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# Evaluation of the Electrical Power Transformer Fins Design Technology: Numerical Analysis and Experimental Validation

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**ABSTRACT**

The study includes numerical analysis and experimental verification on an electrical power distribution transformer (250 kVA, 11 kW, Oil Natural Air Natural). ANSYS Fluent R3 2019 software was used to develop the numerical simulation model. The validity of the numerical model was confirmed by comparing the results of the numerical model and experimental data. The study aims to improve the efficiency and performance of electrical power distribution transformers by proposing a design that reduces the temperature of the transformer while maintaining its traditional size. Numerically, the effect of fin geometry on the temperature and density of transformer oil was studied. Four different fin designs were proposed and compared with the traditional design. According to the results, all proposed designs contributed to improving the cooling performance of the transformer compared to the traditional design. Design A is similar to the traditional transformer design, with the only modification being manipulation of the fin length, and achieves an average oil temperature reduction of 4 K. Design B showed the smallest temperature drop of the four designs, with a 3 K drop. Designs C and D include ventilation channels that match the shape of the fin, providing distinct design differences. The difference between both designs relied on the fact that for design C, the orthogonally of fin plates was retained. On the other hand, in design D, skewing of fin plates was introduced. Design D proved to be the most effective in reducing the average oil temperature, being reduced by 10 K. On the other hand, Design C reduced the average oil temperature by 7 K.

## 1. Introduction

The electrical transformer, a critical component of the electrical power transmission network, plays a pivotal role in voltage manipulation for efficient electrical energy transmission. However, complete consumption of the generated energy is not achievable due to inevitable losses. These losses manifest in various forms, contributing to power dissipation within the electrical transformers, resulting in elevated internal temperatures and subsequent performance degradation [1,2]. In many countries, the efficiency of transformers decreases due to unsuitable operating environment and overloading that exceeds the transformer's design capacity. Most electrical power distribution

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transformers are designed to operate within a safe temperature between (55 - 65) °C [3]. According to the Montsinger formula, the life span of the transformer is reduced by half when the temperature increases by 8 °C above Its design temperature is due to damage to the insulators [4]. Recently, studying the behaviour and performance of the cooling system of electrical power distribution transformers has been a real challenge for many researchers. Hasan [5] studied the thermal behaviour of an electrical power distribution transformer under the influence of air temperature. nano oils were used to replace traditional transformer oil. Four types of nano-oils were prepared using solid nanoparticles Cu, SiC, $Al_2O_3$ and $TiO_2$. Of all the nano fluids examined, SiC oil nano fluid provides the lowest transformer temperature. Rui [6] conducted a 3D simulation of an electrical transformer to verify the use of different oils instead of conventional oil. The results indicate that graphite, CNT, and diamond nano fluids have a higher heat transfer coefficient compared to the original transformer oil. CNT-based nano fluids show superior heat transfer performance compared to other nano fluids such as diamond and graphite. Hasan *et al.,* [7] analyzed a proposed thermal model for a transformer (250 kVA). Also, the effect of adding nanoparticles (CuO and $Al_2O_3$) on the heat transfer process was examined. It turns out that the maximum temperature drop is 5%. When using nano-oils. Pendyala *et al.,* [8] investigated numerically the heat transfer and fluid motion features of transformer oil and oil-based nano fluids. They found that there is better heat dissipation in nano fluids compared to transformer oil. Also, it was shown that the overall heat transfer performance in nano fluids decreases with any increase in density. Hannun *et al.,* [9] investigated the modelling of the power converter by using ANSYS-Fluent 17.1 code. A connection is made between the power transformer and the air-to-ground heat exchanger to reduce the temperature of the transformer. The results showed that the temperature of the transducer decreases with increasing depth of the underground air heat exchanger and tube length. Medved *et al.,* [10] investigated improving the life of power transformers using ANSYS CFX through the use of insulation and cooling oil. It turns out that natural and synthetic oils are more suitable for cooling. The thermal conductivity of natural or synthetic oils is greater than that of mineral oils. Özgönenel *et al.,* [11] conducted an investigation using COMSOL to convert the distribution of an oil-insulated transformer to a gas-insulated sulfur hexafluoride transformer. The new design provides safer transformation of security risk sites such as mines, submarines and nuclear power plants. Arun and Manavendra [12] replaced mineral oil with synthetic oil for cooling and insulation such as corn oil, palm oil, sunflower oil and coconut oil. Among all the synthetic oils selected, the coolant fin outlet temperature reduction for corn oil was found to be 2.3% lower than for conventional mineral oil. Si *et al.,* [13] analyzed numerically the leakage magnetic flux of metal components and oil tank of an electrical transformer (400 kVA-15 kV/400 V). They found that the current is generated by the magnetic flux leaking inside the coils (the core of the transformer), and as a result of the oil coming into contact with the metal components, heat is transferred from the coils through the oil to the fins, so that the temperature of the hot spot, which does not have a fixed location, decreases. Kanafiah *et al.,* [14] Analyzed articles that rely on the mathematical model to solve fluid flow problems using the thematic analysis program ATLAS.ti 8. This review paper adopts a review of only 50 articles on the topic as final articles from 2015 to 2020. Studied will be useful in determining the expansion of the mathematical model for the problems Related to fluid flow and convection as well as the geometric condition and appropriate boundaries. Jackwin and Bharathi [15] modified the design in cooling tubes to give better turbulent generation and improved heat transfer. A cooling tube with coaxial grooves and fins was found to be the most effective. In addition, it was found that the natural heat flow of transmission oil can be effectively simulated using fluid dynamics calculation due to the density variation with increasing temperature. Ţălu and Ţălu [16] used the finite element analysis method to optimize the dimensions of the front radiators of the cooling system of electric power transformers. The model was validated by experimental results. As a result, optimization was obtained: reducing the cooling elements and their size, reconfiguring the design, changing the dimensions of the oil tank, and optimal location of the front and rear radiators on the oil tank. Chandak *et al.,* [17] conducted a CFD analysis to investigate the effect of radiation on transformer coolant heat dissipation. Close inspection provides the possibility of increased heat dissipation even with the central coolant fins. Also, much higher heat dissipation is provided in the final fins due to the entire face being opened to the periphery. These results can be useful for designers to learn about the different effectiveness of fin configuration. Rodriguez *et al.,* [18] simulated experimental and dynamic computational measurements achieved on a typical 30MVA power transformer. The main purposes of this study are to evaluate the cooling capacity of current radiator design operating in ONAN mode. It has been shown that convective heat transfer in plate is approximately 10 times slower than heat transfer in oil. Bachinger and Hamberger [19] studied the operation of electrical power transformers under low ambient temperatures (-30 to -50) degrees Celsius. It was noted that temperatures rose instead of decreased when using enhanced cooling fans. Kaymaz [20] studied the thermal behaviour and flow pattern in a transformer radiator filled with oils (Natural ester, metal and silicon). Natural ester oil was found to have the best heat transfer and pressure drop performance. Abdolzadeh *et al.,* [21] studied the thermal performance of transformer work inside a closed and open space. The results showed that operating the transformer inside a closed space causes a decrease in its efficiency due to lack of ventilation. Paramane *et al.,* [22] examined the effect of fan mounting arrangement and air flow direction on the thermal performance of power transformer radiators by using CFD analysis. The study examined four 3-meter-high radiators, 30 0.52-meter-wide blades, and two 1-meter-diameter fans in the horizontal and vertical airflow direction. It was found that fans placed on one side of the radiators compared to the investigated arrangements lead to greater heat dissipation. Wu *et al.,* [23] presented an accurate numerical method to investigate the cooling effect of dry-type transformer unit with external heat exchangers in comparison with laboratory experiments. It has been shown that CFD simulation tools have a higher potential to be useful in practice either for developing design recommendations for transformer cooling or to support the design and development of transformer products. Anishek *et al.,* [24] conducted numerical simulations of the coolant (oil and air) of natural power transformers with the aim of determining the cooling capacity. Also, the optimal sections (spacing's and lengths) of the radiator are set. An optimal radiator design for measuring cooling capacity is presented and simulated. The proposed design is 14% more efficient compared to the original design. Kumar and Singhal [25] reviewed some studies on the efficiency improvements that can be made in pin fins to enhance the heat transfer rate. It was concluded that there are many methods and techniques by researchers in order to increase heat transfer by pin fins. Balaji *et al.,* [26] emphasized the commitment to take the original dimensions of the electrical transformer and take into account the materials used for the body of transformers when studying their design. Conduct a thermal analysis to compare the use of mild steel and aluminum for the transformer structure. Analysis proved that mild steel has better strength than aluminum. They also found that mild steel has a good ability to transfer heat through the fins surrounding the transformer body. Azbar *et al.,* [27] conducted 3D numerical modelling to test the effects of transformer shape and fins on the cooling performance of ONAN type electrical power distribution transformer. The results showed that the best heat dissipation performance and a significant 12% reduction in oil temperature compared to the conventional transformer were obtained when using the transformer with a perforated trapezoidal fin, hexagonal shape. Basher and Kadhem [28] analyzed fin shapes (trapezoidal, wavy, and triangular) using Ansys Fluent 22 R1 software to examine their effect on the cooling efficiency of electrical distribution transformers. They found that the highest effectiveness in reducing the surface and core temperatures of the transformer was at the trapezoidal fin shape. Mahdi *et al.,* [29] examined a numerical model of an electrical transformer using ANSYS Fluent-15.0 software. Four different fin designs were proposed. Design A with rectangular ventilation ducts has the same effect as the traditional design. Slightly better performance was seen in the perforated rectangular design (Design B). The best thermal performance was in Design C. Also, in terms of thermal distribution, the conventional design had higher performance compared to Design D. Lee *et al.,* [30] studied the design technique of transformers with respect to pressure variation by simulating fluid-structure interaction. The amount of oil expanding inside the corrugated fin was estimated for different load cases, with a corrugated fin design proposed to control oil pressure variations inside. Under operating conditions, the proposed transformer design reaches thermal and structural safety requirements. Farhan *et al.,* [31] recommended different fin shape under different flow powers to verify the optimal design to enhance the flow and heat transfer features that can be used in transformer cooling. The prevailing stresses decrease in a rectangular shape with a higher aspect ratio (h/s). Also, for cone-shaped fins, they note a smooth temperature drop.

The literature review conducted above highlights that temperature rise plays a crucial role in the efficiency of electrical transformers. Significant efforts have been made to enhance the thermal performance, i.e., cooling rate, of transformers through various techniques. These techniques include the use of heat exchangers, different types of oil, nanoparticle additives, and modifications to the fins shape and transformer geometry. However, limited research has been conducted on the potential of altering the design of the fins to increase the cooling rate of transformers. To address this research gap, the primary objective of this study is to enhance heat transfer and optimize oil flow patterns inside transformer fins by improving their design. This was achieved by developing a numerical model of the thermal behaviour of a capacity 250 kVA, 11 kW type oil natural air natural (ONAN) transformer using ANSYS Fluent, which was subsequently experimentally validated. Four new fin designs were suggested, evaluated, and compared to the traditional transformer while maintaining the same operational parameters. The ultimate goal is to prevent transformer breakdown, extend their lifespan, and reduce the need for maintenance.

## 2. Problem Description

Efficient cooling of a transformer is crucial for maintaining temperature rise within acceptable limits. During operation, the heat generated by active components is transferred to the oil, which in turn conducts this heat to the walls of the transformer tank. The heat then dissipates from the walls to the surrounding air through natural convection [32]. Fins are utilized to enhance the heat transfer rate from the oil, flowing within the fins, to the external air. The current work includes selecting an electrical power distribution transformer commonly used in electrical networks (250 KVA, Oil Natural Air Natural (ONAN) type) as a case study. Figure 1 depicts an image of this transformer and a schematic diagram. The components of the transformer include the transformer core, oil, and outer shell. The core of the transformer includes a steel core carrying three oil-immersed copper coils, while the transformer body is equipped with fins to increase the surface area for heat dissipation. The dimensions of this electrical transformer are as follows: (0.7, 0.9 and 0.45) m represent height, length and width transformer body, (0.6 and 0.2) m represent height and length of fins, the total number of fins is 50, and the spacing between fins is 0.04m.

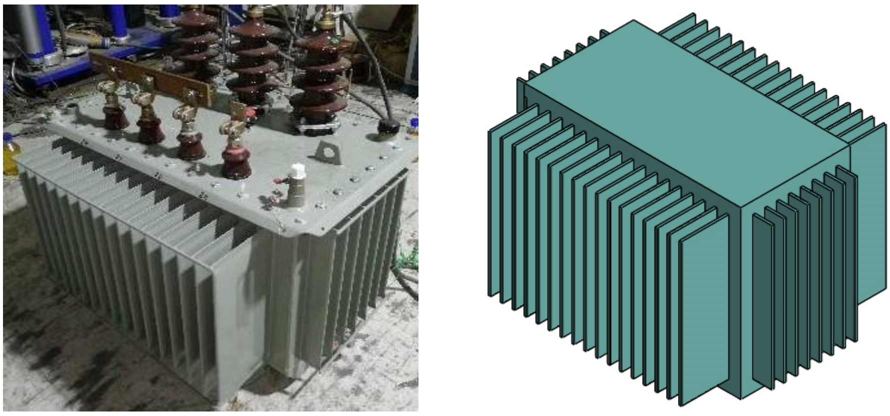
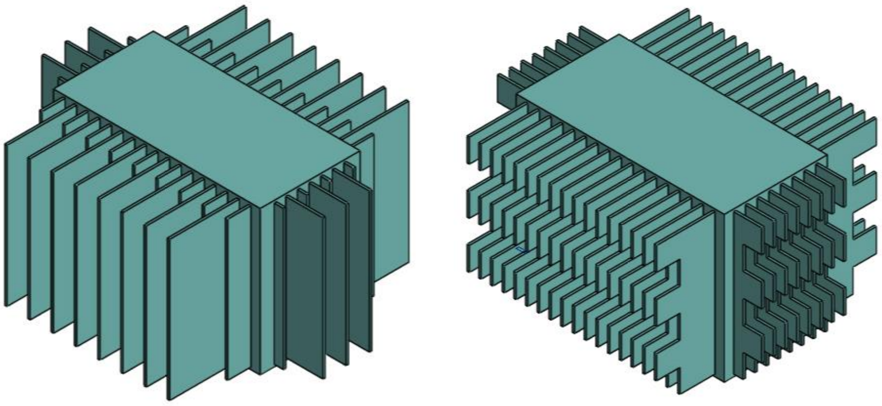

(a) (b)

**Fig. 1.** ONAN type transformer (a) Traditional transformer image (b) Schematic diagram

In this work, the thermal behaviour of four distinct transformer designs was examined using numerical simulations and experimentally validated. These proposed transformer designs were compared to a traditional design. To ensure a fair comparison, all case studies maintained nearly identical oil volumes and external surface areas. Figure 2 illustrates the geometric characteristics of the four different transformer designs (A, B, C, and D). While all designs share similar features, the distinguishing factor lies in the fin shape. The total surface area of the fins in all proposed designs amounts to 9.6 m$^2$.


Design A Design B

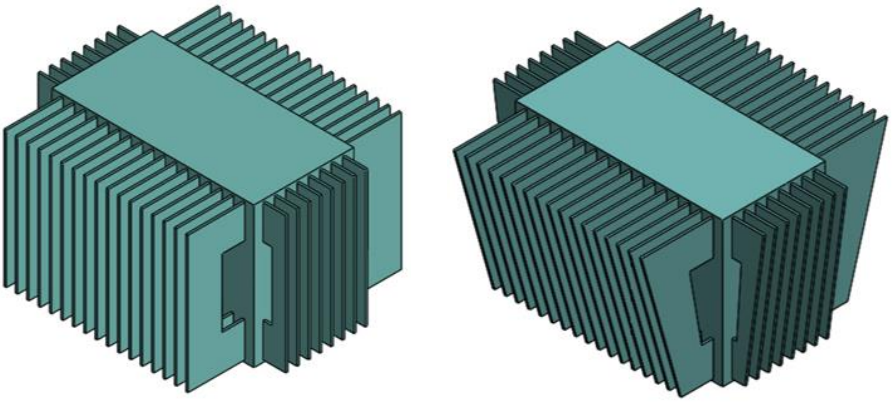

Design C Design D

**Fig. 2.** The geometrical details of the four transformer designs

## 3. Numerical Model

### 3.1 Governing Equations

The oil flow within the transformer enclosure is simulated using a three-dimensional, steady-state, and incompressible model. It is important to note that the properties of the oil are temperature-dependent. The relationship between temperature and the oil properties can be described using the following equations [33]

$$\rho = 1098.72 - 0.712\, T_{Oil} \tag{1}$$

$$C_p = 807.163 + 3.58\, T_{Oil} \tag{2}$$

$$\mu = 8.467 \times 10^{-2} - 4 \times 10^{-4}\ T_{Oil} + 5 \times 10^{-7}\, T_{Oil} \tag{3}$$

$$\mathrm{k} = 15.09 \times 10^{-2} - 7.101 \times 10^{-5}\ T_{Oil} \tag{4}$$

The model's governing equations can be summarized as follows [34]

*Mass conservation*

$$\nabla\, V^{\rightarrow} = 0 \tag{5}$$

*Momentum conservation*

$$\rho(\,V^{\rightarrow}.\nabla)\ V^{\rightarrow} = -\nabla P + \mu\, \nabla^2\ V^{\rightarrow} + \rho\beta g^{\rightarrow}(T - T_o) \tag{6}$$

*Energy conservation*

$$\nabla.\left(\rho\ V^{\rightarrow}\, C_p T\right) = \nabla.(k\nabla T) \tag{7}$$

Where ρ: Density, μ: Dynamic viscosity, CP: Specific heat, and k: Thermal conductivity, V: velocity, P: pressure, β: thermal expansion coefficient, $T_{Oil}$: oil temperature K, $T_o$: reference temperature K, g: acceleration of gravity.

In order to simulate the heat source, the transformer core surface was treated as a constant heat flux boundary. The heat source in the transformer represents the electrical loss from the transformer core of 4215.3 W when the transformer electrical load is 300 kVA. As for the outer surface of the transformer, it is assumed to be a thermal surface with a heat transfer coefficient of 19 W/ $m^2$.K. This heat transfer coefficient was determined in a previous study, which successfully validated the model [34]. The air stream temperature was set to 308 K to represent the cooling effect of outside air on the transformer. The transformer enclosure plate was considered to be made of a material with high thermal conductivity, of negligible thickness.

### 3.2 Numerical Approach

To numerically solve the governing equations and associated boundary conditions, the commercial software ANSYS FLUENT R3 2019 was used. The coupling of velocity and pressure is solved using the SIMPLE algorithm, while a second-order upwind scheme is used for pressure. As for turbulent dissipation and kinetic energy, a first-order solution was adopted. A relaxation technique was applied to control the iteration process to ensure convergence. Relaxation drop factors were determined as follows: 0.7 for momentum, 0.8 for energy equation, 0.3 for pressure and 1 for viscosity. Two methods were used to verify the solution, the first was to track the average temperature (less than 1°C every 3000 iterations), and the second was to keep the residual values for the momentum and turbulent equations below $10^{-4}$, and below $10^{-5}$for the energy equations.

### *3.3 Grid Independence Test*

In any numerical simulation, constructing a grid for the body is a crucial step where the appropriate grid size is selected to ensure accurate results within the shortest possible time. Once the geometry is constructed, the mesh is generated, and the boundary conditions are assigned, multiple meshes need to be examined to determine an optimal grid system. Figure 3 illustrates the outer view of the mesh employed in the computational model for design C. To assess mesh independence, six different mesh sizes were evaluated, and the corresponding results for the average temperature of the oil, considering an outer air temperature of 308 K, are presented in Table 1. The analysis of Table 1 reveals that after the fourth mesh, further increases in the grid size do not significantly affect the solution. Therefore, the fourth mesh is utilized for all numerical computations.

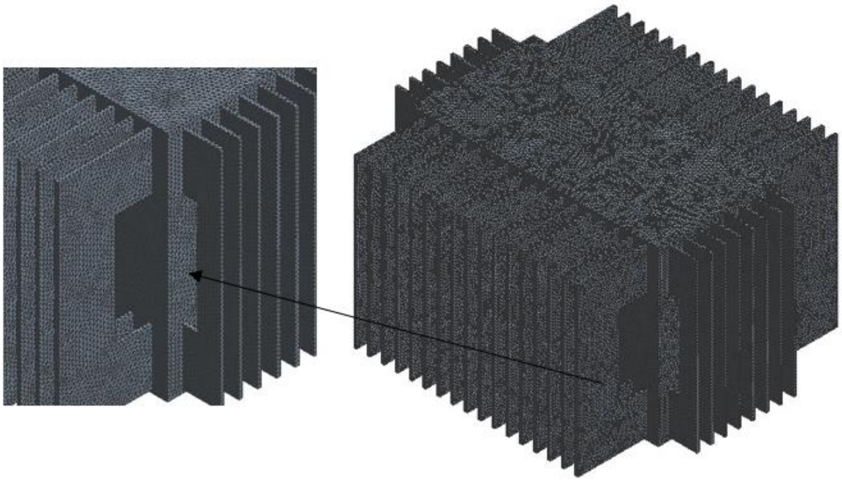


**Fig. 3.** Mesh generated for the computational model of the design C

**Table 1**
Grid size

| Grid size | Average oil temperature (K) |
|---|---|
| 983.456 | 347.34 |
| 1.263.571 | 342.41 |
| 1.518.523 | 340.35 |
| 1.824.261 | 338.02 |
| 2.091.629 | 337.31 |
| 2.301.814 | 337.72 |

## 4. Model Validation

To ensure the reliability of the generated model in simulating the thermal behaviour of the proposed transformers, a comparison is made between the estimated steady-state temperatures at a point situated 3 cm above and below the coil surface and the temperature readings obtained from thermocouples placed at the same location. An in-situ test is conducted at the State Company for Electrical Industries in Al-Waziriya, Iraq, to acquire temperature measurements while the transformer is in operation. Figure 4 depicts the electrical transformer during the testing process. The measured temperatures serve as validation data for the generated model. The test takes place in a well-ventilated large building. Type K thermocouples positioned 3 cm above and below the core of the transformer core are used to measure the oil temperature. A data logger is used to record the thermal measurements directly to the computer every 3 hours. The thermocouple has a total uncertainty of ±1 °C. The average air temperature surrounding the transformer, measured from four different locations one meter from the transformer walls, is 299.5 K. The transformer is loaded at 1.2 times its rated load, which amounts to 300 kVA (since the capacity of the transformer is 250 kVA, the test load is calculated as 250 kVA x 1.2 = 300 kVA). Testing continues until a stable temperature is reached, which is indicated by a temperature rise of less than 1 K per 3 hours. Figure 5 displays the transformer oil temperature measured during the test, showing a sharp increase initially until it reaches the steady-state temperature. Figure 6 shows the average oil temperature over time for the numerical and experimental results. The comparison showed a clear convergence between the numerical results and experimental data, as the linear error rate did not exceed 9% for the average temperature of the transformer oil. This convergence within an acceptable error rate determines the reliability of the model.

**Fig. 4.** The electrical transformer during the testing process

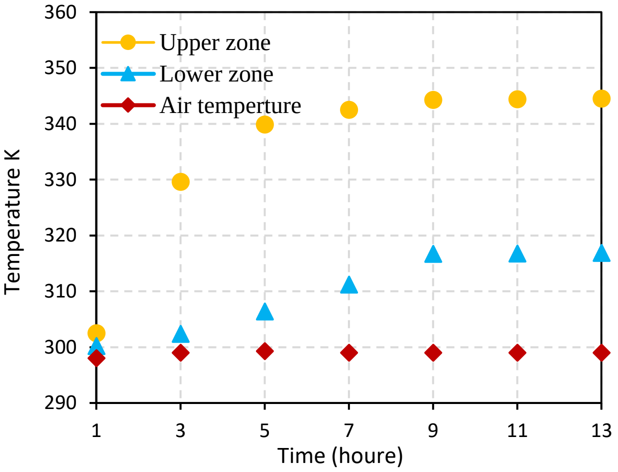


**Fig. 5.** Oil temperature in the upper and lower zone during testing with constant air temperature 299.5 K, load 300 kVA

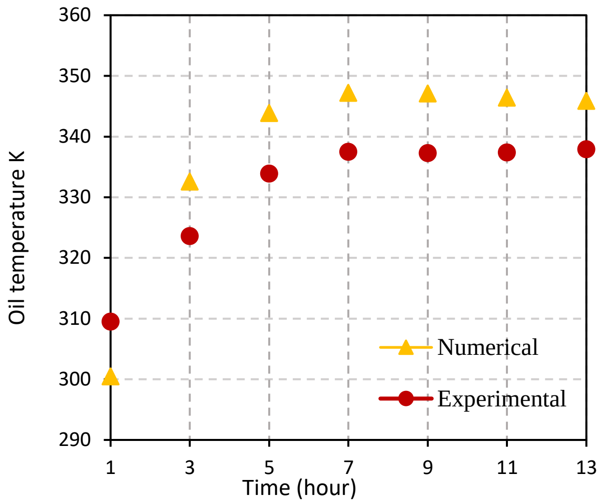


**Fig. 6.** Comparison between numerical simulation results and experimental data for the relationship of average oil temperature with time

## 5. Results and Discussion

Numerical investigations are conducted to analyse the thermal behaviour and density variations of the transformer's oil across four different transformer designs. Ratings are made taking into account an ambient air temperature of 308 K and electrical losses from the transformer core, which amount to 4215.3 W for a 300 kVA transformer load. Figure 7 illustrates the average oil temperature for both the traditional transformer and the four proposed designs. The average oil temperature for a traditional electrical transformer is recorded as 337 K. Design A, which shares similar design parameters with the traditional transformer except for adjustments made to the fin length, demonstrates an increase in the distance between fins. This modification prevents the convergence of adjacent thermal layers formed on the surfaces of opposing fins. Although the decrease in average oil temperature is marginal, reaching 333 K, the objective of studying Design A is not to deviate from the conventional transformer design but to emphasize the crucial role played by fin length and spacing in heat transfer. Design B exhibits an average oil temperature of 334 K, representing the smallest temperature drop among the four designs and a reduction of 3 K compared to the standard design. Despite the enlarged surface area of the fin in the upper hot region of the transformer, the fin's shape impedes oil movement, which relies on the buoyancy phenomenon caused by density differences, thereby reducing the heat transfer rate. Designs C and D present alternative designs featuring ventilation channels that align with the fin's shape, aiming to ventilate the heated base of the fins and keep them separate from direct contact with the transformer body. Design C conforms to the shape of a conventional transformer fin with the addition of rectangular ventilation channels that distance the base of the fin from the hot transformer body. The average oil temperature for Design C was recorded as 331 K. I note that design D achieves an average temperature of 327 K. This indicates that cooling is significant compared to the traditional design. This is attributed to two factors: First, the fin design allowed for increased surface area for heat transfer in the upper hottest region of the transformer, which is in line with the recommendations of the researcher Azbar *et al.,* [27]. Second, large ventilation channels that conform to the shape of the fin helps keep the fin base away from the hot transformer body. It also allows the circulation of oil within the fin to facilitate heat exchange with the surrounding areas. The average oil temperature results for Designs C and D indicate that the distance between the fin base and the transformer body allows direct heat transfer between the fin surface and the surrounding areas without the fin base being affected by the temperature of the transformer body. Figure 8 indicates the variation of the average oil temperature with time for all proposed designs in addition to the traditional transformer. It is noted that the average oil temperature rises sharply at the beginning of the test until reaches stability over time, and this temperature is considered the stable temperature of the electrical transformer.

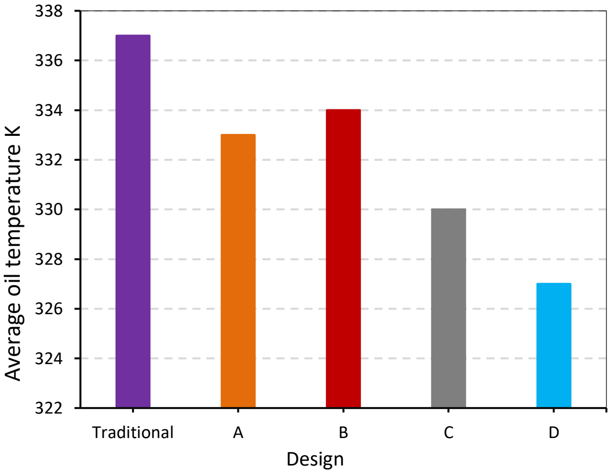


**Fig. 7.** Average oil temperature for the conventional transformer and the four proposed designs

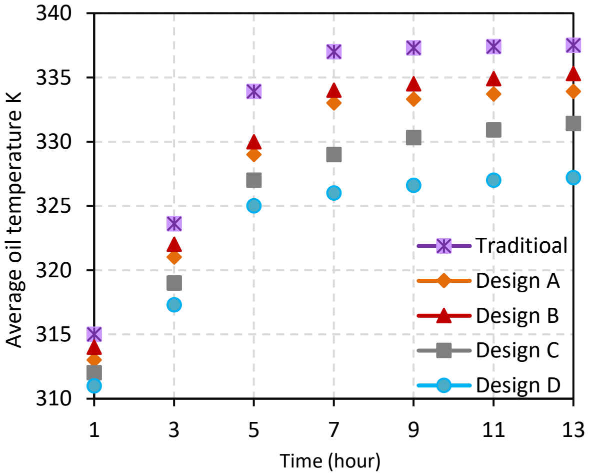


**Fig. 8.** Variation of average oil temperature with time for conventional transformer and proposed transformer designs

Figure 9 presents the variation in average oil density for both conventional transformers and the proposed transformer designs. The behaviour of oil density exhibits a complete inverse relationship to that of oil temperature, which aligns logically. The figure illustrates that Design D showcases the lowest average oil density compared to the conventional transformer and other designs. This can be attributed to the ability of Design D to facilitate oil flow into the fin cavities, allowing for heat exchange away from the high-temperature region of the transformer, particularly in the upper area known as the hot zone. With the presence of a large fin area in this region, a higher rate of heat transfer is achieved, resulting in a decrease in oil temperature and, consequently, an increase in density values. Figure 10 Shown the variation of average oil density with time for conventional transformer and proposed transformer designs. It is noted that the average oil density decreases sharply at the beginning of the test until it reaches stability after seven hours, and this degree is considered the stable oil density of the electrical transformer.

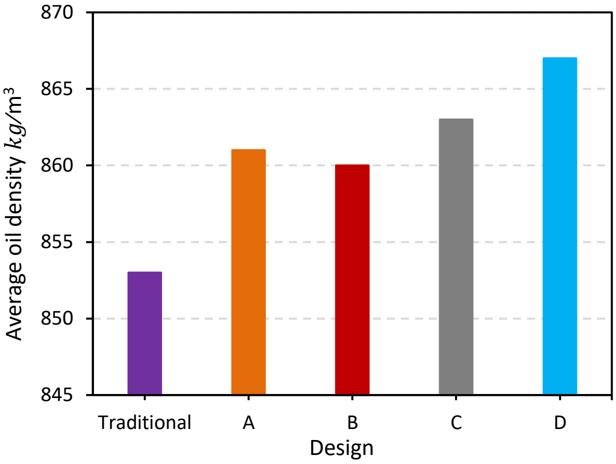


**Fig. 9.** Average oil density for conventional transformer and proposed transformer designs

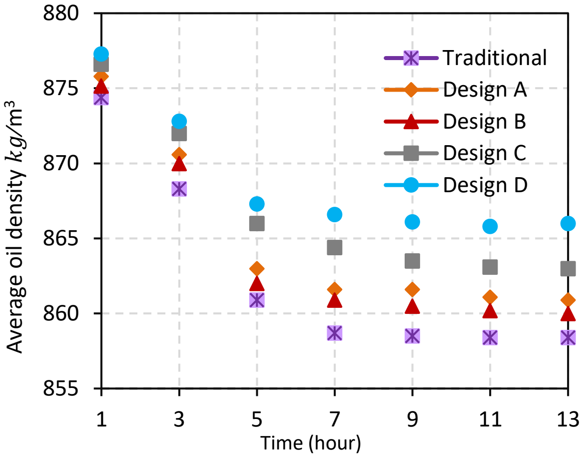
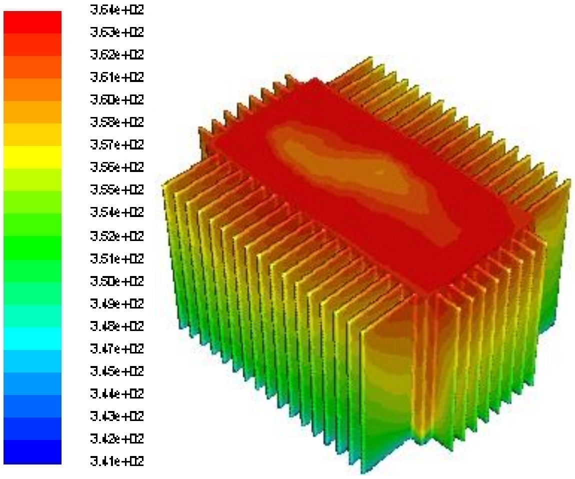
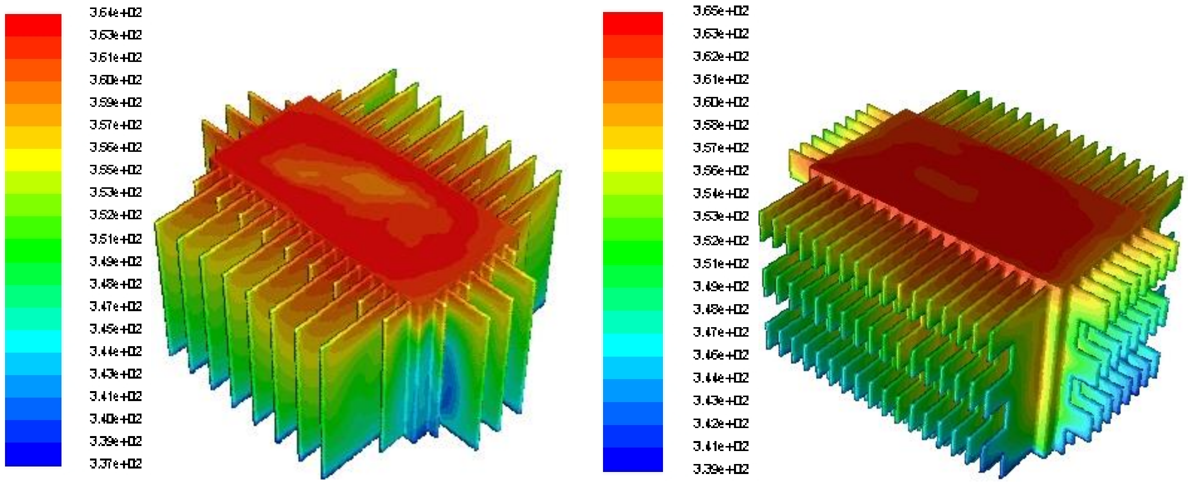


**Fig. 10.** Variation of average oil density with time for conventional transformer and proposed transformer designs

Figure 11 displays the transformer oil temperature limits throughout the entire computational domain. The thermal behaviour of the designs studied showed a difference in temperatures depending on the height of the transformer. Due to the natural convection current, heat is transferred from the core of the transformer (coils) to the surroundings through the fins. During the process of heat dissipation, it finds that the lowest oil temperature is at the bottom of the transformer and increases gradually as we move toward the top. Therefore, the hottest area is at the top and close to the surface of the heat source (the core of the transformer). This is due to the effect of the buoyant force, which causes the low-density oil (hot oil) to rise to the upper part. This phenomenon has been previously described by Tampinyo and Srikunwong [35], and Azbar and Jaffal [36]. Regarding oil density, it is observed that it exhibits an inverse relationship with temperature. Figure 12 displays the oil density contours for the traditional transformer and the four designs across the entire computational domain. In general, the lower section exhibits higher oil density compared to the upper section. The oil serves as an insulator for the coil while simultaneously transferring heat to be dissipated into the surroundings. As the oil temperature rises, its density undergoes changes, leading to a floating phenomenon.

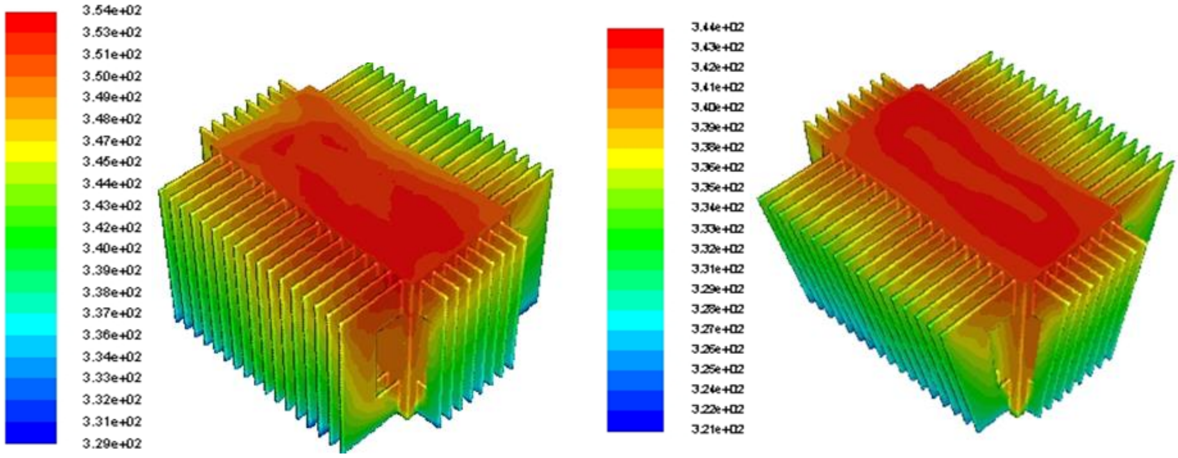


Traditional electrical transformer



Design A

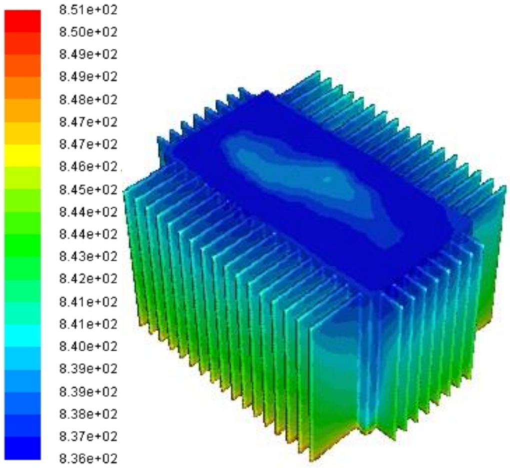
Design B



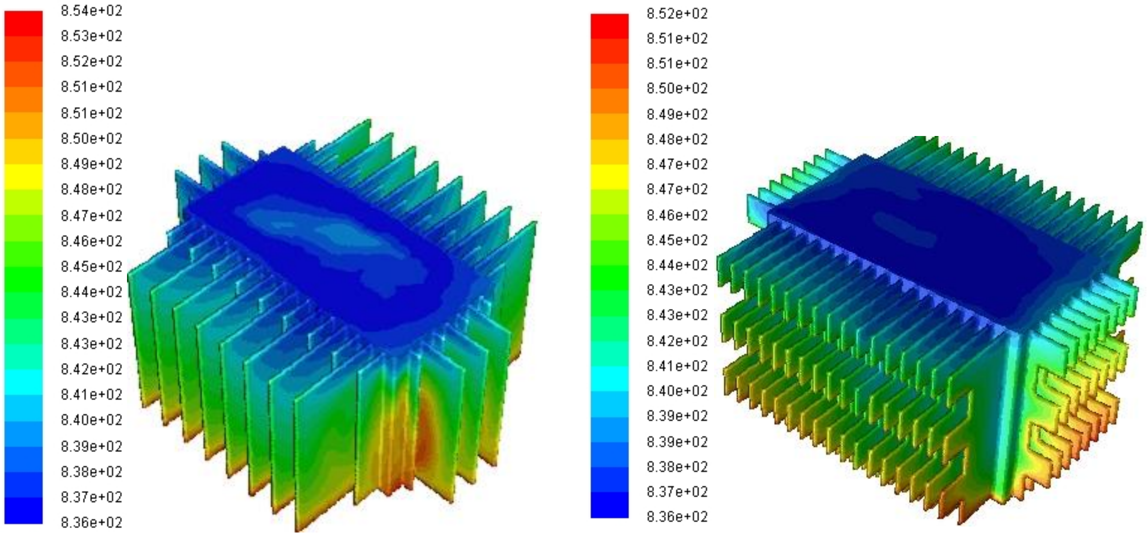
Design C

Design D

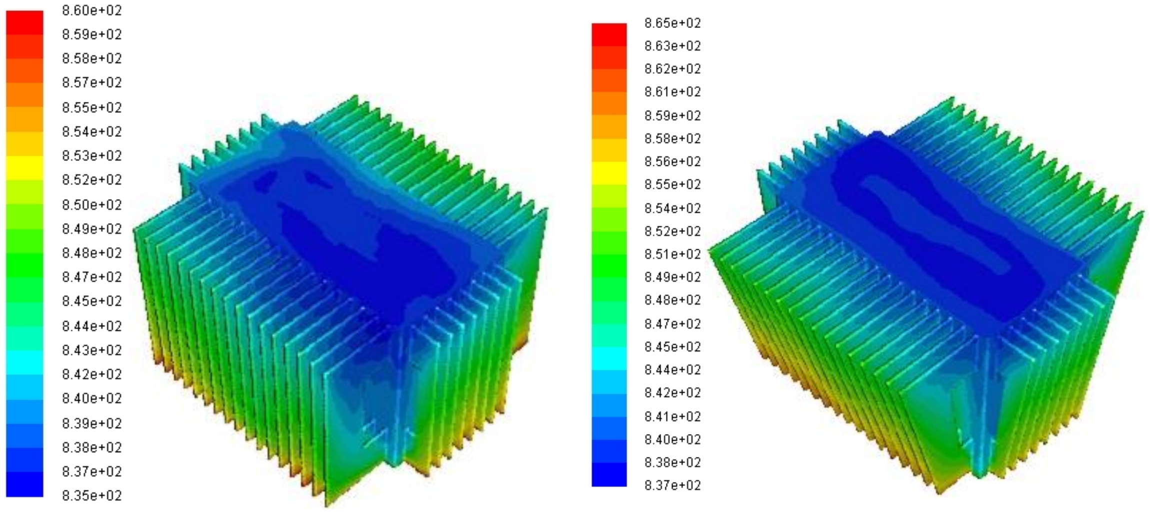
**Fig. 11.** The temperature contours of the transformer's oil at the full computational domain



Traditional electrical transformer



Design A Design B



Design C Design D

**Fig. 12.** The oil density contours of the traditional transformer and the four designs at the full computational domain

## 6. Conclusion

This paper presents a numerical study accompanied by experimental verification to investigate the thermal behaviour of a three-dimensional model, specifically focusing on the impact of fin geometry on the cooling efficiency of a capacity 250 KVA transformer type (ONAN). The current work aims to improve the performance and efficiency of electrical transformers by proposing a design that effectively reduces the temperature of the transformer while keeping its overall size similar to that of a conventional transformer. The accuracy of the numerical model was evaluated by comparing the numerical simulation model with the experimental data of the traditional transformer. The simulation model is reliable, with a maximum error of about 9%. Four new designs are presented and compared with the traditional transformer design. It can be concluded that the design and shapes of the transformer fins play an important role in the heat transfer process, as their effect depends on the large surface area of the hot components. Of the designs, Design D proved to be the most effective in reducing the average oil temperature, achieving a temperature reduction of 10 K compared to a traditional transformer. Design C, Design A, and Design B reduce the average oil temperature by 7 K, 4 K, and 3 K, respectively.

## Acknowledgement

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