper was written to demonstrate the value of using nanofluids for cooling high-power transformers while also providing current techniques for business and academia. A numerical analysis of the improvement caused by the cooling of a high-voltage transformer using nanofluids has been done. A tank with a temperature source inside and a charge of mineral oil-barium titanate nanoparticles is used to study natural convection. This study investigates the effects of variables on the thermal efficiency of the tank, including the thermal Rayleigh number and volume fraction. The results show that quenching varies with low and high Rayleigh thermal numbers and depends on the volume percentage of used nanoparticles. The effects were illustrated in thermal transfer rate representations as functions of the thermal Rayleigh number (Rat = 10^3 and 10^6) and the solid volume particle from the nanoparticles ($0 \le \varphi < 10\%$). The findings showed that improving the solid volume particle of the nanoparticles by 10% causes the fluid being utilized to become more effectively conductive, which improves the rate of heat transfer by roughly 10% when compared to the case of the base fluid.
Keywords: *volume fraction, tank enclosure, natural convection, nanofluid, thermal Rayleigh numbers.*

1. Introduction

In electrical networks, a high-voltage power transformer is an important electrical component. It is a static device with two or more windings that, in order to transmit power, uses electromagnetic induction to change one system of voltage and alternating current into another system of voltage and current that has generally different values but operates at the same frequency**.** Its main use is to reduce losses in electrical networks. Transformers have the defect of being noisy, of being able to catch fire, and of causing losses, even if they are small in proportion. Current research is trying to remedy these problems and reduce their losses, noise, and general ecological impact. New types of mineral oil and superconducting materials are being explored. It should be understood that even if the power transformers have efficiencies ranging from 99.5 to 99.8%, the powers passing through them are so great that the losses represent, in absolute terms, great values. Thus, for an 800 MVA transformer, has been, with 99.8% efficiency, losses of 1.6 MW in the form of heat that is difficult to evacuate. Thus, a cooling system is always in place to maintain the temperature of the windings and the insulation (oil, for example) at acceptable levels. The use of nanofluids is the most basic method of cooling. The heat created by the transformer's coils and magnetic circuit, which evacuate the heat by convection towards the outside, cools the nanofluid, which in turn transfers the heat towards the outside of the transformer. Increased thermal conductivity is attainable thanks to nanofluids with good thermal conductivity (high). The active party of broad transformers is generally immersed in a heightened-quality insulating nanofluid. This nanofluid needs to be liquid dielectric, as dry and oxygen-free as feasible, and free of combustible gases and particles. Engineers have studied various coolants, and researchers are interested in increasing heat transfer in heat exchangers. The thermal and electrical characteristics of specific liquids and their applicability to high-voltage techniques have been the subject of several studies. It is therefore of fundamental interest to study inventive and operational techniques that help natural convection output for various forms of transformers. Nanofluids have also been utilized to improve the rate of heat transfer by raising the thermic conductivities of the ground fluid utilizing hanging nanoparticles. Among the existing works, has been cited in some experimental and/or numerical works with or without the use of nanofluids. Fernández et al. [1] discussed and compared the physical, chemical, and electrical characteristics of dielectric fluids made from vegetable oils. Chairul et al. [2] examined the treated used cooking oil's physical, chemical, and electrical characteristics in line with specifications in order to explore the idea of using it as a possible dielectric liquid for high-voltage power transformers. To assess the oil's capacity to withstand breakdown under such intense electrical stressors, Ghani et al. [3] subjected transformer-insulating oils to repeated electrical shocks or breakdowns inside power transformers. Tlhabologo et al. [4] developed mineral oil, which was the material of choice for transformer liquid dielectrics until synthetic and natural esters. Ester-based oils are the substitute for petroleum-based mineral oil, which is non-biodegradable and has insufficient dielectric effects, and are the subject of intensive study to enhance its qualities. This study looked into the dielectric and disbanded gas testing is chemical, electrical, physical, and aging characteristics. Yamana et al. [5] improved dependability cost-effectiveness, and environmentally warm liquid insolation from transformers. Previously, solid-insulated mineral oil was the key constituent of oil-replete transformers. The increase in requests appears for the modification of liquid insolation as M O exhibits negative estates. To improve the condition of liquid insolation, it is very advised to present alternative liquid insolation for the more useful usefulness of gear and potency supply. Provided, reviewed, and summarized extensive research on numerous types of nanoparticles, the process for creating nanofluids, and the effects these materials have on physical, chemical, and electrical domains. Investigation of natural-convection of hybrid nanofluid is extensively studied by [6-13]. Using Williamson nanofluid, Yurong et al [14] examined the effects of activation energy, motile microorganisms, and bioconvection. Mariprasath et al. [15] experimentally studied the spectroscopic examination of alternating liquid dielectrics for transformers. Used mineral oil impregnated with insulating materials as an insulating middle in transformers. They made an effort to show that Pongamia pinnata oil can function as a substitute liquid dielectric for a transformer. They carried out a study of the deterioration of strong insulating material was taken out using DGA, SEM, XRD, and UV-Vis spectroscopy. Ali et al. [16] analyzed the impact of the purification process on thermic conductivity. They discovered that the presence of water or humidity promotes early thermic ageing, which reduces transformer oil's lifespan. They concluded that the presence of water affects the thermal properties favorably and the dielectric qualities negatively. Xue et al. [17] investigated the mobility of load porters in ester and mineral oils fluids. They discovered that compared to natural and manufactured ester fluids, mineral oil had superior load-carrying mobility. Rozga et al. [18] explored esters from a variety of angles, including from a fundamental perspective on rupture mechanisms and from an application standpoint. They are still acting in defiance by using elevated voltage equipment, thus a deeper comprehension of the various variables that can be matched in their operation is necessary. Their intention is to present recent advances in synthetic liquid ester research in relation to the assigned problems that the authors believe are most important to ester development. Bajestan et al. [10] employed the heat transfer fluid made from leftover cooking oils as a universal replacement for petroleum-based lubricants used in cooling transformers. They created a numerical example to compare the effectiveness from the researched vegetable oil to traditional transformer oil in cooling transformers. The impacts demonstrate a more suitable cooling arrangement for vegetable oil compared to petroleum-based oil. Altay et al. [19] used mineral oil as the heat transfer fluid in a study on transformer cooling. Using a 3D computer model, they compared the cooling capacities of two ester-based fluids to those of mineral oil. Oparanti et al. [20] presented the impact of nanoparticles (TiO_2& Al_2O_3) on the methyl ester generated from palm kernel oil for oil-filled electrical equipment. Examining the methyl ester-based nanofluid's loss deviation, AC conductivity, and AC breakdown force. It was shown that adding the two nanoparticles decreased the methyl ester's loss tangent and AC conductivity while improving the Al_2O_3 nanofluid. Qiu et al. [21] determined the distribution conductivity of molecules of water for mineral oil by studying the distribution conductivity of water molecules in palm oil using the molecular dynamics approach. Siddique et al. [22] focused on the preparation of mixing from natural ester oil and a mixture from mineral oil as basis fluid and the study of the dielectric conduct of this fluid behind existing distributed with nanoparticles of TiO_2 and ZnO. Kiesewetter et al. [23] examined the electrical resistance of mixing two transformer dielectric liquids—petroleum oils and silicone liquids. It is thought that when these dielectric liquids are combined, colloidal structures may form that influence the electrical effects of the combination. Manerot et al. [24] presented the chemical and physical characteristics of palm oil and compared them to those of mineral oil as an insulating liquid. They examined the new liquids' physical and chemical impacts both before and after the transformer process. It has been determined through tests that palm oil is a potential replacement liquid insulation to be utilized in the transformer six months after the functioning of the transformer.

All previous studies on improving the cooling capacity during transformer operation only investigated the effect of nanofluid preparation on thermal conductivity. Therefore, this study focused on the heat transfer performance of nanofluids, which includes the two factors that affect the change in heat transfer coefficient: thermal conductivity and convection.

2. Theoretical analysis

The section assumed consists of a transformer (winding-core), located inside a closed tank loaded with a nanofluid Mineral oil-Barium titanate ($BaTiO_3$) (figure 1). The external tank covers sustained in a fixed feeble-temperature T_c, and the internal transformer surfaces are maintained at a set tall-temperature T_h. In the course of this paper, the thermic Rayleigh number, Ra_t, varies from 10^3 to 10^6. The mineral oil-barium titanate nanofluid is thought to be the source of the two-dimensional flow, which is brought about by natural laminar convection. The nanofluid is thought to be incompressible and newtonian due to its low viscosity and pressure performance. The thermophysical characteristics of the nanofluid are assumed to be stable, with the exception of density, which is thought to evolve through chording in accordance with the Boussinesq approach. The buoyancy influence is modeled using the Boussinesq estimator.

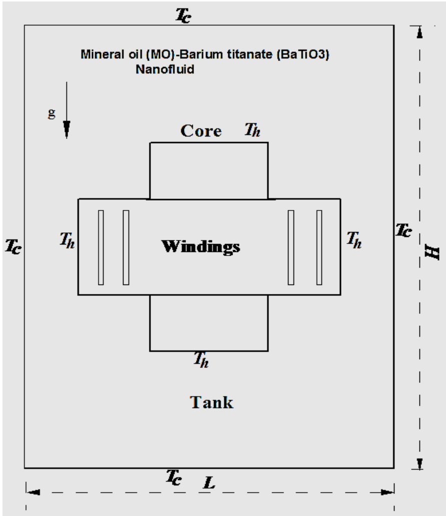

Fig. 1 Physical prototype's schematic graph

Mass, momentum, and energy conservation are used to describe the interior of the tank on a heated transformer in the government equations. The following nondimensional variables [25–26] transform governmental equations into dimensionless states:

$$X = \frac{x}{H}, = \frac{y}{H}, U = \frac{uH}{\alpha_f}, V = \frac{vH}{\alpha_f}, \theta = \frac{T - T_c}{T_h - T_c}, P = \frac{\bar{p}H^2}{\rho_{nf}\alpha_f^2}, Pr = \frac{\vartheta_f}{\alpha_f}, Ra_t = \frac{g\beta_f(T_h - T_c)H^3}{\alpha_f\vartheta_f}$$

The continuity equation is written as follows:

$$\frac{\partial U}{\partial \mathrm{X}} + \frac{\partial V}{\partial \mathrm{Y}} = 0 \tag{1}$$

The momentum equations are written as follows:

$$U\frac{\partial U}{\partial X} + V\frac{\partial U}{\partial Y} = -\frac{\partial P}{\partial X} + \frac{\mu_{\mathrm{nf}}}{\rho_{\mathrm{nf}}\alpha_f}(\frac{\partial^2 U}{\partial X^2} + \frac{\partial^2 U}{\partial Y^2}) \tag{2}$$

$$U\frac{\partial V}{\partial X} + V\frac{\partial V}{\partial Y} = -\frac{\partial P}{\partial Y} + \frac{\mu_{\mathrm{nf}}}{\rho_{\mathrm{nf}}\alpha_f}\left(\frac{\partial^2 V}{\partial X^2} + \frac{\partial^2 V}{\partial Y^2}\right) + \frac{(\rho\beta)_{\mathrm{nf}}}{\rho_{\mathrm{nf}}\beta_f}Ra_t Pr\theta \tag{3}$$

The energy equation is written as follows:

$$U\frac{\partial \theta}{\partial X} + V\frac{\partial \theta}{\partial Y} = \frac{\alpha_{\mathrm{nf}}}{\alpha_f}\left(\frac{\partial^2 \theta}{\partial X^2} + \frac{\partial^2 \theta}{\partial Y^2}\right) \tag{4}$$

In the X and Y directions, respectively, U and V are the dimensionless speeds. The thermophysical characteristics of liquids (mineral oil) and nanoparticles (barium titanate) are shown in Table 1.

Table 1. Basis fluid and $BaTiO_3$ nanoparticle thermophysical properties

	$\rho(kg/m^3)$	$C_p\ (Jkg^{-1}K^{-1})$	$K\ (Wm^{-1}K^{-1})$	$\beta\ (K^{-1})$	$\mu\ (Ps.s)$
MO	*845*	*1877*	*0.13*	*7.8x10-4*	*0,004394*
$BaTiO_3$	*5750*	*299,054*	*3,6747*	*5.30x10-6*	-

According to Brink-Man [27], the effective values for the effective nanofluid density, heat capacity, thermic expansion factor, and effective dynamic viscosity are as follows:

$$(\rho)_{nf} = (1-\phi)\rho_f + \phi\,\rho_p \tag{5}$$

$$\left(\rho C_p\right)_{nf} = (1-\phi)\left(\rho C_p\right)_f + \phi\left(\rho C_p\right)_p \tag{6}$$

$$(\rho\,\beta)_{nf} = (1-\phi)(\rho\,\beta)_f + \phi(\rho\beta)_p \tag{7}$$

$$(\mu)_{nf} = \frac{\mu_f}{(1-\phi)^{2.5}} \tag{8}$$

The MO-$BaTiO_3$ nanofluid's effective thermic conductivity for spheroidal nanoparticles is [28]:

$$K_{nf} = K_f \frac{\left(K_p + 2K_f\right) - 2\phi\left(K_f - K_p\right)}{\left(K_p + 2K_f\right) + \phi\left(K_f - K_p\right)} \tag{9}$$

To arrive at a solution, the system of equations must first define the boundary conditions. The external enclosure is kept at a constant temperature, T_f, equal to the ambient temperature, while the internal transformer surfaces (the localized heating) are maintained at a fixed high temperature, T_C.

These many limit requirements in dimensional format can be summarized as a follow

- The initial states are:

$$\theta(X,Y) = 0 \tag{10}$$

$$U = V = 0 \tag{11}$$

In addition, the border conditions of the system are:

- Internal cylinder (Transformater)

$$\theta(X,Y) = 1 \tag{12}$$

$$U = V = 0 \tag{13}$$

- Outer cylinder (Tank)

$$U = V = 0 \tag{14}$$

$$\theta(X,Y) = 1 \tag{15}$$

3. Numerical approach

The isolated approach is used to process the equations one at a time. The use of fluent software permits us to create a numerical model capable of dealing with the problem of flowing and heat transfer by convection with the use of nanoparticles for the two-dimensional case. First, it is necessary to generate the mesh utilizing Gambit software (figure 2). This method has the advantage of meeting the mass, the conservation of momentum, and the energy in all the considered volumes as well as in all the fields of calculation with the assessed boundary conditions based on the finite volume approach.

To confirm a satisfactory solution in regions with a high-temperature gradient, livery structured mesh close was supposed. The second-order scheme was thought since it allows some stability and minimizes the numerical diffusion though it can make the calculation diverge. The simple algorithm of Patankar and Spalding [29] was employed for speed-pressure coupling. In addition, the computational residue was utilized to confirm the convergence and the stability of the resolution.

Another useful quantity like the Nusselt number for each cylinder is perhaps chosen after solving the dominant equations. Since [29], the local Nusselt numeral along the exterior and inner walls, as well as the mean Nusselt numeral, can be estimated.

$$Nu_h = -\frac{K_{\mathrm{nf}}}{K_{\mathrm{f}}}\left(\frac{\partial T}{\partial Y}\right)_{Y=0} \quad (16)$$

$$Nu_c = -\frac{K_{\mathrm{nf}}}{K_{\mathrm{f}}}\left(\frac{\partial T}{\partial Y}\right)_{Y=1} \quad (17)$$

$$\overline{Nu}_{avg} = \frac{Nu_h + Nu_c}{2} \quad (18)$$

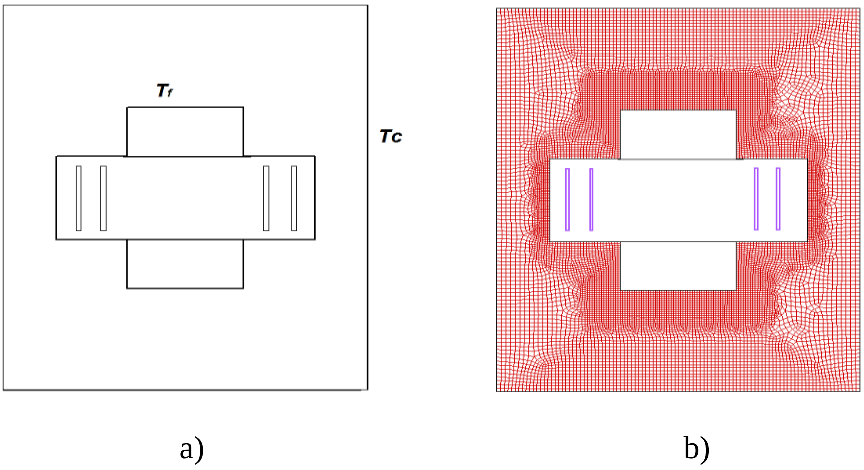

Fig. 2 Diagrammatic representation of the a) perfect physical, b) grille generations

4. Results and discussion

The numerical results of the natural convection of a transformer submerged in a closed tank with an incompressible nanofluid of kinematic viscosity ν_{nf} and thermic diffusivity α_{nf} are presented in this study. The temperatures in the two cylinders are fixed. The operating system of equations governing the phenomenon is numerically solved using a finite volume technique based on the SIMPLE algorithm. The fields of dynamic and thermal flow are shown. Among the parameters dictating the studied system, the thermal Rayleigh number (Ra_t) characterizes the temperature variance. Analyses are executed for thermic Rayleigh numbers, 10^3, 10^4, 10^5, and 10^6.

4.1 Study of the mesh

The variations in the mean Nusselt numbers the inner surface with the grid number are given in figure 3. The physical phenomena were addressed, particularly in the region of the boundary layer indicated by the presence of significant gradients in the parietal areas. An interior isothermal transformer delivers a grid refinement reading to a tank at Ra_t = 10^4 in order to get the best mesh possible (figure 3). In this study, six combinations of test volumes (40 x 40, 60 x 60, 80 x 80, 100 x 100, 120 x 120, and 140 x 140) were used to investigate the impact of the grill's size on the accuracy of the indicated impacts. Figure 2 depicts the mean Nusselt number's convergence to the level of the internal cylinder warmed by grid refining. It should be observed that while control volumes (100 x 100) are joined during mesh liberation, the average Nusselt number is not significantly affected by thin grid refining. The agreement was judged to be very good, which indirectly compares to the present calculation since the relative fault in this grid is smaller than 0.1%.

4.2 Impact from heat transfer and volume fraction

Natural convection using ambient air was used to cool the first generation of high-voltage transformers. As this got shorter, more fans were added to the mix to immediately blow air over the radiator's fins. Many studies examined the effects of nanofluids and how to employ them in heat exchange methods. As a result, it is critical to investigate innovative and operating methods that favor natural convection output in various types of transformers. By enhancing the thermic conductivities of the necessary fluid with suspended nanoparticles, nanofluids have also been employed to speed up heat transfer.

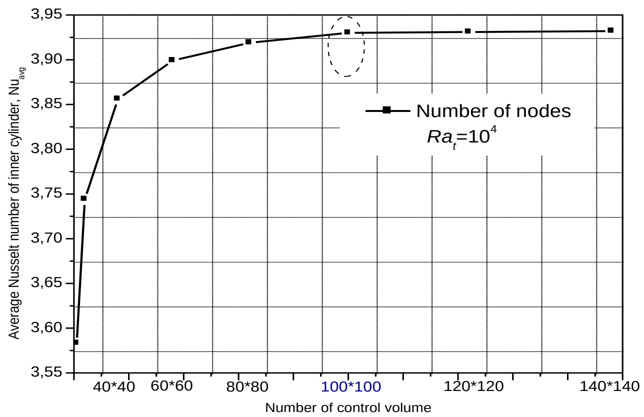

Fig. 3 Convergence with mesh refinement at Ra_t = 10^4 along the thermal internal cylinder from the average Nusselt number

Figure 4 depicts the isocurrents and isotherms at various Rayleigh numbers (Ra_t= 10^4, Ra_t = 10^5, and Ra_t = 10^6), as well as the pure fluid (φ = 0.0) and nanofluid (φ = 0.05) cases. In order to understand how buoyant forces and nanoparticles affect dynamic and thermal fields and heat flow, it is important to understand the thermic Rayleigh numeral and nanoparticle volume percentage. Thus, for the type of nanofluid under study and the four valors of Rayleigh numeral Ra_t=10^3, Ra_t=10^4, Ra_t=10^5, and Ra_t=10^6, the impacts of Rayleigh number and nanoparticle volume percentage of streamlines (right) and isotherms (left) are shown in Figures 8, 9, and 10.

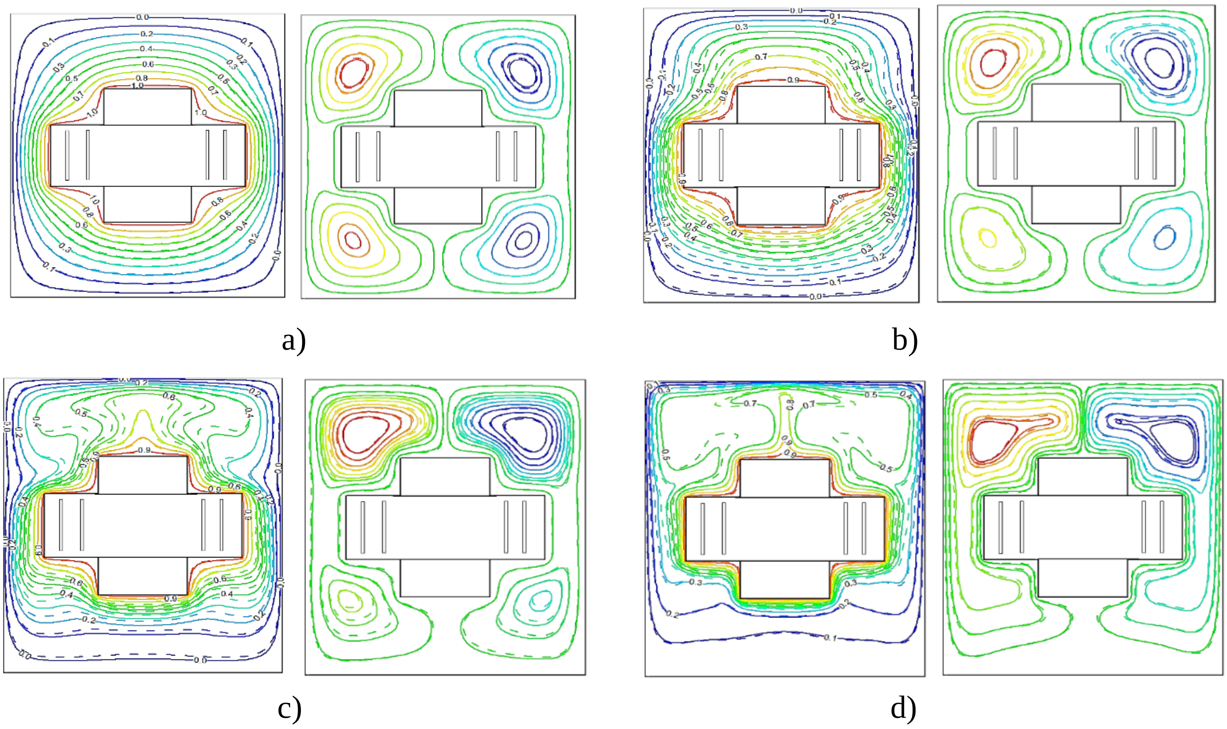

Fig. 4 Isocurrents (right) and isotherms (left) from nanofluid with φ = 0.05 (____) and clean fluid (− − −), a) Ra_t=10^3, b) Ra_t=10^4, c) Ra_t=10^5, d) Ra_t=10^6

It is noticed that the recirculation intensity inside the enclosure increases with increasing Rayleigh number, and the centers of the streamlines move upward. The most significant point relates to the volume percent at which φ = 0.05, where the recirculation intensity increases above that at which φ = 0. In this instance, it can be argued that a higher recirculation intensity is attained when nanoparticles are added to the base fluid (MO). The comparable analysis between mineral oil-barium titanate nanofluid and pure mineral oil shows that the highest values from streamlines are always more elevated for nanofluid compared to clean mineral oil, it means that the conductivity and, hence, the warmth transmission coefficient, increases as the percentage of volume increases.

4.3 Nusselt average and thermal Rayleigh number correlation

The influence from the thermic Rayleigh about the mean Nusselt numbers is presented in figure 5. These results demonstrated that when Ra_t> 10^3, the mean Nusselt number increases due to an increase in the thermal Rayleigh number, however when Ra_t = 10^3, the values of Nu_{avg} are essentially identical and have the same values. This increase is more important when the volume fraction raises.

These results indicate that as the volume fraction of the employed nanofluid increases, so does its equivalent thermic conductivity.

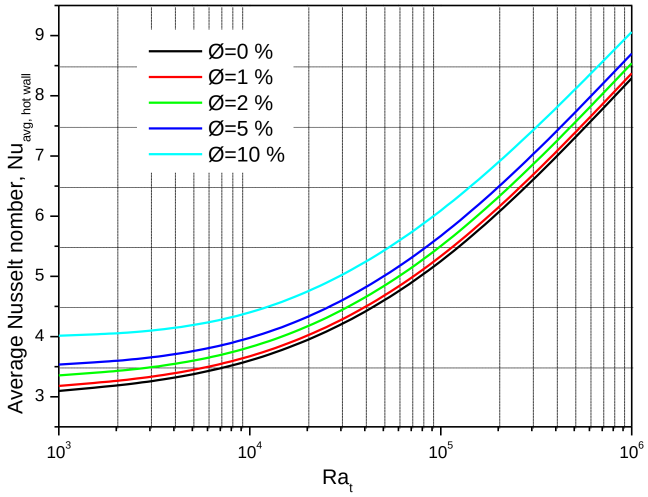

Fig. 5 Thermal Rayleigh's distribution of the mean Nusselt number around an internal transformer at various volume fraction values

In different thermal Rayleigh numerals, Figure 6 demonstrates how to interpret the ratio of the mean Nusselt number from the pure fluid to that of the nanofluid. ($Nu_{avg,nf}$ / $Nu_{avg,f}$). The evolutions show that increasing the percentage by volume causes an increase in the ($Nu_{avg,nf}$ / $Nu_{avg,f}$) for all considered thermal Rayleigh numbers. The rate of this augmentation is clearly visible in the obtained results. It was noticed that the increase in inertial forces promoted the heat transfer process. Additionally, the rate of heat transfer increases linearly and monotonically with volume fraction when the solid particles and nanoparticles are separated. As the volume of nanoparticles in the base fluid increases, the thermic conductivity of the nanofluid also increases, causing this expansion.

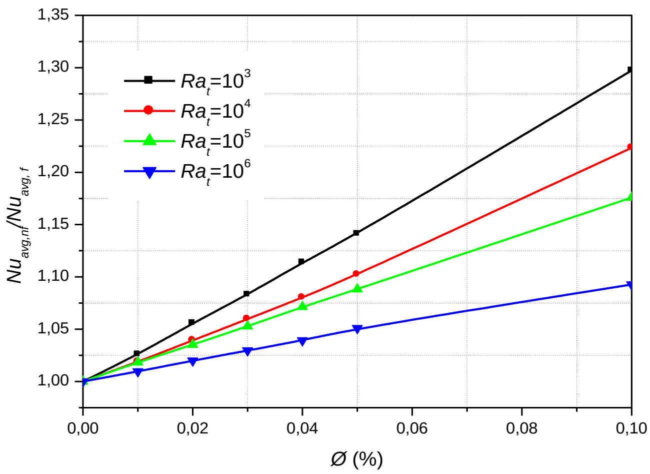

Fig. 6 Variation of ($Nu_{avg,\,nf}/Nu_{avg,\,f}$) at various thermal Rayleigh numbers

4.4 Evolution of inner and outer local Nusselt number

The distribution profiles of the local heat transfer rates with the perimeters of the exterior and internal cylinders (i.e. A_B_C_D_A) and (i.e. A'_B'_C'_D'_E'_F'_G'_H'_A') for various nanoparticle percentage by volume and thermic Rayleigh numeral $10^5$are shown in figure (7) and (8). A uniform temperature is performed in the internal flanks of the transformer, which are inclosed into a tank. When local heat transfer rates are evolved and combined, the values from the nanofluid are greater than those for pure wate. These are brought on by the nanofluid's higher conductivity than that of pure water, which improves heat transfer and dispersion inside the cylinder. In thermic Rayleigh numeral 10^5, as indicated in figure 7, Thermic convection and nanoparticle volume % values have significant effects on the local heat transfer rate values, increasing it. From figure (7), it has been observed that the external local heat transfer rate is maximum in the top area (A_B) and minimum in the bottom part of the tank (C_D), where the fluid is almost unmoving. On the inner wall in figure 8, the variations are reversed. Such oppositions are found regardless of the geometry studied and can be explained if the distributions of the isothermal and current lines are known. If the point of the fence is found just amid two counter-rotating vortex clusters, the local heat transfer rate is minimal if the fluid is moved far from the fence and maximal if the fluid arrives towards the fence.

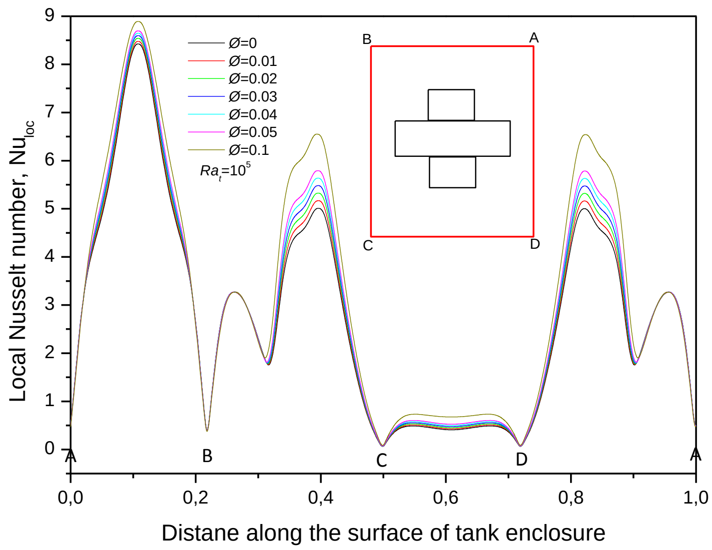

Fig. 7 Distribution of the local heat transfer rate along the surface (A_B_C_D_A) of the external wall by different values of the nanoparticle volume percent for *Rat* = 10^5

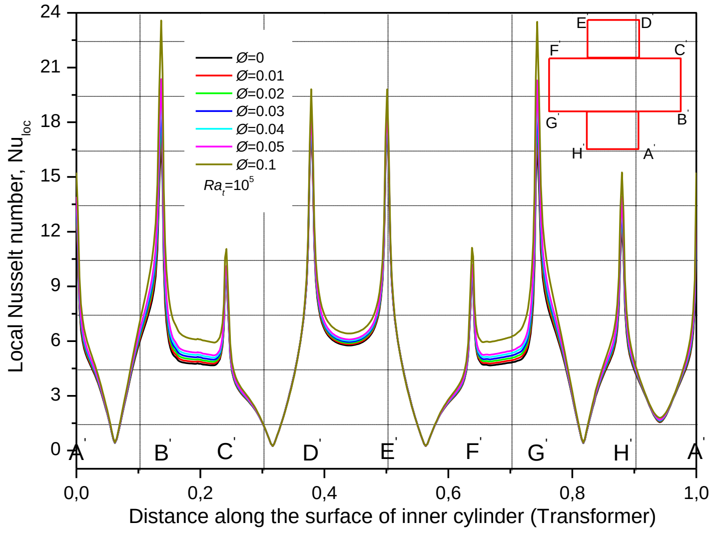

Fig . 8 Distribution of the heat transfer rate along the surface (A'_B'_C'_D'_E'_F'_G'_H'_A') of the internal fence at various values for the percentage by volume concerning the nanoparticles at $Ra_t = 10^5$

Figures 9 and 10 show the evolutions of the dimensionless temperature (θ) and the perpendicular constituent to the flow speed (V) along the horizontal direction expanding on the upper flank from the hot transformer ($Y = 0.01$). These figures confirm the results obtained previously and to understand the flow behavior inside the tank for the pure MO and the nanofluid MO-$BaTiO_3$ at various thermal Rayleigh numbers. Both sides of the tank's dimensionless temperature evolutions along the $Y = 0.01$ axis increase toward the hot transformer side. Along this axis, as the thermic Rayleigh numeral rises, the temperature decreases. At $Ra_t = 10^6$, the MO-$BaTiO_3$ nanofluid has a higher velocity and a lower temperature than pure fluid due to stronger buoyant fluxes and higher thermal Rayleigh numbers. The motion of stronger floating fluxes in the tank with the higher thermal Rayleigh number is what causes the magnitude of V to grow as thermal Rayleigh number increases. This explains why warmth transfer is in the convection mode at an elevated thermal Rayleigh number, while conduction is accountable for warmth transfer at low thermal Rayleigh number.

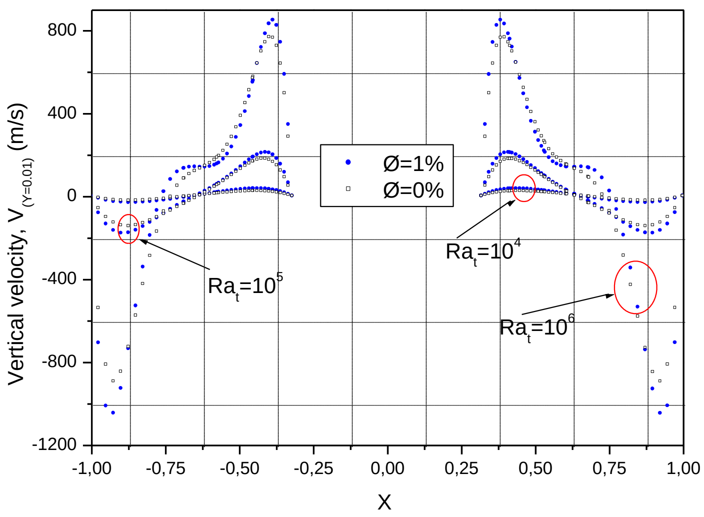

Fig. 9 Evolution of the dimensionless temperature in Y = 0.01 of the pure fluid and the nanofluid

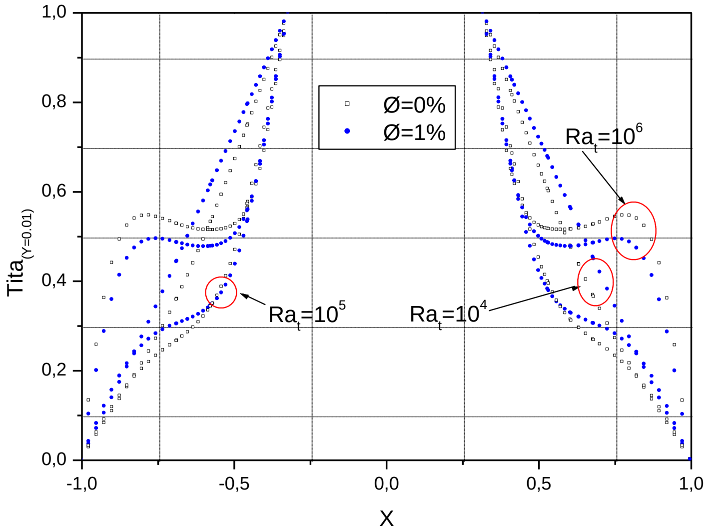

Fig. 10 Perpendicular velocity into Y = 0.01 for both pure fluid and Nanofluid

5. Conclusions

In this paper, natural convection is investigated numerically for the purpose of improving the cooling of a high-voltage transformer (heat source) enclosed in a tank containing mineral oil and the barium titanate nanoparticle $BaTiO_3$. For various nanoparticle volume percentages and different Rayleigh numbers.

In this work, it was shown how high temperatures and the volume percentage of nanoparticles affect the flux fields and the local Nusselt number.

The results showed that increasing the solids percentage by volume of nanoparticles in the nanofluid improves heat transfer and accelerates heat transfer. The thermal Rayleigh number increases the importance of the percentage by volume impact. The amount of convection can be estimated using the speed (V). The more elevated the thermal Rayleigh numeral, the more elevated the complementary velocity, which leads to the presence of larger buoyant flows. The addition of nanoparticles to the pure fluid increases the thermic conductivity of the nanofluid, resulting in improved heat diffusion. This increases the rate of heat exchange to the outside of the transformer. It is desirable to consider heat transfer investigations into nanofluids, the impacts of nanoparticle volume and shape, as well as stationarity and flow rate, can be tested.

During this study, nanoparticles dispersed in mineral oil confirmed the improved behavior of nanofluid properties compared to base mineral oil. As a follow-up to this work, it would be interesting to investigate heating with a periodic variation in time to better represent the case of transformer and electronic component cooling. Another aspect would concern the use of another type of nanofluid that has gained momentum in recent years: hybrid nanofluids.

References

[1] Fernández, I., *et al.*, Comparative evaluation of alternative fluids for power transformers, *Electric Power Systems Research, 98* (2013), pp.58-69

[2] Chairul, I. S., *et al.*, Potential of Used Cooking Oil as Dielectric Liquid for Oil-Immersed Power Transformers, *IEEE Transactions on Dielectrics and Electrical Insulation*, *28* (2021), 4, pp. 1400-1407

[3] Abghani, S., *et al.*, Effect of repeated electrical breakdowns on mineral and natural ester insulating oils, *Bulletin of Electrical Engineering and Informatics. 10* (2021), 2, pp. 2989-2996

[4] Tlhabologo, B. A., *et al.*, Alternative liquid dielectrics in power transformer insulation: A review, *Indonesian Journal of Electrical Engineering and Computer Science*, *2* (2021), 3 , pp. 1761-1777

[5] Yamuna, M., *et al.*, A comprehensive review on nanotechnology for enhancement in performance of transformer liquid insulation, *Materials Today*: *Proceedings*, *47* (2021), 2, pp. 229-234.

[6] Rusdi, N. D., *et al.*, The thermal properties of water-based hybrid nanofluid (CU-AL2O3) beyond an inclined plane, *Thermal Science*, 26 (2022), 6, pp. 4561-4570

[7] Ahmed, S. E., *et al.*, Magnetohydrodinamic dusty hybrid nanofluid peristaltic flow in curved channels, *Thermal Science*, *25* (2021), 6, pp. 4241-4255

[8] Asmadi, M. S., *et al.*, Nanoparticle shape effect on the natural-convection heat transfer of hybrid nanofluid inside a u- shaped enclosure, *Thermal Science*, *26* (2022), 1B, pp. 463-475

[9] Farooq,U., *et al.*, Modeling and Computational Framework of Radiative Hybrid Nanofluid Configured By a Stretching Surface SubjectTo Entropy Generation: Using Keller Box Scheme, *Arabian Journal of Chemistry*, *16* (2023), 3, pp. 104628-104635

[10] Farooq, U,. Tahir.M, Waqas.H, Taseer. M,. Alshehri. A;. Imran.M, Investigation of 3D flow of magnetized hybrid nanofluid with heat source/sink over a stretching sheet, *Scientific Reports*, *12*, (2022), pp. 12254–12265

[11] Farooq. U ., *et al.*, Cattaneo-Christov heat flux model in radiative flow of (Fe3O4–TiO2/Transformer oil) and (Cu– TiO2/Transformer oil) magnetized hybrid nanofluids past through double rotating disks, *Case Studies in Thermal Engineering*, *45* (2023), pp. 102905-102916

[12] Sobia, N., *et al.*, Comparative study of ternary hybrid nanofluids with role of thermal radiation and Cattaneo-Christov heat flux between double rotating disks, *Scientific Reports*, *13* (2023), pp. 7795-7802

[13] Waqas, H., *et al.*, A Numerical and Computational simulation of blood flow on hybrid nanofluid with heat transfer through a stenotic artery: Silver and gold nanoparticles, *Results in Physics*, *44* (2023), pp. 106152-106162

[14] Yurong, L, *et al.*, A Numerical Exploration of Modified Second-Grade Nanofluid with Motile Microorganisms, Thermal Radiation, and Wu's Slip. *Symmetry*, *12* (2020), 3, pp. 393–402

[15] Mariprasath, T. S., *et al.*, An experimental study on spectroscopic analysis of alternating liquid dielectrics for transformer, *Electrical Engineering*, *103* (2021), pp. 2

[16] Ali, M., *et al.*, Effect of purification process on the thermal conductivity and breakdown voltage of inhibited, isoparaffinic transformer oil used in electric train, *Journal of Physics Conference Series*, *1878* (2021), 1, pp. 012009-012015.

[17] Xue, Q., *et al*., Mobility of charge carriers in mineral oil and ester fluids, *High Voltage*, *6* (2021), 6, pp. 1040-1050.

[18] Rozga, P., *et al.*, A Review on Synthetic Ester Liquids for Transformer Applications, *Energies*, *13* (2020), 23, pp. 1-33

[19] Bajestan, E. E., *et al*., Thermal Behavior of Power Transformers Filled With Waste Vegetable Oil-Based Biodiesel Under Dynamic Load, *Journal of Energy Resources Technology, Transactions of the ASME*, *143* (2021), 9, pp. 1-9

[20] Altay, R., *et al*., Use of Alternative Fluids in Very High-Power Transformers. Experimental and Numerical Thermal Studies, *IEEE Access*, *8* (2020), pp. 207054-207062

[21] Oparanti,S., *et al*., AC breakdown analysis of synthesized nanofluids for oil-filled transformer insulation, *The International Journal of Advanced Manufacturing Technology, 117* (2021), 5, pp. 1-9.

[22] Qiu, Q., *et al.*, Simulation of the diffusion behavior of water molecules in palm oil and mineral oil at different temperatures, *Renewable Energy, 174* (2021), 1, pp. 909-917.

[23] Siddique, Z. b., *et al*., Dielectric Behavior of Natural Ester Based Mineral Oil Blend Dispersed with TiO_2 And ZnO Nanoparticles as Insulating Fluid for Transformers, *Journal of Molecular Liquids*, *339* (2021), 4, pp.116825-116837

[24] Maneerot, S., The Comparative Study of Physical and Chemical Properties of Palm Oil and Mineral Oil Used in a Distribution Transformer, 8th International Conference on Condition Monitoring and Diagnosis (CMD), 2020, Vol. 1, pp. 385-388

[25] Labib, N. M., *et al.*, Numerical investigation on effect of base fluids and hybrid nanofluid in forced convective heat transfer, *Int. J. Therm. Sci*,*71* (2013), pp. 163-171

[26] Khentoul, M., *et al.*, Numerical Simulation of Nanofluid Cooling Enhancement of Three Fins Mounted in a Horizontal Channel, *Journal of Heat Transfer*, *138* (2016), 1, pp. 091002

[27] Maxwell, J. C., A Treatise on Electricity and Magnetism, vol. II, Oxford University Press, Cambridge, UK, 1873, pp. 54

[28] Patankar, S., *et al.*, A calculation procedure for heat, mass and momentum transfer in three-dimensional parabolic flows, *Int. J. heat and Mass transfer*, *15* (1972), pp. 1787-1806

[29] Sharif, M. A. R., Laminar mixed convection in shallow inclined driven cavities with hot moving lid on top and cooled from bottom, *Appl. Therm. Eng*, *27* (2007), 1, pp. 1036-1042

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