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A numerical study of the effect of different geometrical parameters on the cooling processes in electrical transformer

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Abstract

Efficient heat dissipation is a critical factor in the performance and longevity of ONAN-type electrical transformers. Excessive heat can reduce efficiency and lead to equipment failure. Optimizing the cooling process is essential to ensure reliable operation. This study investigates the impact of various engineering factors on transformer heat transfer to enhance thermal management. ANSYS FLUENT 2019 R1 simulations were used to study the impact of different engineering factors, including the shape of the transformer, the distance between fins, their shapes, and the type and number of appendages (ribs). The results showed that increasing fin spacing lowers the coil temperature from 383 K to 381 K. Triangular ribs improved heat transfer by increasing the surface area. The highest heat transfer coefficient was achieved with Z-shaped fins (1.7 W/m².K) and triangular ribs (1.6 W/m².K)

Keywords: Electrical Transformer, Fin Shape, Heat Transfer Coefficient, ONAN, ANSYS fluent, Numerical Simulation

الخلاصة

:يعد تبديد الحرارة الفعال عاملاً حاسماً في أداء وطول عمر المحولات الكهربائية من نوع ONAN. الحرارة المفرطة يمكن أن تقلل من الكفاءة وتؤدي إلى فشل المعدات. يعد تحسين عملية التبريد أمرًا ضروريًا لضمان التشغيل الموثوق. تبحث هذه الدراسة في تأثير العوامل الهندسية المختلفة على انتقال الحرارة في المحولات لتعزيز الإدارة الحرارية. تم استخدام محاكاة ANSYS FLUENT 2019 R1 لدراسة تأثير العوامل الهندسية المختلفة، بما في ذلك شكل المحول، والمسافة بين الزعانف، وأشكالها، ونوع وعدد الزوائد (الأضلاع). أظهرت النتائج أن تقليل المسافات بين الزعانف يقلل من درجة حرارة الملف من 383 كلفن إلى 381 كلفن. كما تعمل الأضلاع المثلثية على تحسين انتقال الحرارة عن طريق زيادة مساحة السطح. تم تحقيق أعلى معامل انتقال للحرارة مع الزعانف على شكل حرف Z (1.7 واط/م².ك) والأضلاع المثلثة (1.6 واط/م².ك).

1. INTRODUCTION

Heating control in electrical transformer is very important in terms of loading reliability and service life. The layout of the transformer fins is another critical aspect responsible for improving the heat exchanging process. Several researchers have examined the effects of fin curvature on heat transfer rates and enhancements, specifically in improving the conventional structurally formed fin geometries. Fluorescent transformers are mostly-cooled by oil and air expulsion techniques in the event that they create heat during powering. Electrical losses occur due to the internal resistance current and resonances within the transformer and gets converted to heat which is carried by the oil in the transformer and deposited on the fins. These fins in further exhale the heat to the surrounding air through conduction that is either natural or forced. Different fin designs consequently have a tremendous impact of the efficiency of this heat transfer process.
Several studies have confirmed the efficacy of rectangular fins, but, sometimes, they have also proved that the thermal performance is not quite as high as desired since the fins have less surface area and there is less disturbed air around the fins; this is according to El Wakil et al. (2015) [1]. They noted that based on their study, improvement in fin spacing and size can cause a moderate effect in the efficiency of heat transfer. Joshi and Webb (2007) [2]

studied that heat exchange enhancement due to triangular fins to be higher as they claimed that it creates more chaos around the fin thus leading to higher convective heat transfer. However, triangular fin manufacturing can be fairly intricate because of the structure stability issues that may arise when developing the structures. Contemporary

research has indicated that wavy fins provide the capability to boost the overall heat transfer capacity of the condenser. In a study conducted by Zhang et al (2019), [3] CFD simulations were conducted to look at the performance of wavy fins as opposed to regular rectangular fins. From the work done by them, it was concluded

that with the wavy fins, available surface area is higher and creates more turbulence and hence enhanced convective heat transfer. The study provided significant insight into the kind of fins that can be most effective, especially with natural convection cooling.

For example, Kays and Crawford (2018) [4] carried out extensive analysis on shapes of fins such as rectangular, triangular, wave forms. They substantiated their research to the established ones which reaffirmed the fact that the wavy fins provide better thermal improvement since it helps in increasing turbulence rate of the air flow as well as the heat transfer coefficient. I believe that such numerical investigations constitute a framework for creating improved fin forms with practical configurations that can be tested and applied in practice.

Although the basic models which have been used give a good deal of theoretical indications, experimental verifications have to be done to ensure the actual application of the optimized fin designs. In their studies, Bapat et al. (2019) and Kumar et al. (2021) [5] have specifically tested the prototype transformers with changes in the geometries of fins. Based on their findings l, wavy and triangular fins made cooling performance improve dramatically under real-working conditions. In addition to these considerations, application of these optimized designs into practical use incorporates issues such as manufacturing topic restrictions and economical profitability. Another source of information was a study by Park et al. (2022) [6] that stated that employing 3D printing and precision casting, it is possible to manufacture various shapes, including wavy and triangular fins with a relatively high accuracy compared to a simple shape at a reasonable increase in manufacturing costs. Apart from the different fin designs discussed above, there are other ideas that have been studied by researchers to improve the heat transfer in transformers. For instance, Khandekar et al. (2018) [7] have explored on the efficacy of micro-structured surfaces and nano-fluids for enhanced heat transfer rate. In their study, they identified that with the help of these advanced techniques there are several opportunities to complete the optimized fin geometries to enhance thermal management in transformers. In another study conducted by Marcinichen et al. (2020) [8], the authors focused on adopting phase change materials (PCMs) into transformers cooling systems. From this they realized that PCMs could act to reduce temperatures and thereby resolve thermal stresses during maximal loads for transformers and other fin structures.

In recent years, numerous studies have examined the design and efficiency of thermal energy systems, with a focus on improving energy storage and optimizing heat exchange processes. One approach has been the integration of solar energy with other technologies to improve energy efficiency. According to a study by Hasan and others (2021)[9], solar energy systems can be optimized using advanced design strategies to enhance thermal performance, particularly when addressing inefficiencies associated with traditional heat storage methods. This research emphasizes the need for hybrid solutions that combine renewable energy sources with innovative storage systems to meet increasing energy demands. Another study by Zhao and colleagues (2021) [10] discusses the challenges associated with the degradation of thermal energy systems over time, noting that energy losses occur primarily due to thermal inefficiencies in storage units. Their findings suggest that novel materials, such as Phase Change Materials (PCMs), could be employed to reduce heat losses and increase the overall energy retention in thermal tanks. The integration of PCMs within these systems allows for the efficient capture and release of heat, significantly boosting energy storage capacities while mitigating loss. In the context of industrial applications, Ali and coworkers (2019) [11] explored the use of absorption refrigeration systems, specifically lithium bromide (LiBr) water-based machines. Their research focuses on the need to optimize these systems for better energy consumption and operational efficiency. The study demonstrated that such machines, when coupled with enhanced heat exchangers, provide a viable alternative to traditional refrigeration units, particularly in sectors where thermal energy recovery is critical . Further extending the discussion on heat exchanger technologies, Liu et al. (2019) [12] conducted an experimental study to evaluate the performance of heat exchangers in various environmental conditions. Their work highlights how design improvements in heat exchangers can lead to a significant reduction in energy consumption, contributing to more sustainable industrial processes. By focusing on the relationship between flow dynamics and heat transfer efficiency, their research provides valuable insights into the potential for improving heat exchange systems in energy-intensive industries Finally, Norazman and team (2022) [13] have examined the role of nanofluids in enhancing the thermal performance of heat exchangers. Their study indicates that the use of nanoparticles suspended in conventional fluids can dramatically improve heat transfer rates. This approach not only improves system efficiency but also opens new pathways for designing more compact and effective heat exchangers, which are crucial in reducing the overall environmental impact of industrial heat management. In addition to the previous research efforts, other studies have continued to explore various methods for improving the efficiency of thermal energy systems and heat exchange processes. A notable trend is the integration of new technologies that allow for the optimization of energy storage and transfer mechanisms. For instance, Mohamed et al. (2020) [14] explored the utilization of microchannel heat exchangers, which have garnered attention due to their compact design and high heat transfer rates. Their research demonstrated that microchannel heat exchangers significantly improve energy efficiency in solar energy applications, primarily by reducing the thermal resistance between the working fluid and the heat exchange surface. This advancement offers substantial potential for integration into various energy systems where space and efficiency are critical. The study by Chen and colleagues (2018) [15] also contributes to this growing body of knowledge, focusing on the development of nanostructured materials for heat exchangers. Their work shows that nanostructures embedded in conventional heat transfer fluids can significantly increase the thermal conductivity of the fluid, leading to improved heat transfer performance. This approach not only enhances the efficiency of heat exchangers but also allows for the design of smaller, more compact systems without sacrificing performance. The implementation of nanomaterials in heat transfer systems marks a substantial step forward in both the performance and sustainability of energy-intensive industrial processes. On a larger scale, the concept of thermal energy storage (TES) has also seen significant advancements. Williams et al. (2020) [16] examined large-scale TES systems, specifically focusing on the use of latent heat storage with Phase Change Materials (PCMs). Their findings indicate that PCMs, which store energy by undergoing phase transitions, offer a high energy density and can be integrated into various industrial and residential heating and cooling systems. The use of PCMs in thermal tanks not only improves the overall efficiency of the systems but also reduces energy costs and the environmental impact by enabling load shifting and better energy management. In another notable study, Rahman and his team (2020) [17] explored the impact of using hybrid materials, combining both nanofluids and PCMs, to further enhance energy storage and transfer in TES systems. Their research demonstrates that hybrid materials can significantly increase the thermal performance of TES systems by leveraging the high thermal conductivity of nanofluids and the latent heat capacity of PCMs. This synergy between different materials opens up new possibilities for designing advanced TES systems that can store and release energy more efficiently, making them suitable for both renewable energy applications and conventional power systems. Finally, in the realm of renewable energy integration, Kumar et al. (2021) [18] evaluated the performance of integrated solar PV-Thermal (PVT) systems that combine photovoltaic cells with thermal collectors. Their research found that integrating thermal energy storage into PVT systems enhances their overall efficiency by storing excess heat generated during the day for later use. This integration helps mitigate the intermittency challenges associated with solar energy while also optimizing the energy yield from solar panels. The study suggests that such hybrid systems could play a key role in meeting the growing energy demands while promoting the use of clean energy technologies. The transformer core and windings are central to heat generation and dissipation. Kulkarni and Khaparde (2004) [19] noted that the core's size, shape, and material significantly affect thermal performance. Zhao et al. (2018)[20] conducted numerical simulations showing that altering the core's geometry, particularly its cross-sectional area, can reduce hot spots and improve overall cooling efficiency. Similarly, Sun et al. (2017) [21] demonstrated that winding configurations, such as the spacing between layers and the winding pitch, have a substantial impact on the thermal management of transformers. The design of cooling channels within transformers plays a vital role in heat dissipation. Zhou et al. (2019) [22] explored the effects of cooling duct arrangements on oil flow distribution in oil-immersed transformers. Their study concluded that optimizing the number and placement of these ducts could significantly enhance cooling efficiency. Hong et al. (2020) [23] further extended this work by investigating the effects of varying channel widths, showing that wider channels could improve cooling but may require larger transformer tanks, impacting the overall design. The application of Computational Fluid Dynamics (CFD) and thermal analysis has become increasingly important in studying transformer cooling. Dutta and Sen (2016) [24] utilized CFD to model the heat transfer processes within transformers, focusing on the impact of geometric alterations on fluid flow and temperature distribution. Their findings highlighted the importance of detailed modeling in predicting the thermal behavior of transformers with complex geometries. He et al. (2021) [25] further illustrated how advanced CFD techniques could optimize the design of cooling systems, considering various geometrical parameters to achieve better thermal performance.

2.Methodology

2.1 Physical Models

The 250 KVA, Oil Natural Air Natural (ONAN) type transformer is designed using real dimensions and specifications using the SOLIDWORKS program, which is an engineering program in which geometric shapes are designed with precise dimensions. The transformer was designed externally, represented by the air surrounding the electrical transformer for heat exchange with air enclosure a length of 1700 mm, a width of 1300 mm, and a height of 1250 mm. Inside it is a rectangular electrical transformer with a length of 884 mm, a width of 375 mm, and a length of 735 mm, with fins that are 595 mm long, 145 mm wide, and 8 mm thick. Which contains inside the oil that works on thermal cooling, with dimensions of 844 mm in length, 335 mm in width, and 695 mm in height, as in Figure 1. and inside it is coil cylinders with dimeter 200 mm and length 400 mm.

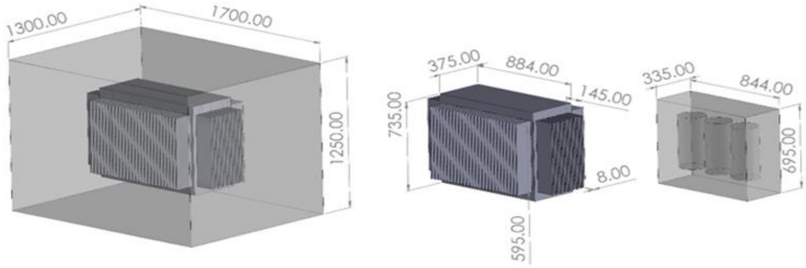
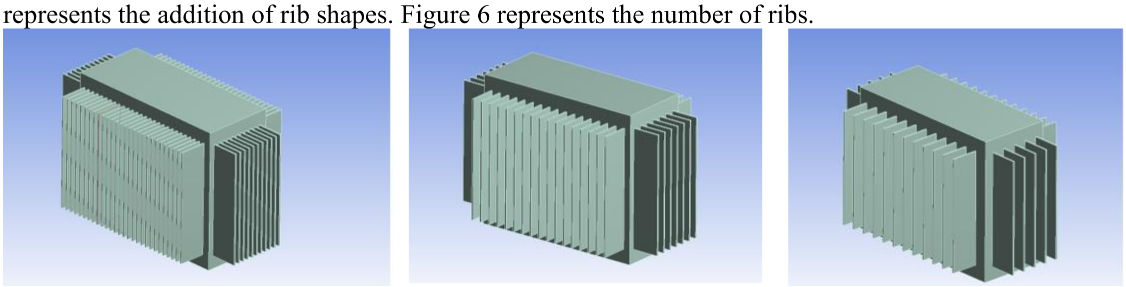


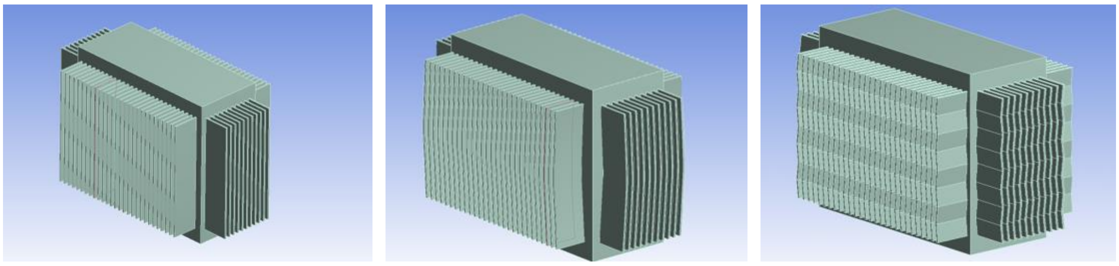
Fig.1 Rectangular electrical transformer domain.

The shape of the electrical transformer was changed to increase the surface area for the transfer of thermal energy to improve cooling of the portable electrical unit as follows: As these represent the cases used in the simulation process, Figure 2 represents the difference in the distance between the fins. Figure 3 represents the difference in the shape of the fins. Figure 4 represents the difference in the shape of the electrical transformer. As for Figure 5, it represents the addition of rib shapes. Figure 6 represents the number of ribs.



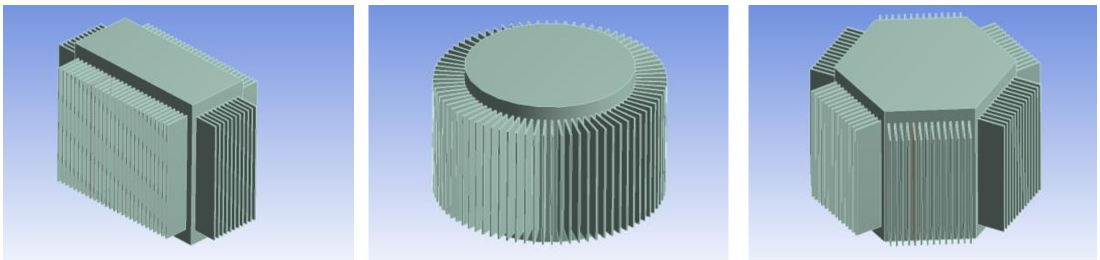
(a) (b) (C)

Fig.2 Space between fins electrical transformer domain. (a)3cm,(b)5cm,(c)7cm



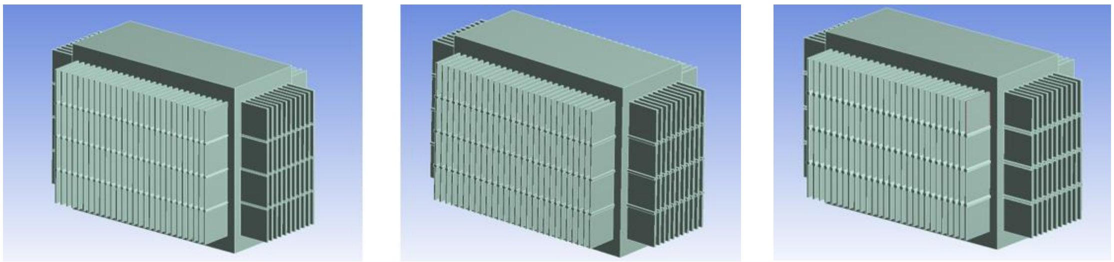
(a) (b) (c)

Fig.3 Fins shape electrical transformer domain. (a) Line shape,(b) curve shape,(c) zigzag shape.



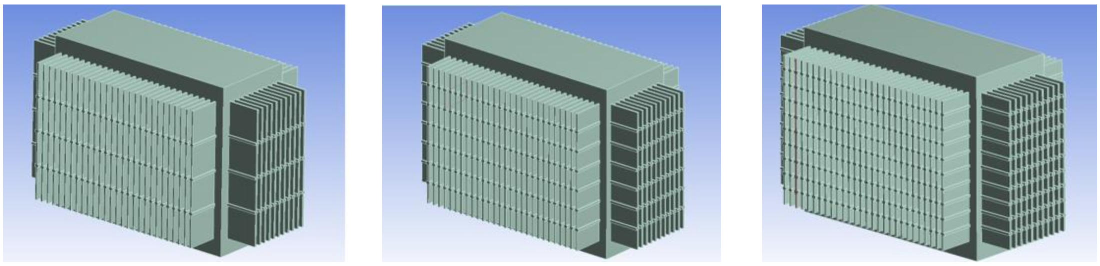
(a) (b) (c)

Fig.4 Transformer shape electrical transformer domain. (a) rectangle shape, (b) circle shape, (c) hex shape.



(a) (b) (c)

Fig.5 Ribs type electrical transformer domain. (a) triangle type, (b) rectangle type, (c) circular type.



(a) (b) (c)

Fig.6 Ribs number electrical transformer domain. (a) 3 ribs per fin, (b) 6 ribs per fin, (c) 9 ribs per fin.

2.2 Mesh Generation

Being the fact that unstructured grids perform well for the complicated geometries makes use of the tetrahedral grid method in this study. In ANSYS fluent 2019 R1, a single input can provide output in terms of the mesh through its solid geometry or model. The solution of the matrix domain equations involves the implementation of complex algorithms which makes a correct mesh requirement. And after that I would work reliability of a mesh in order to become a final steady state with the results. This is mainly because of the variety of utilized models that cause programmers to develop more than one mesh for the sake of reliability. As figure 7 showed 7062504 was assigned to the element when the Maximum coil temperature was 383.3 K as table 1.

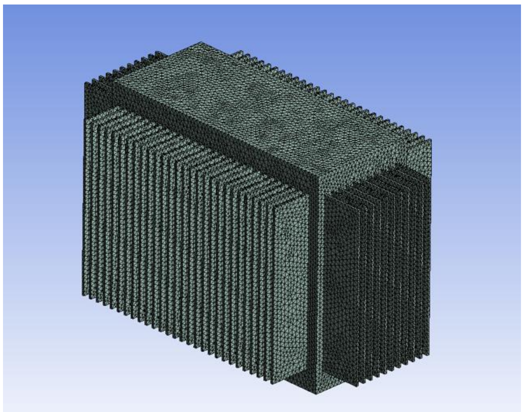


Fig.7 Mesh geometry

Table 1: Mesh independency

Case	Element	Node	Max coil temperature (k)
1	4403298	604543	389.2
2	5323567	824356	384.8
3	6234540	1043646	383.9
4	7062504	1296488	383.2

2.3 Boundary condition

The boundary conditions must be first determined to facilitate the numerical solution of a mathematical model for simulating the selected power transformer. The working conditions, such as the ambient temperature, air velocity, and coil temperature, were determined on the basis of the information provided by the laboratories that are related to those of the ONAN power transformers. Figure (8) shows the 3D computational domain that indicates the boundary conditions for all regions. The following are the conditions for the electrical transformer parts, such as oil, the body of the transformer, and its fins [19]:

1 Ambient: the external environment of the electrical transformer is represented by static air under 1 atm pressure and different temperatures determined for the study.

2 Core: the inner coils were the surfaces emitting heat, and their minimum and maximum temperatures were determined under the operating conditions of the electrical transformer.

3 Oil: the distance between the windings and the walls of the transformer is filled with oil, and the area is defined with the oil specifications changing with temperature.

4 Side, upper, and lower walls: the top and bottom surfaces and sides of the transformer are defined as the heat transfer surfaces generated with the heat transfer coefficient of the load $(0.5\ W/m^2\ K)$.

5 Fins: the sides of the transformer represented by the fins are defined as the diffused surfaces of heat generated to the ambient air with the heat transfer coefficient $(1\ W/m^2\ K)$ indicating the transfer of heat by the load.

6 Fluid velocity: Nonslip conditions are applied on all solid surfaces (exterior and interior). The above defined areas have an initial temperature of 298 K.

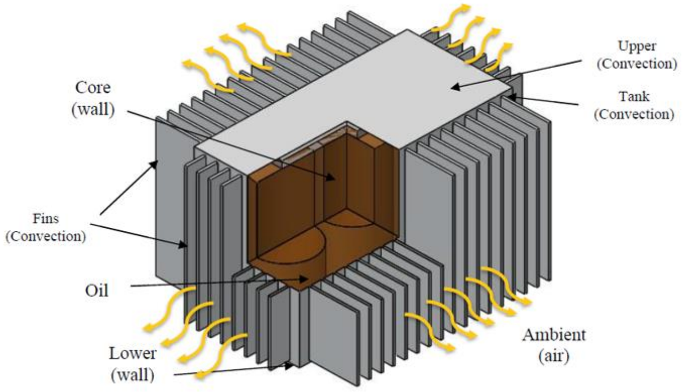


Fig. 8 Boundary condition

2.4 Assumption

Three-dimension model
Turbulent model
Non-nutinuon material
Incompressible flow
Transient study

Table 2: Oil properties [19]

Property	Typical Value	Units
Density	850 - 890	kg/m³
Specific Heat Capacity	1900 - 2200	J/kg·K
Thermal Conductivity	0.12 - 0.15	W/m·K
Dynamic Viscosity	0.02 - 0.06	Pa·s
Thermal Expansion Coefficient	7×10^{-4} - 8×10^{-4}	1/K
Flash Point	140 - 170	°C
Pour Point	-30 to -50	°C
Boiling Point	> 300	°C
Prandtl Number	150 - 300	Dimensionless

2.5 Governing equations

2.5.1 Continuity equation

The Continuity Equation is fundamental in fluid dynamics and describes the conservation of mass in a fluid flow. In ANSYS, this equation is solved alongside other governing equations such as the Navier-Stokes equations for momentum conservation and the energy equation for energy conservation.

- Continuity Equation

The general form of the continuity equation for an incompressible fluid is:

$$\nabla \cdot \mathbf{u} - 0 \quad (1)$$

where:

- $\mathbf{u}$ is the velocity vector.

For a compressible fluid, the continuity equation is:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) - 0 \quad (2)$$

where:

- ρ is the fluid density.
- t is time.

2.5.2 Momentum equation

The Momentum Equations, also known as the Navier-Stokes Equations, describe the motion of fluid substances and are fundamental in fluid dynamics simulations in ANSYS. These equations account for the conservation of momentum in a fluid flow and are crucial for solving various engineering problems involving fluid flow. The general form of the momentum equations for an incompressible fluid is:

$$\rho \left(\frac{\partial \mathrm{u}}{\partial t} + \mathrm{u} \cdot \nabla \mathrm{u} \right) - -\nabla p + \nabla \cdot \tau + \mathrm{f} \quad (3)$$

Where:

- ρ is the fluid density.
- $\mathbf{u}$ is the velocity vector.
- t is time.
- p is the pressure.
- τ is the stress tensor.
- $\mathbf{f}$ is the body force per unit volume (e.g., gravity)

2.5.3 Energy equation

The Energy Equation in fluid dynamics describes the conservation of energy within a fluid flow and is fundamental for solving heat transfer problems. In ANSYS, the energy equation is solved alongside the continuity and momentum equations to analyze thermal-fluid problems. The general form of the energy equation in ANSYS for a compressible fluid is:

$$\frac{\partial (\rho E)}{dt} + \nabla \cdot (\mathbf{u}(\rho E + p)) - \nabla \cdot (k \nabla T + \mathbf{u} \cdot \tau) + S_E \quad (4)$$

Where:

- ρ is the fluid density.
- E is the total energy per unit mass.
- t is time.
- $\mathbf{u}$ is the velocity vector.
- p is the pressure.
- k is the thermal conductivity.
- T is the temperature.
- τ is the stress tensor.
- S_E is the energy source term.

3. Results and discussion

In this paragraph, all the results obtained through the simulation program will be discussed regarding the temperature action with time for the coil, the oil, and the heat transfer coefficient. Depending on the shape of the transformer and the additions to the cooling fins.

3.1 Coil temperature

The geometric configuration of fins plays a very crucial role in determining the mode of heat transfer between the electrical transformer coil and the environment. This is because during the operation of transformers, heat is produced mainly with the coils which have to be cooled for improved efficiency and reduced heat build-up. The fins cause the surface area to have the function of dissipating heat by conduction, convection, and radiation. The amount of heat transfer surface increases, with the fin shape such as wavy or finned type enhancing the fins surface area. The evenly distributed fins also enhance the heat transfer due to improved air flow or convective heat transfer. Fin thickness is an important determinant of heat conduction, whereby thickening the fins makes the item unnecessarily heavy while using thin ones will make the heat transfer suboptimal. Location is an important factor, for example dense fins that are vertical are beneficial since they are aligned with forced convection currents. Turbulent convective heat transfer might be improved by fins with specific shapes that would maximize turbulence at the boundary layer. The structure and density of the fin material determines its ability to transfer heat, and metals such as aluminum and copper are used. The use of coatings or texturing on the surfaces can determine emissivity and consequently the radiation of heat. Fin efficiency is influenced by factors such as air temperature, air flow and the existences of cooling fluids or systems. Thus, the shape of transformer fins is one of the key factors a that affects thermal management of the devices. It can be seen in Figure 9, which shows the temperature gradient of the coil with time depending on the distance between the fins, where the temperature value of the coil reached 383 K when the distance between the fins was 3 cm, and when the distance was 5 cm, the temperature reached 381 K. However, in the case where the distance is between the 7cm fins, the temperature of the coil reached 381 K. Reducing the distance between the fins increases the surface area for heat energy transfer and thus reduces the temperature value.

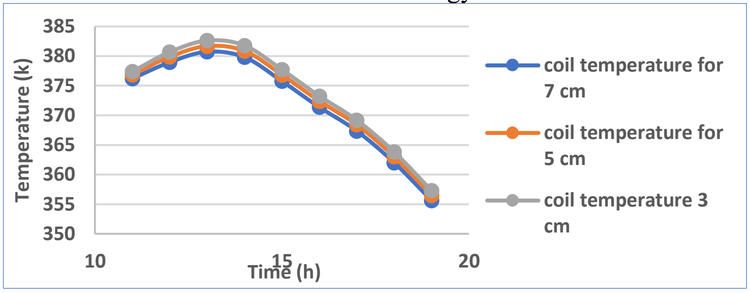


Fig.9Temperature coil with time at different Space between fins

It can be seen in Figure 10, which shows the temperature gradient of the coil with time depending on the fins shape, where the temperature value of the coil reached 381 K when the fins shape is l shape, and when the fins shape is c shape, the temperature reached 378 K. However, in the case where fins shape is z shape, the temperature of the coil reached 376 K. z shape increases the surface area for heat energy transfer and thus reduces the temperature value.

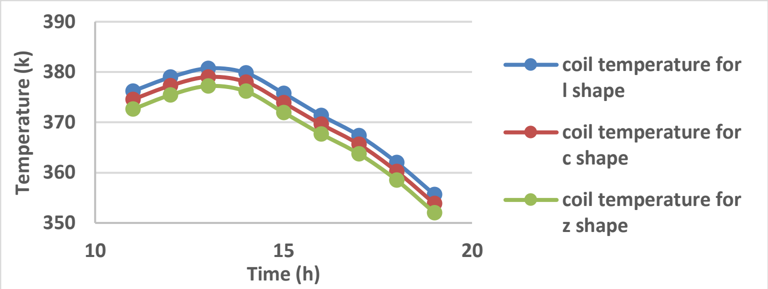


Fig.10 Temperature coil with time at different Fins shape

It can be seen in Figure 11, which shows the temperature gradient of the coil with time depending on the transformer shape, where the temperature value of the coil reached 382 K when the transformer shape is circular shape, and when the transformer shape is rectangular shape, the temperature reached 381 K. However, in the case where transformer shape is hexagonal shape, the temperature of the coil reached 380 K. hexagonal shape increases the surface area for heat energy transfer and thus reduces the temperature value.

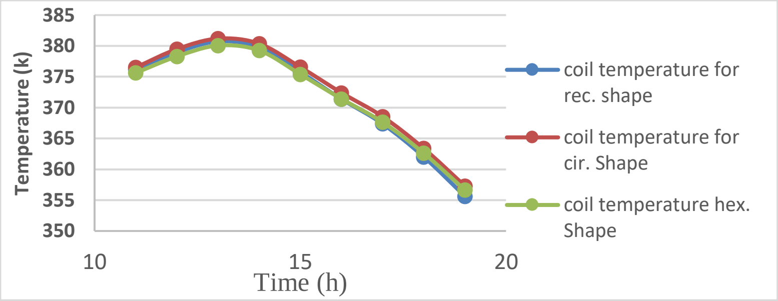


Fig. 11 Temperature coil with time at different Transformer shape

It can be seen in Figure 12, which shows the temperature gradient of the coil with time depending on the ribs type, where the temperature value of the coil reached 383 K when the ribs type is rectangular ribs, and when the ribs type is curve ribs, the temperature reached 381 K. However, in the case where ribs type is triangular ribs, the temperature of the coil reached 377 K. triangular ribs increases the surface area for heat energy transfer and thus reduces the temperature value.

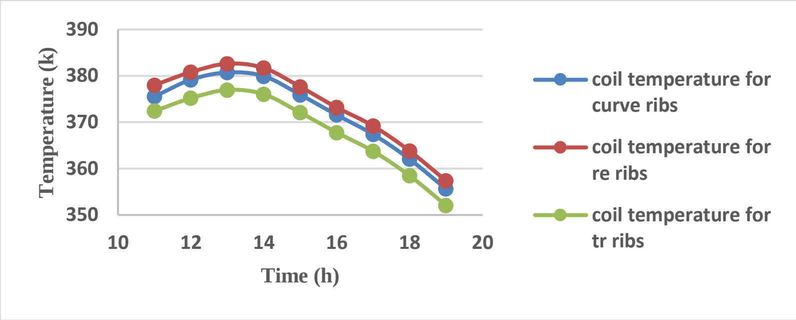


Fig. 12 Temperature coil with time at different Ribs type

It can be seen in Figure 13, which shows the temperature gradient of the coil with time depending on the ribs number, where the temperature value of the coil reached 381 K when the ribs number is 3 ribs, and when the ribs number is 6 ribs, the temperature reached 378 K. However, in the case where ribs number is 9 ribs, the temperature of the coil reached 376 K. 9 ribs increases the surface area for heat energy transfer and thus reduces the temperature value

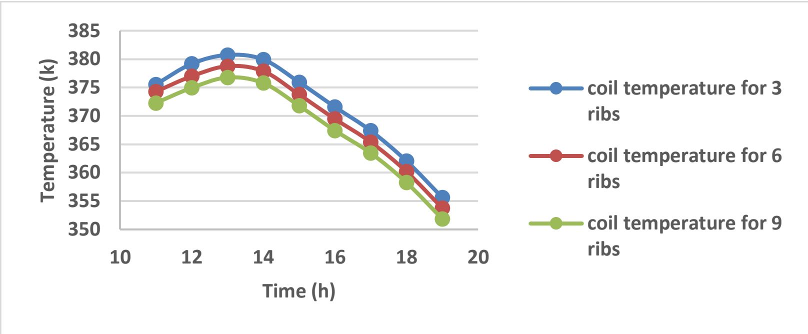


Fig.13 Temperature coil with time at different Ribs number

3.2 Oil temperature

The design of the transformer fins greatly affects the rate at which heat is transferred to the cooling oil that is used in the transformer cooling system. The fins' shape can enhance surface area, oil flow, and convection. Such fins as wavy or corrugated ones offer larger surface area through which heat transfer from the core and windings of the transformer to the oil can be enhanced. The spacing of fins plays an important role in the flow of oil and the dissipation of heat. Fins can also improve the natural or forced convection of the oil, with vertical fins providing better heat transfer as they are in the same direction as the natural convection currents. Material conductivity, like high thermal conductivity material like aluminum or copper, can also enhance the transfer of heat to the oil. The configuration of the fins plays a role in the heat transfer between the fins and the oil whereby shapes that create more turbulence and oil mixing increase the heat transfer coefficient. The more complicated the fin shape is, the more difficult it is to clean and maintain, thus reducing overall efficiency in the long run. However, complex shapes can be challenging to manufacture, and the cost may be higher than for simpler forms. It can be seen in Figure 14, which shows the temperature gradient of the oil with time depending on the distance between the fins, where the temperature value of the oil reached 356 K when the distance between the fins was 3 cm, and when the distance was 5 cm, the temperature reached 354 K. However, in the case where the distance is between the 7cm fins, the temperature of the oil reached 353 K. Reducing the distance between the fins increases the surface area for heat energy transfer and thus reduces the temperature value.

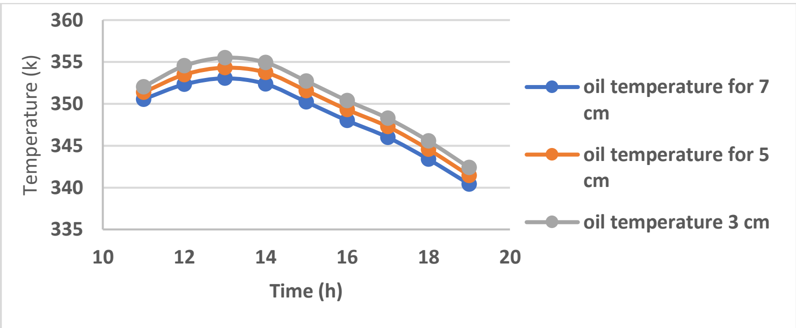


Fig.14 Temperature oil with time at different Space between fins

It can be seen in Figure 15, which shows the temperature gradient of the oil with time depending on the fins shape, where the temperature value of the oil reached 353 K when the fins shape is l shape, and when the fins shape is c shape, the temperature reached 352 K. However, in the case where fins shape is z shape, the temperature of the oil reached 349 K. z shape increases the surface area for heat energy transfer and thus reduces the temperature value.

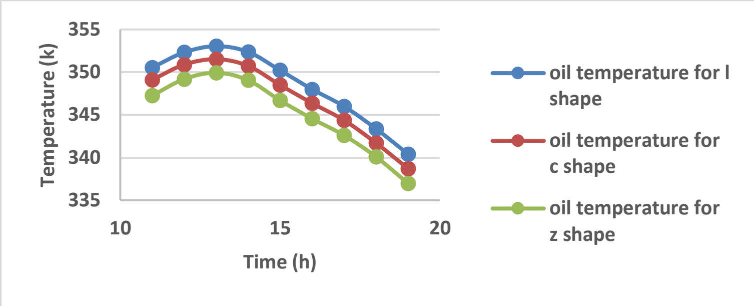


Fig.15 Temperature oil with time at different Fins shape

It can be seen in Figure 16, which shows the temperature gradient of the oil with time depending on the transformer shape, where the temperature value of the oil reached 353.5 K when the transformer shape is circular shape, and when the transformer shape is rectangular shape, the temperature reached 353 K. However, in the case where transformer shape is hexagonal shape, the temperature of the oil reached 352 K. hexagonal shape increases the surface area for heat energy transfer and thus reduces the temperature value.

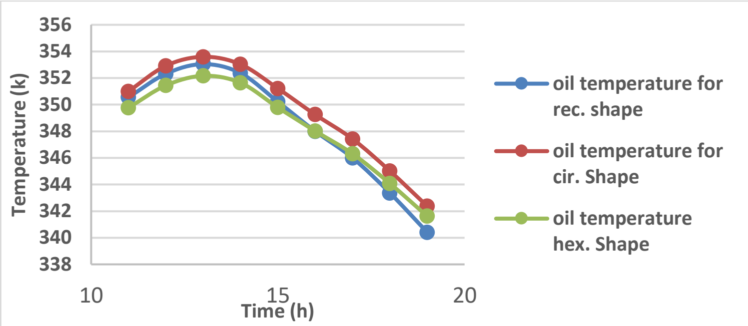


Fig.16 Temperature oil with time at different Transformer shape

It can be seen in Figure 17, which shows the temperature gradient of the oil with time depending on the ribs type, where the temperature value of the oil reached 355 K when the ribs type is rectangular ribs, and when the ribs type is curve ribs, the temperature reached 354 K. However, in the case where ribs type is triangular ribs, the temperature of the oil reached 350 K. triangular ribs increases the surface area for heat energy transfer and thus reduces the temperature value.

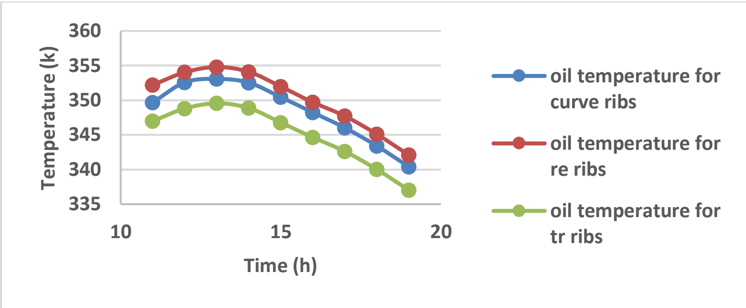


Fig. 17 Temperature oil with time at different Ribs type

It can be seen in Figure 18, which shows the temperature gradient of the oil with time depending on the ribs number, where the temperature value of the oil reached 353 K when the ribs number is 3 ribs, and when the ribs number is 6 ribs, the temperature reached 351 K. However, in the case where ribs number is 9 ribs, the temperature of the oil reached 349 K. 9 ribs increases the surface area for heat energy transfer and thus reduces the temperature value.

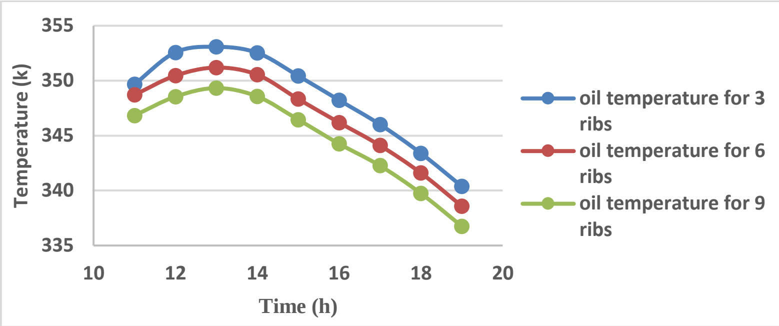


Fig. 18 Temperature oil with time at different Ribs number

3.3 Heat transfer coefficient

The number of fins that are incorporated in the electrical transformer plays a critical role in determining the heat transfer coefficient that is the heat transfer rate per unit area per unit temperature difference. Parameters like area of contact, flow regime, and thermal conductivity of substances in contact affect the coefficient of heat transfer. The larger surface area will cause a higher heat transfer coefficient, because the heat can transfer more effectively. Improved fluid flow can be gained by finned structures that generate vortices to penetrate the thermal boundary layer. This helps in achieving good flow of fluid, minimal accumulation of fluids and hence better heat transfer. The form of the fins can also affect the way in which the external conditions affect the transformer, for instance, the wind or fluid flow speeds. Thus, transformer fins can enhance heat dissipation and thus the overall performance and lifespan of the transformer by controlling these parameters.It can be seen in Figure 19, which shows the heat transfer coefficient gradient of the transformer surface with time depending on the distance between the fins, where the heat transfer coefficient value of the transformer surface reached 1.5 W/m^2. K when the distance between the fins was 3 cm, and when the distance was 5 cm, the Heat transfer coefficient reached 2.1 W/m^2. K. However, in the case where the distance is between the 7cm fins, the Heat transfer coefficient of the transformer surface reached 2.6 W/m^2. K. Reducing the distance between the fins increases the surface area for heat energy transfer and thus reduces the Heat transfer coefficient value.

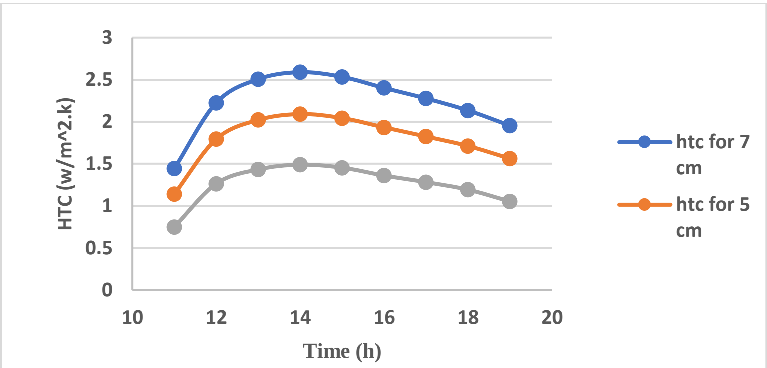


Fig. 19 HTC with time at different Space between fins

It can be seen in Figure 20, which shows the Heat transfer coefficient gradient of the transformer surface with time depending on the fins shape, where the Heat transfer coefficient value of the transformer surface reached 1.5 W/m^2. K when the fins shape is l shape, and when the fins shape is c shape, the Heat transfer coefficient reached 1.6 W/m^2. K. However, in the case where fins shape is z shape, the Heat transfer coefficient of the transformer surface reached 1.7 W/m^2. K. z shape increases the surface area for heat energy transfer and thus reduces the Heat transfer coefficient value.

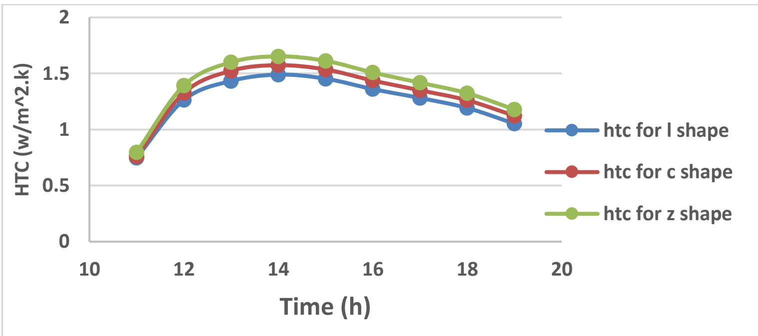


Fig.20 HTC with time at different Fins shape

It can be seen in Figure 21, which shows the Heat transfer coefficient gradient of the transformer surface with time depending on the transformer shape, where the Heat transfer coefficient value of the transformer surface reached 1.5 W/m^2. K when the transformer shape is circular shape, and when the transformer shape is rectangular shape, the Heat transfer coefficient reached 1.6 W/m^2. K. However, in the case where transformer shape is hexagonal shape, the Heat transfer coefficient of the transformer surface reached 1.7 W/m^2. K. hexagonal shape increases the surface area for heat energy transfer and thus reduces the Heat transfer coefficient value.

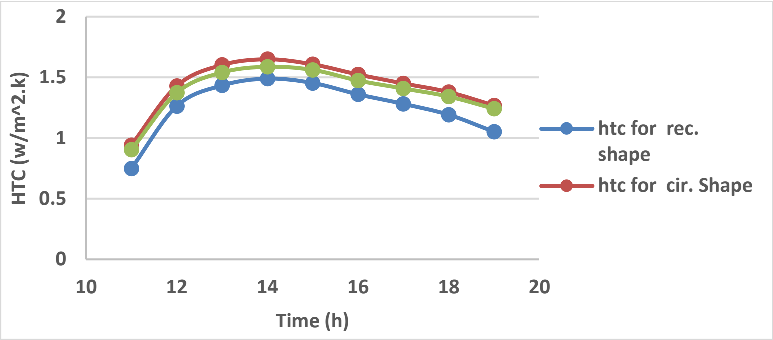


Fig.21 HTC with time at different Transformer shape

It can be seen in Figure 22, which shows the Heat transfer coefficient gradient of the transformer surface with time depending on the ribs type, where the Heat transfer coefficient value of the transformer surface reached 1.4 W/m^2. K when the ribs type is rectangular ribs, and when the ribs type is curve ribs, the Heat transfer coefficient reached 1.5 W/m^2. K. However, in the case where ribs type is triangular ribs, the Heat transfer coefficient of the transformer surface reached 1.6 W/m^2. K. triangular ribs increases the surface area for heat energy transfer and thus reduces the Heat transfer coefficient value.

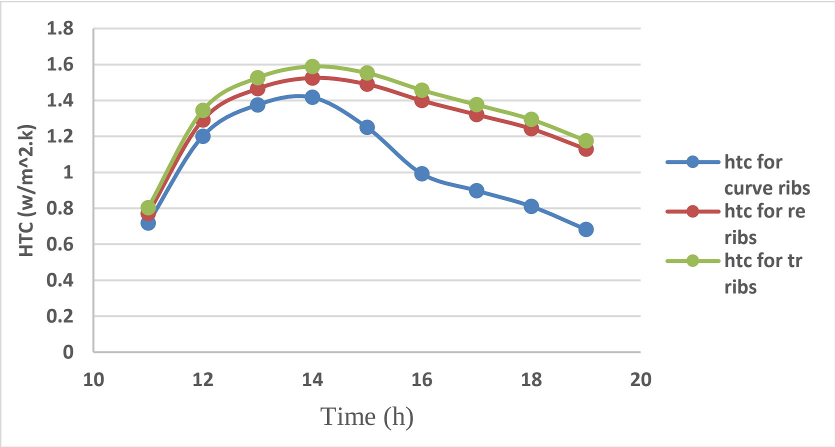


Fig. 22 HTC with time at different Ribs type

It can be seen in Figure 23, which shows the Heat transfer coefficient gradient of the transformer surface with time depending on the ribs number, where the Heat transfer coefficient value of the transformer surface reached 1.4 W/m^2. K when the ribs number is 3 ribs, and when the ribs number is 6 ribs, the Heat transfer coefficient reached 1.5 W/m^2. K. However, in the case where ribs number is 9 ribs, the Heat transfer coefficient of the transformer surface reached 1.6 W/m^2. K. 9 ribs increases the surface area for heat energy transfer and thus reduces the Heat transfer coefficient value.

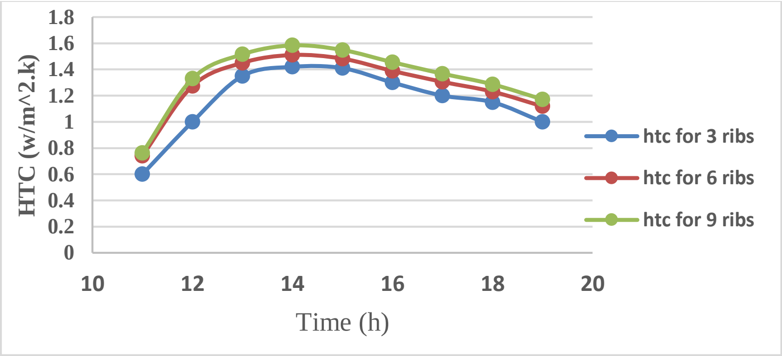


Fig.23 HTC with time at different Ribs number

3.4 The relationship between oil and air temperature

Oil and air temperatures in a transformer system are related in a way that they affect each other. The oil takes heat from the transformer and passes it to the fins and the heat is released to the surrounding air. This process is affected by temperature differences, the design of the cooling system, and the surrounding conditions. Effective thermal control helps to prevent the transformer from overheating and thus ensuring that it performs optimally and lasts longer. Through Figures 23, 24, 25, 26 and 27, it is observed that the oil temperature increases with the increase in the temperature of the surrounding air due to the inability of thermal discharge between the transformer and the surrounding.

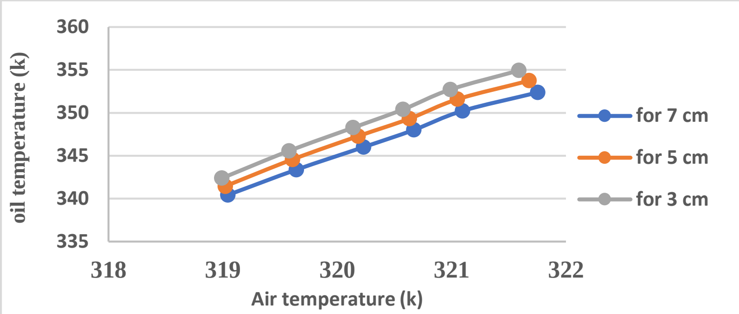


Fig. 24 The relationship between oil and air temperature at different Space between fins

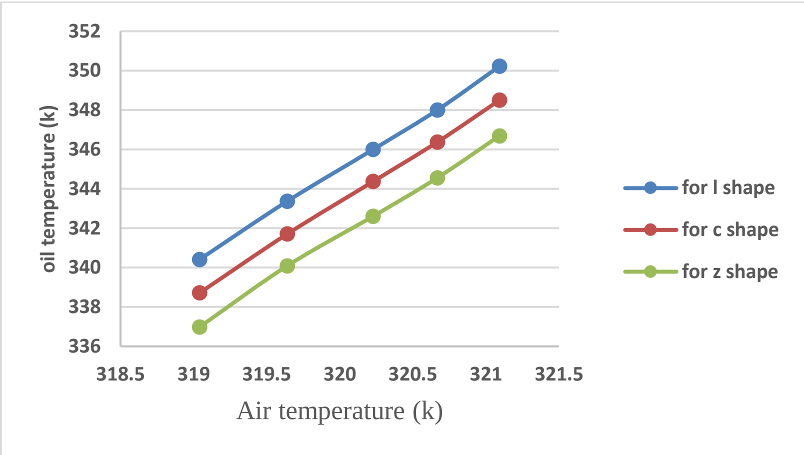


Fig. 25 The relationship between oil and air temperature at different Fins shape

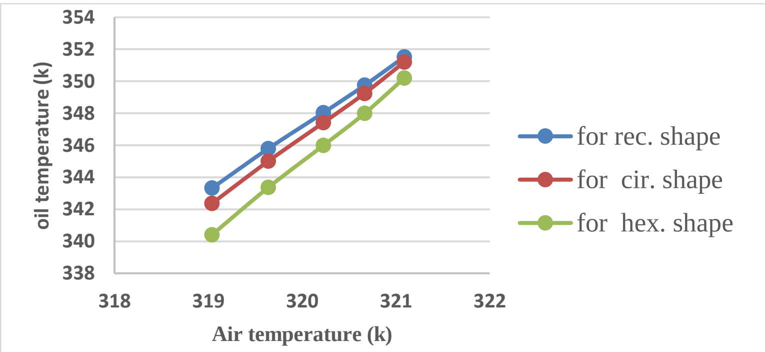


Fig. 26 The relationship between oil and air temperature at different Transformer shape

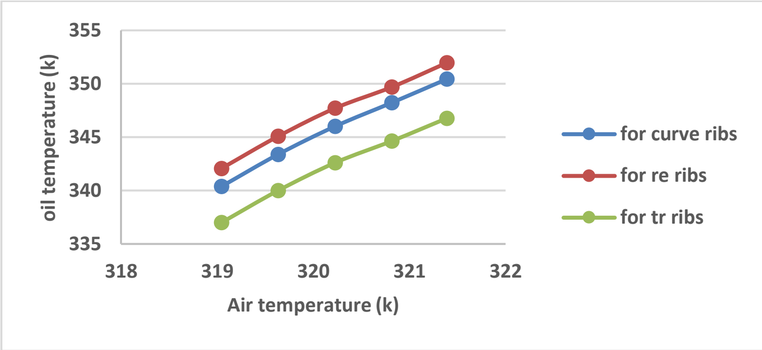


Fig. 27 The relationship between oil and air temperature at different Ribs type

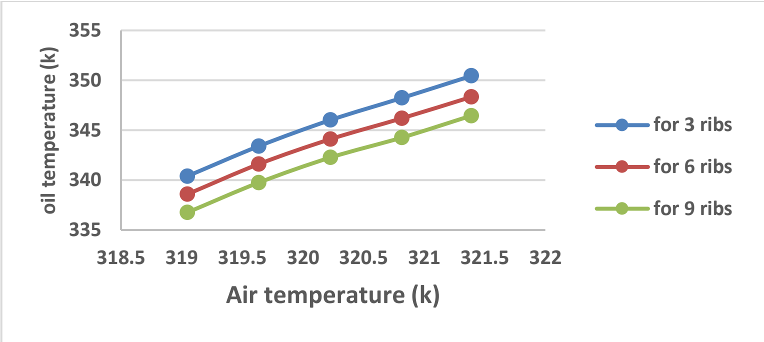
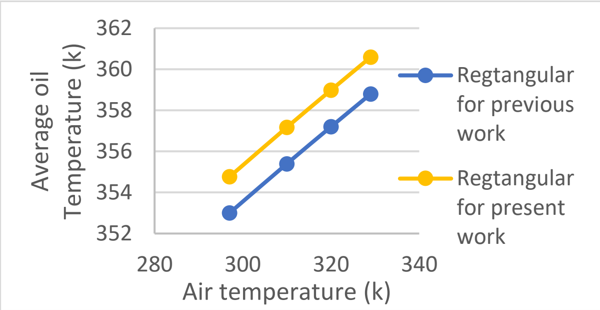


Fig.28 The relationship between oil and air temperature at different Ribs number

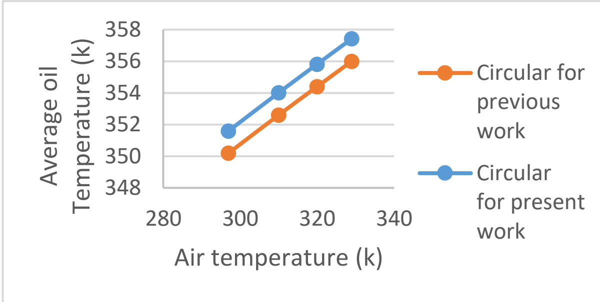
Figure 24 examined the effect of fin spacing on oil and air temperatures. When comparing the smallest spacing of 3 cm with a larger spacing of 5 cm, the percentage difference in oil temperature was approximately 0.57%. This indicates a slight reduction in temperature as the fin spacing increased, which correlates with a decreased surface area for heat dissipation. Figure 25 explored the effect of different fin shapes on temperature profiles. For instance, comparing the Z-shaped fins, which had the lowest oil temperature of 349 K, with L-shaped fins, which had an oil temperature of 353 K, revealed a percentage difference of around 1.14%. This shows the effectiveness of Z-shaped fins in enhancing heat transfer due to their increased surface area. Figure 26 evaluated the transformer shapes. The hexagonal shape, which yielded an oil temperature of 352 K, was compared to the circular shape, which resulted in an oil temperature of 353 K. The percentage difference was calculated to be about 0.28%, indicating that the hexagonal shape offers slightly better thermal performance, likely due to a larger surface area. Figure 27 analyzed the effect of different rib types on temperature variation. Comparing the triangular ribs (oil temperature of 350 K) with rectangular ribs (oil temperature of 355 K), the percentage difference was around 1.42%. This significant difference highlights the superior performance of triangular ribs in facilitating heat transfer by increasing turbulence and surface area. Figure 28 focused on the number of ribs. Increasing the number of ribs from 3 to 9 resulted in a percentage difference of approximately 0.96% in oil temperature, with 9 ribs reducing the temperature more effectively. This suggests that a higher number of ribs enhances cooling efficiency by increasing the overall surface area for heat exchange.

3.3 Validation of the numerical model.

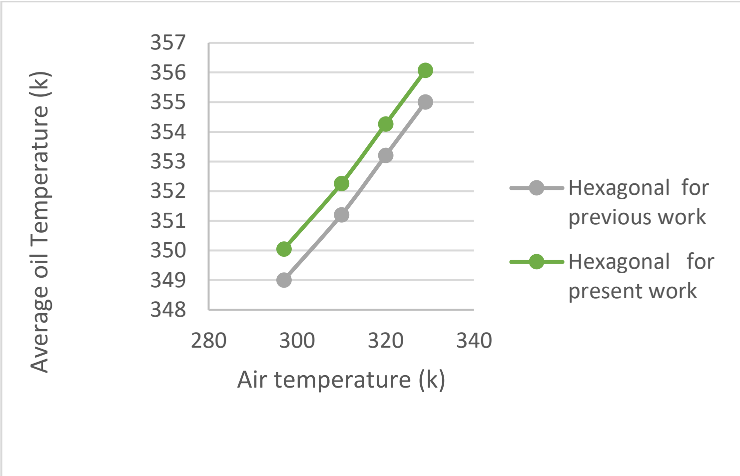
The current work exhibits a higher average oil temperature by approximately 3K at both 295K and 335K compared to the previous work. The circular shape also shows a higher average oil temperature by approximately 3K at both 295K and 335K, while the hexagonal shape shows a higher average oil temperature by approximately 2K at both 295K and 335K. The present work demonstrates a significant increase in average oil temperature at various temperatures, with the rectangular shape showing the highest average oil temperature, possibly due to better heat transfer efficiency or larger surface area. The circular and hexagonal shapes also show similar performance, with the hexagonal shape having slightly lower temperatures. The improvements in the present work are consistent across all shapes, suggesting enhancements in material properties, design optimization, or experimental conditions. The hexagonal shape has slightly lower temperatures. The physical implications of these findings are significant.



(a)

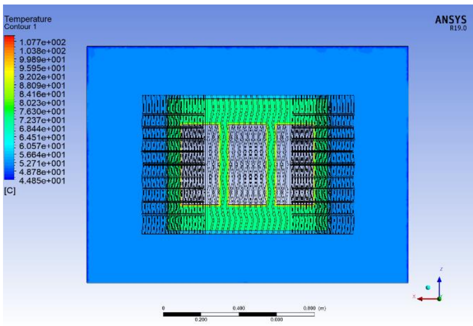


(b)

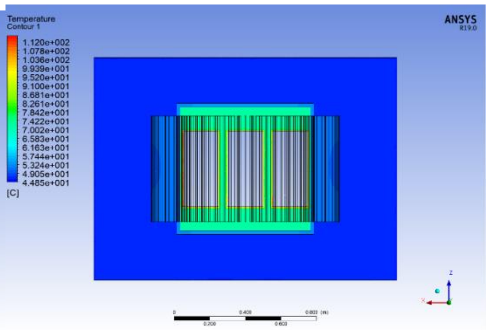


(c)

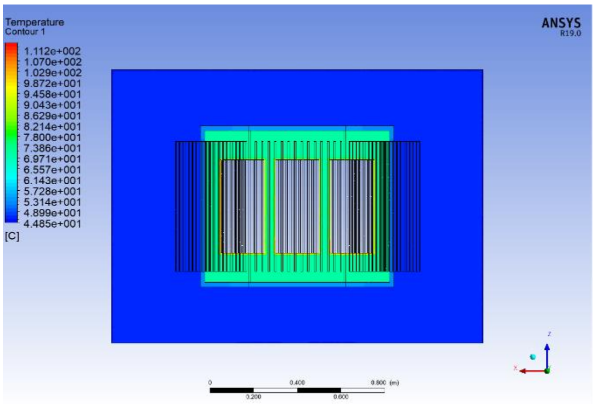
Fig .29 Validation with work [26], (a) for rectangular shape, (b) for circular shape, (c) for hexagonal shape.



(a)



(b)



(c)

Fig.30 Temperature contour of transformer shape, (a) for hexagonal shape, (b) for circular shape, (c) for rectangular shape.

4. Conclusion

This study has demonstrated the significant impact of geometric parameters such as fin shape, fin spacing, transformer shape, rib type, and rib number on the thermal performance of electrical transformers.

1. Effect of Fin Spacing: The analysis showed that increasing the distance between the fins from 3 cm to 7 cm led to a decrease in the coil temperature from 383 K to 381 K and the oil temperature from 356 K to 353 K. This clearly indicates that smaller fin spacing enhances the surface area for heat transfer, thereby improving the cooling efficiency.
2. Effect of Fin Shape: Using different fin shapes had a substantial impact on the heat dissipation. The Z-shaped fins reduced the coil temperature to 376 K and the oil temperature to 349 K, compared to L-shaped fins, which resulted in coil and oil temperatures of 381 K and 353 K, respectively. The increased surface area of the Z-shaped fins contributed significantly to these reductions in temperature.
3. Effect of Transformer Shape: The hexagonal transformer shape yielded the best thermal performance, reducing the coil temperature to 380 K and the oil temperature to 352 K, compared to the circular shape, which resulted in coil and oil temperatures of 382 K and 353.5 K, respectively. The hexagonal shape's larger surface area proved beneficial for heat transfer.
4. Effect of Rib Type and Number: The study found that triangular ribs outperformed other rib shapes, reducing the coil temperature to 377 K and the oil temperature to 350 K. Increasing the number of ribs also improved thermal performance, with 9 ribs reducing the coil temperature to 376 K and the oil temperature to 349 K, compared to 3 ribs, which resulted in coil and oil temperatures of 381 K and 353 K, respectively.
5. Heat Transfer Coefficient: The heat transfer coefficient (HTC) increased with reduced fin spacing and complex fin shapes. For instance, reducing the fin spacing from 7 cm to 3 cm raised the HTC from 1.5 $W/m^2 \cdot K$ to 2.6 $W/m^2 \cdot K$. Similarly, using Z-shaped fins increased the HTC to 1.7 $W/m^2 \cdot K$ compared to L-shaped fins with an HTC of 1.5 $W/m^2 \cdot K$.
6. Relationship between Oil and Air Temperatures: The analysis indicated that oil temperature rises with increasing surrounding air temperature, emphasizing the importance of effective thermal management. For example, with increased air temperature, the oil temperature rose, limiting the system's heat discharge capabilities.
7. Validation of the Numerical Model: The numerical model validation showed a consistent improvement in average oil temperatures compared to previous work. The current model displayed higher oil temperatures by approximately 3 K for both rectangular and circular shapes at 295 K and 335 K, confirming the improved heat transfer efficiency of the new configurations.

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Table 3: Nomenclatures

Abbreviation/Symbol	Meaning
u	Velocity vector
ρ	Fluid density
t	Time
p	Pressure
τ	Stress tensor
f	Body force per unit volume (e.g., gravity)
E	Total energy per unit mass
k	Thermal conductivity
T	Temperature
∇	Gradient operator
$\nabla \cdot$	Divergence operator
∂	Partial derivative
S_E	Energy source term