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Research Paper

Enhancement of the cooling performance of an electrical power transformer using geometrical parameters

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ABSTRACT

This study investigates the influence of electrical transformer shape and fin configuration on the cooling process, emphasizing performance under varying ambient temperatures. Cooling efficiency is critical for transformer reliability, longevity, and operational safety. Traditional transformer shapes often face limitations in heat dissipation, leading to potential hotspots that can affect performance. This research utilized numerical simulations and experimental validation to compare various transformer shapes and fin configurations, focusing particularly on a 250 KVA Oil Natural Air Natural (ONAN) type transformer designed with real-world specifications. Key findings indicated that a hexagonal transformer shape and zigzag-shaped fins with rib configurations spaced at 7 cm intervals provided superior cooling efficiency. This optimized design resulted in a maximum stable temperature of approximately 332.31 K, significantly lower than that observed in traditional rectangular designs. The zigzag fins increased the effective surface area for heat dissipation, facilitating improved thermal performance. Numerical analysis using ANSYS Fluent demonstrated enhanced coolant flow and uniform pressure distribution, with higher coolant velocity reaching 0.252 m/s. This uniformity mitigated potential hotspots and mechanical stress, contributing to overall structural integrity. Experimental validation was conducted under Iraqi weather conditions, reinforcing the numerical results. Temperature tests confirmed that the optimized hexagonal design consistently maintained lower oil and component temperatures than traditional shapes. This study used Finite Element Analysis (FEA) to investigate the impact of changes in geometrical parameters. A theoretical approach based on classical mechanics was applied, where force distribution was modeled using elasticity theory. The percentage difference represents 5.26% of Coil temperature, 5.1% of Oil temperature, and 5.25 % of fins temperature, where the percentage difference represents 1.52% of all coil temperature, comparing the optimum case with previous research with experimental tests.

1. Introduction

Cooling process is important in electrical transformers since it affects the efficiency and durability of the transformer, as well as safety measures. In general studies on efficient cooling of transformers, all aspects which are regarding the construction material and geometrical shape of transformers have been described. The efficiency of cooling systems in transformers has been under enormous focus in transformer design. By Walid Aich et al. (2023)[1] investigates the thermal performance of radiated annular extended surfaces (fins) using advanced nanomaterials under nucleate boiling conditions. The research analyzes the effects of thermal radiation, magnetic fields, and nanomaterial concentration on heat transfer efficiency. This work shows that thermal conductivity and nanomaterials increase the heat dissipation of fins by more than 43%, all without significantly increasing weight. By Maalee Almheidat et al. (2024) [2] explores entropy generation in oscillatory magnetized Darcian flows with mixed thermal convection and mass transfer under Joule heating and radiative effects over a porous stretching sheet. It highlights the influence of physical parameters like thermal radiation, magnetic forces, and Joule heating on thermal and mass transfer, revealing the potential applications in industrial sectors and energy systems. Michal Stebel et al. (2022) [3] present a thermal analysis of an 8.5 MVA disk-type power transformer using biodegradable ester oil and mineral oil under ONAN cooling mode. The research employs advanced EMAG-CFD coupling to evaluate the thermal performance, highlighting the differences in heat dissipation and hotspot temperatures between the two oils. Therefore, the study concludes that ester oils can be a possible substitute, with modifications of cooling systems. Fatigue analysis of cellulose insulation in electrical power transformers is discussed by Paul Jusner et al. (2021) [4]. This paper analyzes the possible chemical reactions that might occur to the cellulose when exposed to high temperatures, and it also looks at ways of modifying the chemical structure of the composite as well as the addition of stabilizers that would increase its heat resistance. Accordingly, the focus of the study is on sustainable strategies for developing new generation cellulose-based insulation systems. Scopus search on sustainable electrical power system and DTR results in Ching-Ming Lai Jiashen Teh (2022) [5]. The paper outlines how DTR might be effectively utilized to improve the flexibility of power networks with regard to the changing thermal ratings caused by environmental variables. Specific topics of concern are associated with losses through the distribution networks, transmission networks, transformers, forecast accuracy, and interconnection with the renewable power sourcesBeing a Weather-sensitive interruption, it can disrupt and affect the distribution networks, transmission networks, and transformers. Alireza Khashaei et al. (2024) [6] conduct an experimental study into the heat transfer and pressure drop characteristics of Al_2O_3 nanofluid in a laminar flow tube with deep dimples under constant heat flux.

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Nomenclature

a	The proportion of absorption coefficient related to material properties	s	The direction of the radiative transfer
k	Absorption coefficient	r	Position vector
k_s	Scattering coefficient	*Greek Symbols*	
T	Temperature	σ	Stefan-Boltzmann constant
$1(r,s)$	Radiative intensity at position r in direction s	$\Phi(s,s^{`})$	Phase function for scattering from direction $s^{`}$ to s
Abbreviations		$d\Omega^{`}$	Differential solid angle
T_w	Wall temperature	ε	The emissivity of the surface
		n	Normal to the surface

Alireza Khashaei et al. (2024) [6] conduct an experimental study into the heat transfer and pressure drop characteristics of Al_2O_3 nanofluid in a laminar flow tube with deep dimples under constant heat flux. The analysis proves that features such as vortex generation and flow mixing enhance thermal performance, increasing the convective heat transfer coefficient over the smooth tube by 3.42. Still, the deep dimpled tube has a relatively high pressure drop penalty, and thus is appropriate for particular industrial uses at greater Re. There is an extensive review of CSP Dish/Stirling system in relation to design and optical and geometrical analysis, in addition to thermal performance by Mohamed E. Zayed et al. (2020) [7]. The paper focuses on the technical-opportunistic characteristics, the various hybridization techniques, and the multiple uses, like electricity production, water treatment, and solar cooking. The results, therefore, confirm the prospects of using Dish/Stirling systems for attaining optimal Dish/Stirling efficiency and cost effectiveness, especially for distributed generation systems. In Guoming Ma et al. (2020) [8], the topic under focus is the use of optical sensors in power transformer monitoring. It focuses on new developments in fibre-optic sensing for partial discharge monitoring, dissolved gas analysis, and temperature indications. The study focuses on the proven benefits of optical sensors, such as the ability to perform nonlinear tasks and be impervious to possible disturbances, and future prospects for increased transformer reliability and enhanced grid stability provided by these solutions, as well as the issues arising in the systemization of such systems, including cost and technical issues. The Coyote Optimization Algorithm (COA), proposed by Mohamed I. Abdelwanis et al. (2020) [9], is used for determining the parameters of single- and three-phase transformers. The performance of the proposed COA is compared with PSO and JOA algorithms, supported by experimental comparison sufficient to prove the worth of the approach. The results indicate that the COA yields higher accuracy, fast convergence rate, and stability in estimating the transformer parameters for the sole purpose of exercising proper voltage regulation and efficiency. The review by Muhamad Hafiz Ab Aziz et al. (2021) [10] considers the solutions of harmonic mitigation of non-linear loads in the electrical power system. It then divides strategies for carrying out mitigation into passive mitigation, active mitigation, and hybrid filters, giving details about when they are implemented, their strengths, and weaknesses. The paper therefore aims at minimizing harmonic distortion in order to achieve better power quality, system reliability, and to avoid cases of equipment damage. Funda Battal et al. (2020) [11] details some developments of PETs and prospects, with emphasis on design aspects, applications, and the contribution of core materials in medium- and high-frequency transformer design. The paper focuses on PETs' benefits: high efficiency, compact dimensions, and compatibility with REs, EVs, and ESS. Comparative analysis has also been made between the core materials, such as ferrite and nanocrystalline, to illustrate their performance frequency ranges. Subbarao Chamarthi and Satyender Singh (2020) [12] provide a detailed analysis of the experimental process and advancement in the efficiency of Solar air heaters (SAH). It provides an outline of test protocols, thermal and exergy efficiency factors, and alterations, including finning, baffling, and flow ducting for heat exchange improvement. In some aspects, the same review draws attention to enhancing the feasibility as an optimal, low-impact, and economic technique for domestic and industrial heating. The potential experimental procedures and thermal performance augmentation procedures of solar air heaters (SAHs) are well reviewed by Subbarao Chamarthi and Satyender Singh in 2020 [13]. Some of the testing standards mentioned in the research include practical testing and theoretical testing, while performance parameters include heat transfer rate, and changes like fins, baffles, and roughened surface are some of the modifications. The study also recommends the need to enhance SAHs for use in future renewable energy systems like space heating and agricultural drying, according to Yusupov et al. (2024) [14] who have provided a simulation model to check the technical health of oil power transformers with the help of vibroacoustic parameters. The work presents a mathematical algorithm and a Simulink environment for the identification of the operational condition of transformers. It underlines the importance of an early fault detection system to improve the reliability and minimize expenditures on maintenance related to urban power grids. Olimjon Toirov et al. (2021 [15]) show the electricity losses in industrial enterprises and the processes of production, transmission, distribution, and consumption. It introduces solutions including deployment of computerized monitoring systems, the correction of power factor, use of reactive power compensation equipment to curb power wastage, and promote energy utilization. They both seek to enhance the certainty and the resilience in energy provision and supply. In Manal M. Emara et al. (2021) [16], a new power transformer fault discrimination approach is proposed using DGA based on two graphical shapes. Based on the concentration of acetylene, the research categorizes low thermal faults into shapes of a square and electrical discharge faults into shapes of a pentagon. On the dataset of 375 samples of DGA, the efficiency of the proposed method is 78.93% of diagnostic accuracy in specific cases, compared to traditional methods. S. A. Nada et al. (2020) [17] present an experimental study of the performance improvement and heat mass transfer parameters of direct evaporative cooling systems that employ corrugated cellulose papers as the new cooling media materials. These factors include outlet air temperature, humidification, specific cooling capacity, as well as COP, which the research assesses and compares. Some of the findings suggest enhanced thermal performance, suggesting that cellulose paper cooling pads work well in hot and dry regions. Pongjet Promvonge and Sompol Skullong (2020) [18] examine the thermal characteristics of tubular heat exchangers with an applied V-Baffle. Through experimentation, it is ascertained that these baffles enhance heat transfer coefficients through the creation of counter-rotating vortices that disrupt the thermal boundary layer and promote turbulence within the fluid. The geometry of blockage ratio (BR) and pitch ratio (PR) allows for optimizing the thermal performance factor (TEF) up to 2.34 compared to plain tubes. Rahul Soni and Bhinal Mehta (2021) [19] provide an in-depth study of asset management of power transformers relating to incipient fault diagnosis and condition-based assessment (CBA). Here, he delves into diagnostic techniques like the Dissolved Gas Analysis (DGA), Sweep Frequency Response Analysis (SFRA), Polarization and Depolarization Current (PDC), and many others. The study focuses on practices to maximize the reliability of the transformer and minimize failure by approaching the optimal health index formulations of the transformers. Vahid Shiravand et al. (2021) [20] present an advanced model for the thermal behavior of power transformers. The proposed model contains extra thermal points: radiator top, middle, and bottom. The merits of the proposed model have been established through improved fault detection capabilities and improved transformer thermal management due to a mental nonlinear resistance, followed by experimental validations of the theory as produced in the model. The cooling performance of using alumina nanoparticles in transformer oil was studied by Zahra Taghikhani et al. (2021) [21] based on the ONAN (Oil Natural Air Natural) mode and the OFAN (Oil Forced Air Natural) mode. It points out the improvement of the heat transfer coefficient and the reduction in hotspot temperature by the use of alumina nanofluids. The research also presents Finemet cores for other improvements in thermal performances, also indicates lower core losses than silicon steel. Ibrahim B. M. Taha et al. (2021) [22] put forward a CNN model on power transformer fault diagnosis based on DGA. The work improves fault prognosis by implementing noise-added data sets and combined gas ratio inputs. In this research, the proposed CNN yields high diagnostic accuracy, including low noise level while providing improved diagnostic performance than traditional and other existing AI diagnostic paradigms. An optimised machine learning (OML) method is employed for power transformer fault diagnosis by Ibrahim B.M. Taha and Diaa-Eldin A. Mansour (2021) [23]. Applying decision tree, discriminant analysis, Naïve Bayes, support vector machines, K-nearest neighbors, and ensemble classification methods advances the research that diagnoses fault conditions using dissolved gas analysis (DGA). The very detailed and improved method of data transformation, including gas percentage and logarithm transformation, improves the accuracy of the prediction. The cooling performance of ferrofluids in a 40 kVA electrical transformer is examined by Raphaël Zanella et al. in [24] using an axisymmetric numerical model. Using thermomagnetic convection and operating primary Coil configurations, the ferrofluid decreases the maximum system temperature by up to

2.2C°in contrast with the conventional transformer oil. The work shows that the localized magnetic body forces enhance heat transfer and can potentially be applied to ferrofluid cooling in transformers. This study aims to optimize electrical transformers' structural and thermal performance by systematically evaluating the impact of key geometrical parameters. The research focuses on enhancing cooling efficiency by exploring various transformer shapes, such as hexagonal, circular, and rectangular, to identify the design that provides superior heat dissipation and structural integrity. Additionally, zigzag-shaped fins, optimally spaced, are introduced to maximize surface area and improve thermal performance. The study uses a comprehensive Finite Element Analysis (FEA) framework to examine how small design changes can enhance heat transfer, minimize material usage, and maintain mechanical stability.

2. Physical models

The 250 KVA, Oil Natural Air Natural (ONAN) type transformer is designed using real dimensions and specifications using the SOLIDWORKS program, 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 an air enclosure of a length of 1700 *mm*, a width of 1300 *mm*, and a height of 1250 *mm*. Inside is a rectangular electrical transformer with a length of 884 *mm*, a width of 375 *mm*, and a height of 735 *mm*, with fins 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 Fig. 1, and inside its Coil cylinders with a diameter of 200 *mm* and a length of 400 *mm*.

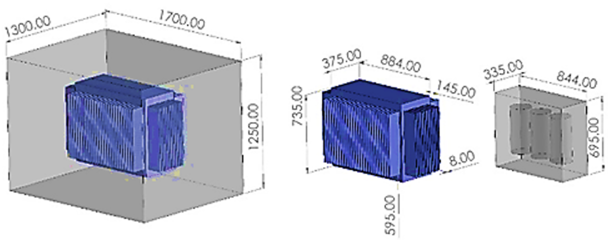


Figure 1. Rectangular electrical transformer domain [25].

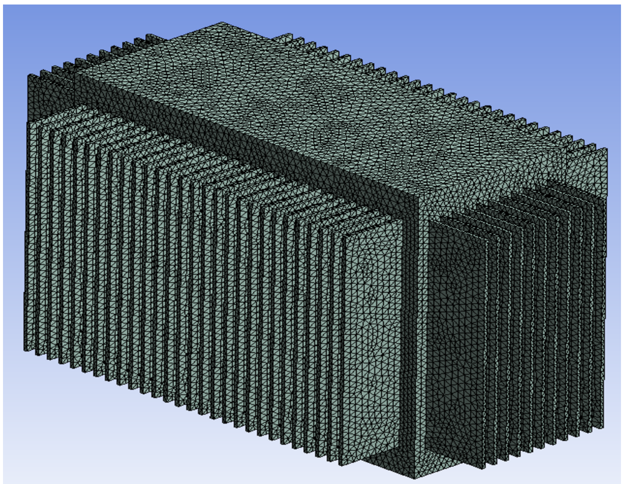


Figure 2. Mesh Geometry.

3. Mesh generation

The fact that unstructured grids perform well for complicated geometries makes use of the tetrahedral grid method in this study. In ANSYS Fluent 2019R1, a single input can provide output in terms of the mesh through its solid geometry or model, Fig. 2. The solution of the matrix domain equations involves the implementation of complex algorithms that make for a correct mesh requirement. After that, I would work on the reliability of a mesh 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 reliability. 7062504 was assigned to the element when the maximum coil temperature was 383.3 K, see Table 1.

Table 1. Mesh independence.

Case	Element	Node	Max Coil temperature (K)	Deviation %
1	4403298	604543	389.2	0.00
2	5326454	824356	384.8	-1.13
3	6234540	1043646	383.9	-1.36
4	7062504	1296488	383.2	-1.54
5	8678567	1445754	423.4	8.78

4. Boundary condition

To provide a simulation of the selected power transformer, it is necessary first to define the boundary conditions for a mathematical model's numerical solution. The working conditions are:

- Ambient: The external environment of the electrical transformer is modeled as static air at 1 atmospheric pressure and various temperatures for the investigation.
- Core: The inner Coils were the heated surfaces, and their minimum and maximum temperatures were measured under the electrical transformer operating conditions.
- Oil: The space between the windings and the walls of the transformer is laden with oil, and the space is categorized by oil characteristics that vary with temperature.
- Side, upper, and lower walls: The outer top and bottom planes and side walls of the transformer, together with the interior top and bottom planes of the transformer, and all the side walls are regarded as the four heat transfer surfaces produced through the coefficient of heat transfer of the load equal to 0.5 W/m^2K.
- 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^2K) indicating the heat transfer by the load.
- Fluid velocity: External and internal solid interfaces are modeled with applied nonslip conditions. The above-defined areas have an initial temperature of 298 *k*.

In this study, the boundary conditions (B. Cs) were established to model the heat transfer within the transformer, considering the thermal properties of the materials involved: the wall, the core, and the oil. The transformer casing (wall) was modeled with a thermal conductivity of $45W/mK$ and a heat capacity of 840 J/kgK, providing some thermal insulation and allowing heat dissipation through the external surface. The core material, typically silicon steel, was assigned a thermal conductivity of 50 W/mK and a heat capacity of 600 J/kgK, essential for understanding heat generation due to eddy currents and hysteresis losses. The insulating oil, crucial for heat dissipation through convection, was modeled with a thermal conductivity of 0.15 W/mK and a heat capacity of 2000 J/kgK. These thermal properties were incorporated into the finite element model to simulate the temperature distribution, ensuring that the transformer design maintains optimal performance and longevity under varying operational conditions.

5. Governing equations

The general ordinary differential equations for a radiation model in ANSYS are normally obtained by solving the radiative transfer equation (RTE). The RTE relates to the transportation of radiant energy through a medium through which it is absorbed, emitted, and scattered. The next section presents general governing equations associated with the radiation model, Eqs. 1, 2, and 3.

$$\frac{dI(r,s)}{ds} = -kI(r,s) + ka\frac{\sigma T^4}{\pi} + \frac{k_o}{4\pi}\int_{4\pi} IdI(r,s^{`})\Phi(s,s^{`})d\Omega^{`} \tag{1}$$

$$(Black\ Body\ Radiation) \Rightarrow I(r,s) = \frac{\sigma T_4^4}{\pi} \tag{2}$$

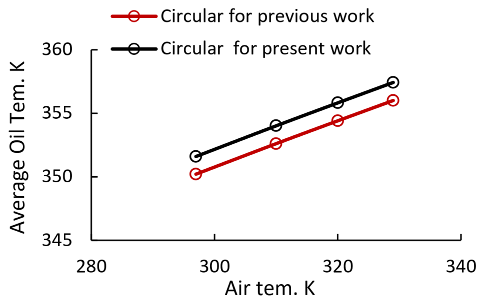
$$(Diffuse\ Surface) \Rightarrow I(r,s) = \varepsilon\frac{\sigma T_4^4}{\pi} + (1-\varepsilon)\int_{2\pi} I(r,s^{`})S.nd\Omega^{`} \tag{3}$$

Where:

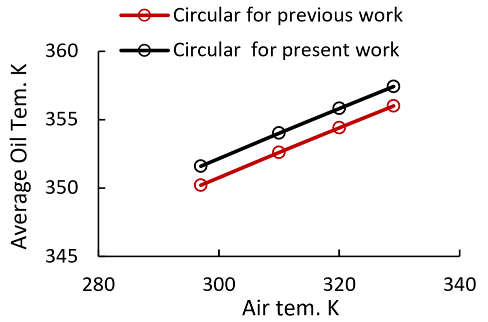
- $I(r,s)$ is the radiative intensity at position r in direction s.
- k is the absorption coefficient.

- a is the absorption coefficient's proportion related to the material's properties.
- σ is the Stefan-Boltzmann constant.
- T is the temperature.
- k_s is the scattering coefficient.
- $\Phi(s, s^{'})$ is the phase function describing the probability of scattering from direction $s^{'}$ to direction s.
- $d\Omega^{'}$ is the solid angle.
- ε is the emissivity of the surface, and bold is normal to the surface.

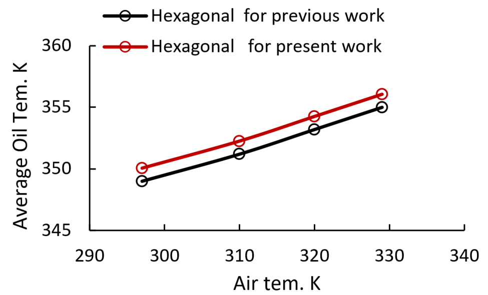
This section will delve deeper into the various components and considerations involved in solving the Radiative Transfer Equation (RTE) to provide a more comprehensive overview of the governing equations of radiation models in ANSYS.



(a) Rectangular shape



(b) Circular shape



(c) Hexagonal shape

Figure 3. Validation with Azbar work of three shapes [26].

6. Validation of the numerical model

The current work exhibits a higher average oil temperature by approximately 3K at 295K and 335K compared to the previous work, Fig. 3. The circular shape also shows a higher average oil temperature of roughly 3K at 295K and 335K. The hexagonal shape shows a higher average oil temperature of approximately 2K at 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 a 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, Table 2.

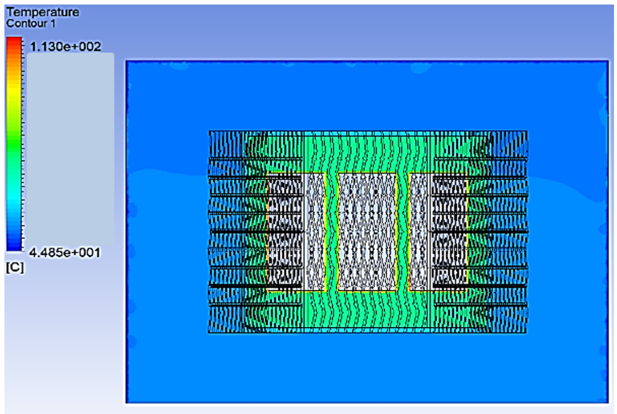
Table 2. Deviation.

Shape	Previous Work Value	Current Model Value	Deviation %
Rectangular	353k	355k	0.85
Circular	350k	352k	0.57
Hexagonal	349k	350k	0.29

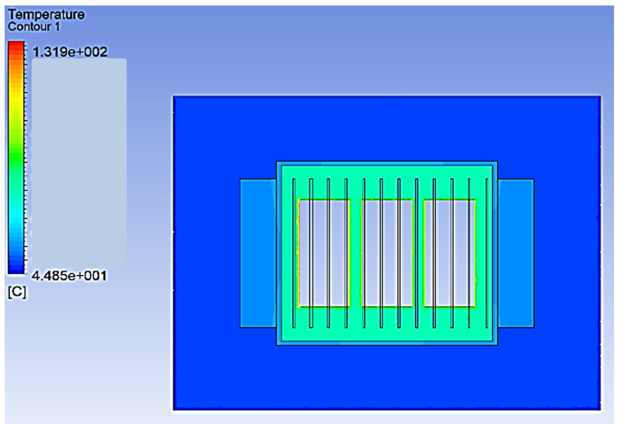
7. Results and discussion

7.1 Optimum case

By changing the general shape of the transformer, previous results regarding the change in the details of the electrical transformer found that the best shape was hexagonal. As for the distance between the fins, the best case was 7 cm. As for the shape of the fins, they were of the zigzag type, which represents the best transfer of thermal energy, with the presence of triangular-shaped ribs, with a number of 9 for each fin.



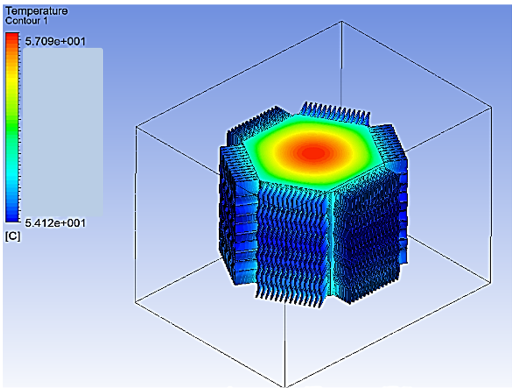
(a) Optimum case



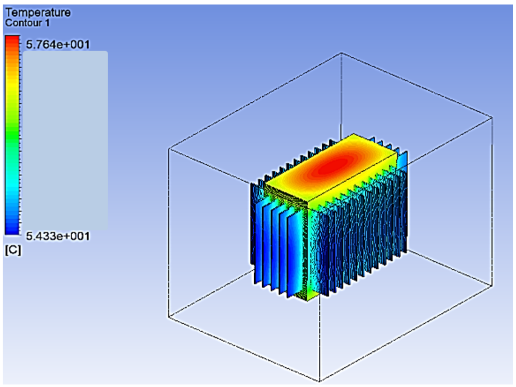
(b) Rectangular case

Figure 4. Temperature contour.

Figure 4, the temperature contour map for the optimum case, shows the temperature distribution within the transformer. The hexagonal shape with a fin spacing of 7 cm and zigzag-shaped fins results in a more uniform temperature distribution, reducing hotspots and improving overall cooling efficiency. The highest temperature observed is around 332.31 K, indicating efficient thermal management. Figure 5 shows the temperature distribution on the fin surface. The triangular fins with zigzag patterns enhance heat dissipation, resulting in a maximum temperature of approximately 332.31K. The design increases the surface area, which improves the heat transfer efficiency. Figure 6, the 3D rendering volume temperature visualization, highlights the internal temperature distribution within the transformer and enhances the heat transfer efficiency.

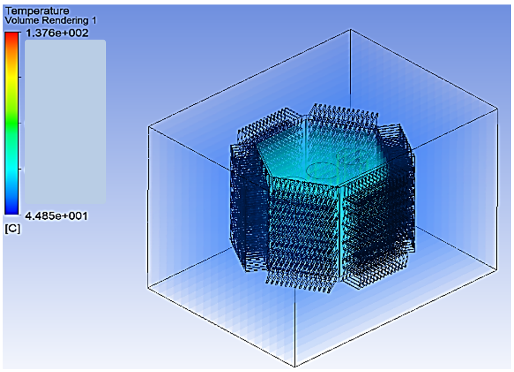


(a) Optimum case

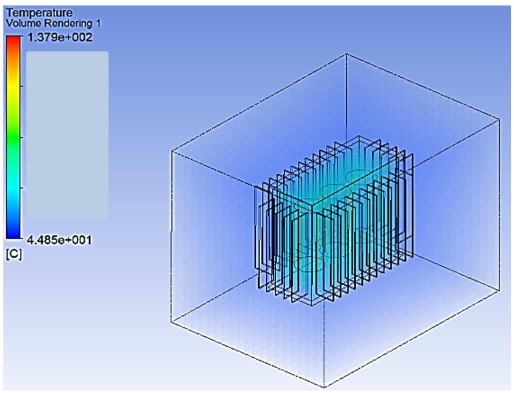


(b) Rectangular case

Figure 5. Temperature contour for fin surface.

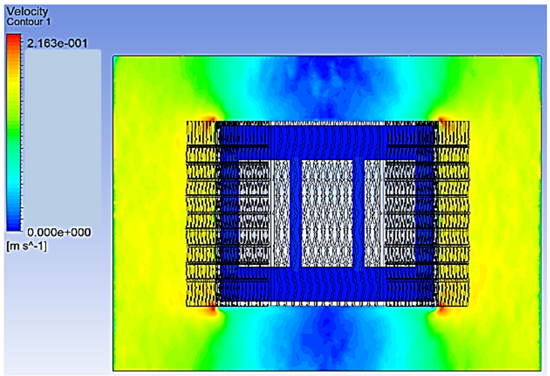


(a) Optimum case

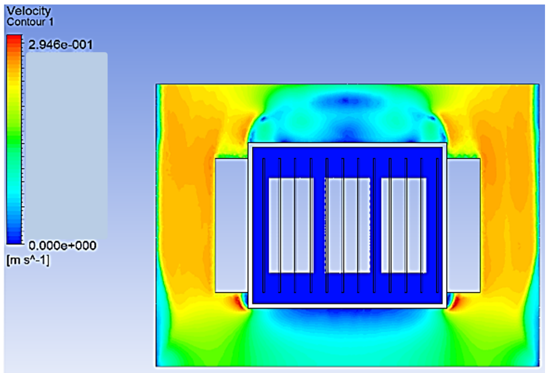


(b) Rectangular case

Figure 6. Rendering volume temperature .

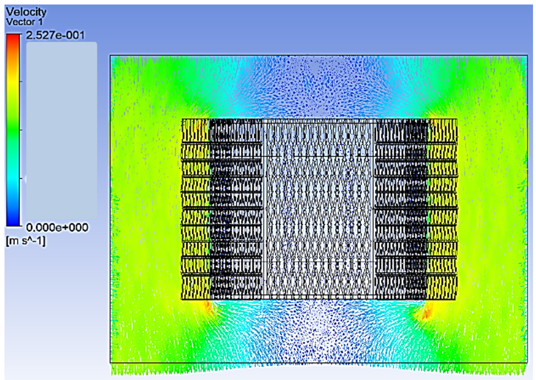


(a) Optimum case

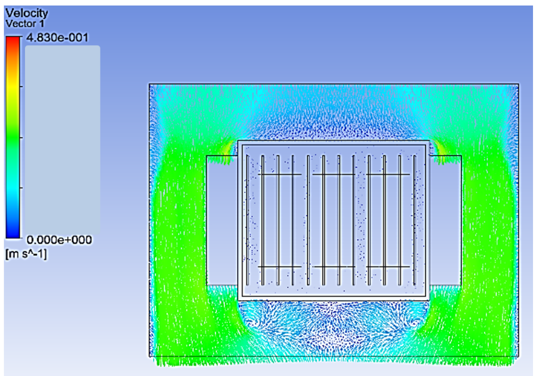


(b) Rectangular case

Figure 7. Velocity contour.



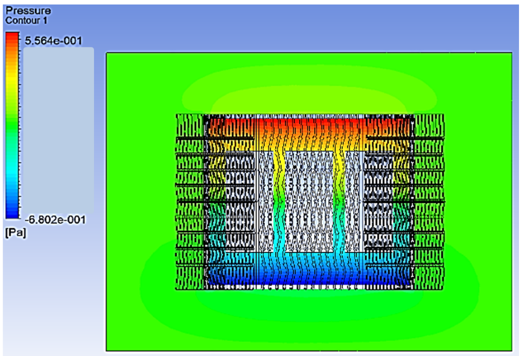
(a) Optimum case



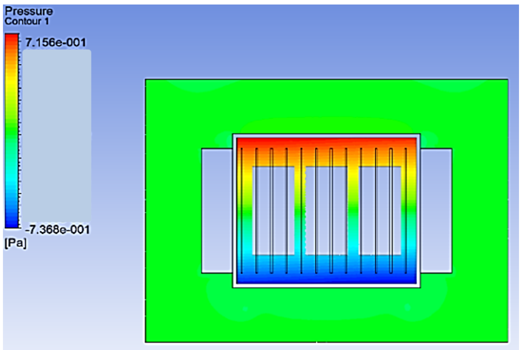
(b) Rectangular case

Figure 8. Velocity contour.

The temperature ranges from 311.46 K to 332.31 K, demonstrating the effectiveness of the design in maintaining lower temperatures throughout the transformer. Figure 7, the velocity contour map, displays the flow patterns of the coolant within the transformer. The optimized design ensures a uniform coolant flow, which enhances heat transfer. The maximum velocity observed is around 0.252 m/s, which helps in preventing stagnant zones and ensures efficient cooling. Fig. 8, the velocity vector map provides detailed information about the direction and magnitude of the coolant flow.



(a) Optimum case



(b) Rectangular case

Figure 9**.** Pressure contour.

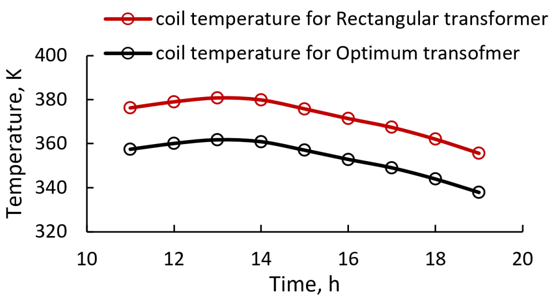


Figure 10**.** Coil temperature with time of rectangular case and optimum case.

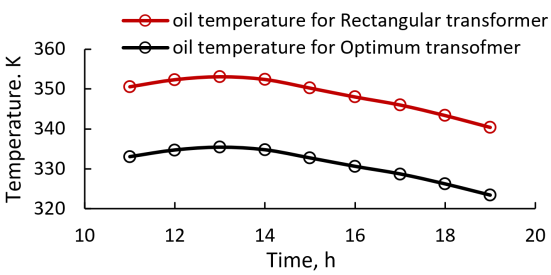


Figure 11**.** Oil temperature with time of rectangular case and optimum case.

The vectors indicate adequate coolant circulation around the fins and other components, with a maximum velocity of approximately 0.252 m/s. This enhances the overall cooling performance. Figure 9, the pressure contour map, shows the pressure distribution within the transformer. Figure 9 indicates that the optimized design maintains a balanced pressure distribution, which is crucial for structural integrity and preventing leaks. The design helps in reducing mechanical stress on the transformer components. These figures illustrate the enhanced thermal and fluid dynamics achieved through the optimized transformer design. The values observed in the contours and vectors demonstrate significant improvements in cooling efficiency, temperature management, and structural stability. Figures 10, 11, 12, 13 and 14 comprehensively analyze the thermal behavior of a rectangular and optimized transformer design over time. The data reveal significant improvements in the optimized (hexagonal) transformer, consistently demonstrating lower temperatures and more efficient heat dissipation. In Fig. 10, the Coil temperature for the optimized design starts at 357.4K. It stabilizes around 337.9K, significantly lower than the rectangular Coil, which begins at 376.2K and ends at 6 355.K. Figure 11 shows that the oil temperature in the optimized transformer stabilizes at 323.4K. In contrast, the rectangular design reaches 340.4K.

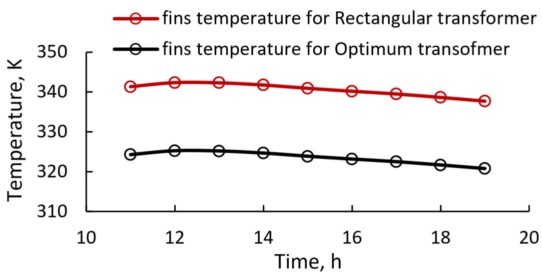


Figure 12**.** Fins temperature with time of rectangular case and optimum case.

This pattern continues in Fig. 12, where the fins of the optimized transformer remain cooler, stabilizing at 3 20.8K compared to 337.6K for the rectangular transformer. These temperature reductions highlight the optimized design's superior cooling capability, further supported by Fig. 13, which compares the heat transfer coefficient (HTC) between the two designs. The optimized transformer shows a higher HTC, peaking at 3.37 W/m^2K, while the rectangular design only reaches 2.59 W/m^2K. This indicates more efficient heat transfer in the optimized design, attributed to better fin shape and spacing, which helps dissipate heat more effectively.

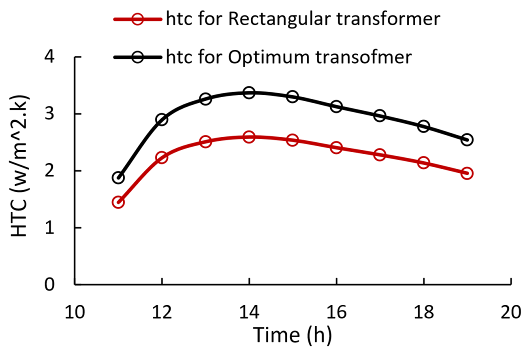
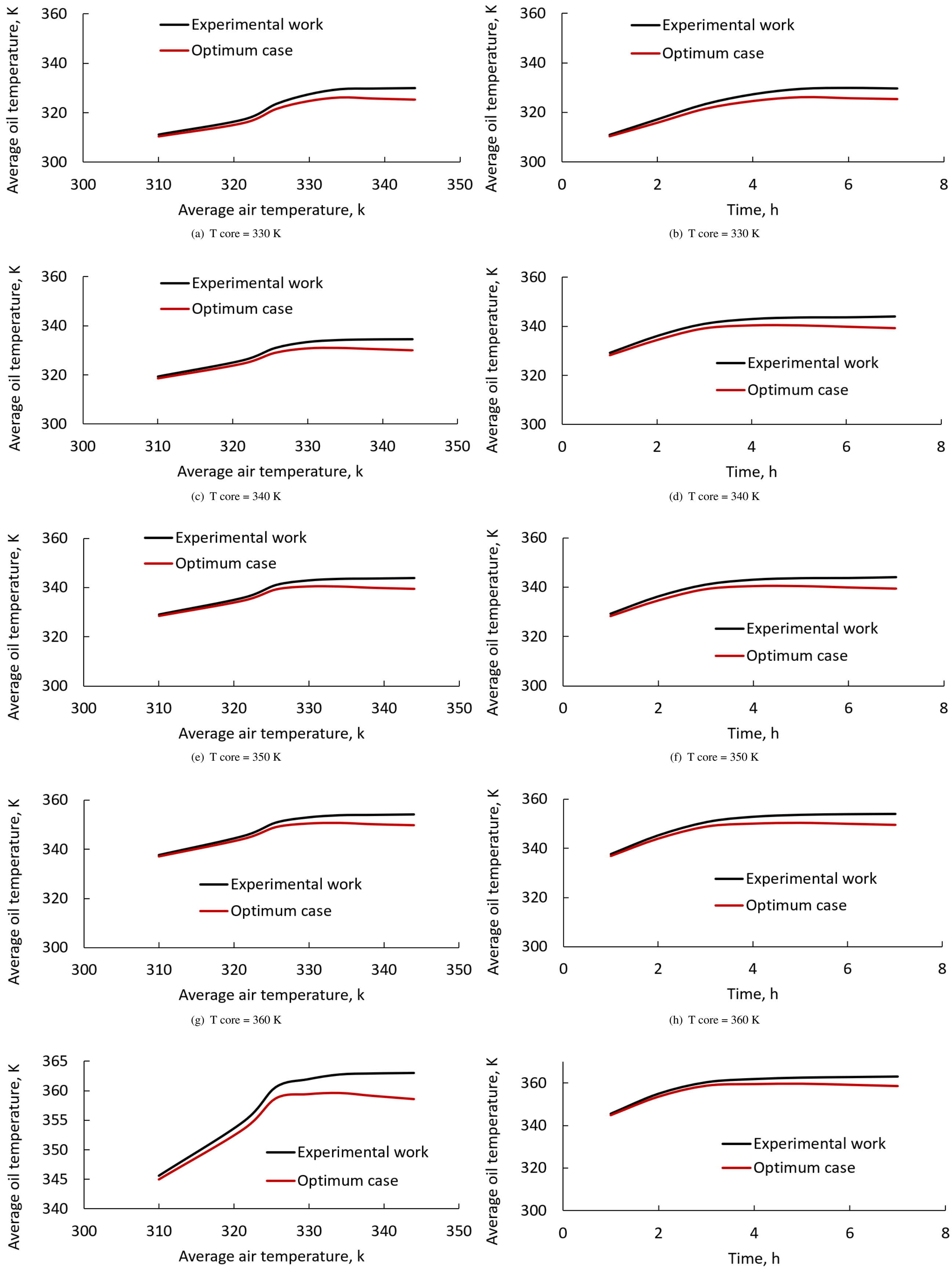


Figure 13**.** Heat transfer coefficient with time of rectangular case and optimum case.

The numerical values show that the proposed transformer design is thermally superior in terms of component temperature and overall cooling capability throughout the design life cycle. The percentage difference as found is 5.26% for Coil temperature, 5.1% for oil temperature, and 5.25% for fins temperature. Comparing the values of the performance parameters between the rectangular and optimized transformers shows enhanced thermal characteristics of the latter design. The Coil temperature of the proposed transformer is lower over time than the current optimized transformer, which means better heat dissipation and lower thermal stress, allowing the extension of the transformer's life expectancy. Likewise, the oil temperature is lower in the optimized design, and this means that the oil cooling is better than in the baseline design due to enhanced fin geometry and spacing. The fins of the optimized transformer also



(a) T core = 330 K
(b) T core = 330 K
(c) T core = 340 K
(d) T core = 340 K
(e) T core = 350 K
(f) T core = 350 K
(g) T core = 360 K
(h) T core = 360 K
(i) T core = 370 K
(j) T core = 370 K

Figure 14. Variation of the average Oil temperature with time and average air temperature measured in Iraq's weather conditions in the summer.

remain cooler than those of the rectangular design shown above, hence good convective heat transfer and temperature distribution to avoid hot spots that may compromise the structural integrity. In addition, the thickness parameter, which affects heat transfer, is lower for the optimized design and increases with distance from the heater; moreover, the HTC is permanently higher and reaches its maximum value earlier and is maintained at a higher level compared to the HTC of the non-optimized heat exchanger. This indicates better cooling characteristics since the torrents with improved coolant flow offer maximum contact area with the surrounding environment. These results confirm that the optimized design is superior to the original as it is freer from defects and provides more efficient and safe use for extended periods and increased loading, which is very beneficial for the application in transformers.

7.2 Comparing the optimum case with previous research with experimental tests

The tests on the conventional type of electrical transformer were performed in the laboratories of the general company for electrical and electronic industries in Baghdad/AL-WAZERIA, in connection with the Ministry of Industry. Following preparation of the electrical transformer, tests pertinent to the present research will follow, these are current tests, temperature of the environment ($308K$), and the temperature ($283K$). After choosing the ambient temperature in the laboratory,y such as winter, some value is picked from the voltages to the transformer, then the temperature sensors are read for each hour until the temperature of the oil has equalized (given that the number of test hours is not less than seven consecutive hours). This is discussed in detail in Chapter four. The observation made by our research has practical implications in this case. The next day, the experiment is run at the same voltages to check that the recorded values are as correct as possible. The recheck is made by putting another value on the voltage at the same selected air temperature, and the test is equally made. The same process is then repeated by applying five voltage values at the same ambient temperature to provide a steady average oil temperature with the transformer temperature. The variation of the average oil temperature compared with the calculated time at Iraqi weather conditions in summer, that is ($308K$), for the different values of the winding temperature of (330, 340, 350, 360, $370K$) is provided in Fig. 14. Analyzing the temperature of all windings from it, the following conclusion can be drawn: the temperature of the oil rises rapidly in the initial stage of the test till it attains a fixed value. This degree is believed to be the steady state temperature of the electrical transformer. Primary results included the assessment of the first few hours, where it was observed that the average oil temperature had risen. The number of rises depends upon the amount of winding temperature, wherein the ambient temperature is set higher while winding the wire to have an increased temperature of the wire more marginal than low Coil temperature [27]. Therefore, the percentage difference of this Coil temperature is 1.52%.

8. Conclusion

The study provided a thorough analysis of transformer cooling mechanisms, focusing on the impact of transformer shape and fin configuration on thermal management. Key findings included:

- Hexagonal Shape Superiority: The hexagonal design emerged as the most efficient shape, outperforming traditional rectangular and circular designs in terms of cooling. This shape allowed for a better distribution of coolant flow and heat dissipation, resulting in lower peak temperatures.
- Zigzag Fin Configuration: Using zigzag-shaped fins with ribs, optimally spaced at 7 cm apart, significantly enhanced heat transfer. This configuration increased the effective surface area, promoting superior heat dissipation compared to straight fin designs.
- Experimental Validation: Numerical models were cross-validated with experimental data conducted under Iraqi weather conditions. This included controlled temperature tests and sensor readings over extended periods, ensuring the reliability.
- Temperature Reductions: The optimized hexagonal design showed a maximum temperature reduction, stabilizing around 332.31 K, compared to higher temperatures observed in rectangular designs. This indicates better thermal management and reduced risk of hotspots.
- Fluid Dynamics and Structural Integrity: The optimized design facilitated uniform coolant velocity (up to 0.252 m/s) and pressure distribution, which are essential for preventing stagnant zones and ensuring the structural integrity of the transformer. The percentage difference represents 5.26% of the Coil temperature, 5.1% of the oil temperature, and 5.25% of the fins temperature. Where the percentage difference represents 1.52% of all Coil temperatures. The optimum case is compared with previous research using experimental tests.

Authors' contribution

All authors contributed equally to the preparation of this article.

Declaration of competing interest

The authors declare no conflicts of interest.

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Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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