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Assessment of Modified Electric Transformer by Integration with Innovated Eco-Friendly Cooling System

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ABSTRACT

Transformers are critical components in electricity distribution systems, necessitating efficient designs capable of withstanding harsh operational environments, such as the extreme Iraqi summer. This study proposes an innovative performance enhancement by integrating an embedded cooling system into transformer designs. A combined approach of experimental investigations and advanced ANSYS-based simulations is employed to optimize thermal behavior. The analysis highlights the impact of air velocity on convective heat transfer and energy efficiency, with tubular modifications enabling a significant reduction in fin dimensions. The fin width is halved while maintaining optimal thermal performance. Experimental results closely align with simulation predictions, demonstrating temperature control improvements between 0.54% and 7.78% with cooling air velocities of 1.0 and 8.0 m/s, respectively. These enhancements effectively reduce hot spot temperatures, preserve insulation integrity, and improve overall transformer efficiency. Notably, reducing fin dimensions from 20 cm to 10 cm achieved the target temperature of 89°C, showcasing a transformative design solution for enhanced thermal management in transformers.

1. INTRODUCTION

In contemporary societies, electricity stands as a central pillar fostering societal development. Nevertheless, the efficient conveyance of electric power to end-users is a sophisticated endeavor involving intricate stages of electrical generation, transmission, and eventual distribution [1, 2]. Transformers in Iraq have severe operating difficulties during the hot summer months, especially because of the high temperatures and the burden on the electrical infrastructure. These elements raise the possibility of fire accidents by causing heat to build up inside the transformers. Such incidents provide significant safety risks in addition to interfering with the power supply. In order to mitigate these hazards, it is essential to address the thermal performance of transformers, especially by investigating ways to reduce oil use. In order to significantly contribute to the resolution of these urgent industrial issues, this study attempts to give workable solutions to increase transformer reliability, lower fire risks, and boost the general effectiveness of power distribution networks in Iraq.

Transformers serve a pivotal function by elevating voltage levels while concurrently reducing transmitted currents to mitigate losses incurred during the protracted transmission of electricity. However, in converting voltage from the primary to the secondary winding, losses manifest within the transformer. These losses encompass both 'no load' and 'load' losses [3]. The 'no load' losses, recognized as iron losses, are a consequence of eddy currents within the magnetic hysteresis phenomenon [4]. Conversely, 'load' losses emanate from copper, resulting from resistive losses proportional to the square of the current and resistance (I^2R) [5].

The dissipation of electrical energy materializes as heat, inducing thermal stresses within the transformer. Consequently, the temperature of the oil amplifies, giving rise to the formation of a maximum temperature hotspot [3]. Maintaining the transformer's efficiency necessitates effective heat transfer, facilitated by the circulation of oil within the transformer and assisted by fins that dissipate heat into the ambient surroundings [6]. The constituents of the transformer are illustrated in Figure 1.

In this domain, numerous research endeavors have delved into the nuances of transformer cooling and heat transfer. For instance, Rosas et al. [7] introduced a system utilizing heat pipes to enhance the cooling process of oil-immersed electrical transformers. Their comprehensive analysis of simulation results and experimental procedures concluded that integrating heat pipes yields notable benefits, including a significant reduction in overall temperature, particularly in critical components such as converters and files. Incorporating heat pipes as auxiliary devices in the cooling process was determined to extend the lifespan of transformer core components, thereby enhancing durability and performance. Farhan et al. [8] conducted simulations to explore diverse fin geometries and flow intensities, aiming to optimize designs for improved flow and heat transfer properties. Al-Jassani [9] investigated the impact of fin spacing on heat transfer rates, identifying an optimal spacing that maximized heat transfer and reduced the base temperature of the heat sink. Hasan [10], in a numerical study, examined the effect of air temperature on the thermal behavior of transformers, revealing that using transformer oil-based nanofluids as a cooling medium enhanced cooling performance and provided better protection for transformer components. Ferneyhough [11] employed 3D numerical simulations to investigate natural convection and the effects of small pins inserted between fins to promote turbulent flow and enhance the thermal boundary layer, consequently facilitating increased heat transfer.

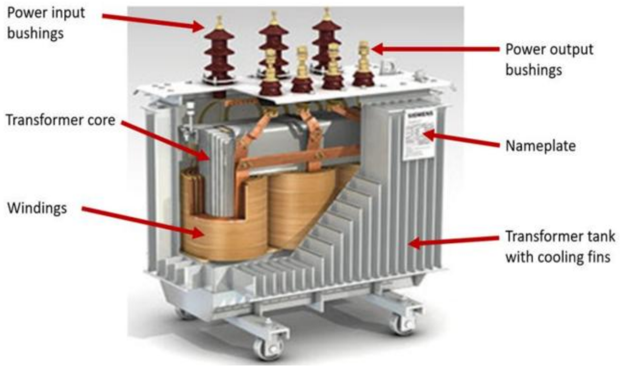


Figure 1. Parts of transformer

Hannun et al. [12] aimed to enhance power transformer cooling (250 kVA) by integrating a ground-air heat exchanger, effectively lowering the transformer's temperature, including oil, core, and coils, and enhancing overall efficiency to prevent damage and outages. Their study utilized code software (ANSYS 17.1/FLUENT) for analysis.

Farge et al. [13] utilized a thermosyphon to lower oil temperatures and improve heat transfer, resulting in a percentage improvement of 10.15% and 10% in convection coefficients for low voltage (below and top) and 6.66% and 8% for high voltage (below and top), respectively. Salama et al. [14] evaluated the thermal performance of environmentally friendly oils, including synthetic ester (Midel 7131), rapeseed (Midel 1204), and soybean (Midel 1215), in comparison with conventional mineral oil in transformers. A model was developed that combines COMSOL simulations and MATLAB predictions using experimental data to evaluate oil temperature, maximum winding temperature, transformer aging, power losses also, energy and environmental impact. The results highlight the superior performance of ester oils, particularly synthetic ester (Midel 7131), in reducing aging and environmental costs, with potential applications under certain load power factors. Consideration of ester oil thermal properties and load power factor is crucial in transformer planning. Daghrah et al. [15] conducted a comparative experimental study of the thermal performance of three types of transformer oils, mineral hydrocarbon, gas-liquid, and synthetic ester, in a zigzag winding model. The results highlight substantial variations in terms of flow distribution and temperature, notably with better flow uniformity observed in the case of synthetic ester. However, increased pressure losses have been noted with the use of the synthetic ester, particularly in the context of directed cooling. Dixit et al. [16] introduced the study of the back-feeding of distribution transformers with laminated windings with natural ester. The study focused on thermal performance, with CFD analysis and fiber optic sensors, comparing mineral and natural ester oils. The results highlight the impact of oil characteristics on winding temperature. A moderate increase in temperature was noted during retroceding. This study sheds light on the feedback choices of distribution transformers with laminated winding.

Dey et al. [17] evaluated power transformer losses using electromagnetic field simulations. The thermal performances of prototype power transformers with coil vs. without coil are then evaluated with the coupled losses from the electromagnetic simulations. The results of the coupled Multiphysics simulations are validated experimentally, and the numerical results align within a range of 10 to 13% of the experimental results. Ultimately, bobbinless transformers show lower hot spot temperature (HST) and better heat distribution between winding and core, making them thermally superior alternatives to conventional coil-based transformers. Mahdi et al. [18] introduce a numerical study and experimental validation on a 250 kVA, 11 kV submerged electrical distribution transformer. Temperatures were monitored experimentally, and an ANSYS Fluent 15 numerical model was used. Four new fin designs were compared to a standard design, showing significant improvements in thermal performance.

Raeisian et al. [19] developed a numerical model to analyze the parameters influencing the thermal management of distribution transformers and optimize their cooling systems. Response surface methodology (RSM) was used to minimize the hot spot temperature. The results showed that the height, length, and spacing of the fins are the most impactful parameters. The proposed optimal configuration reduced the hot spot temperature by 16°C compared to the initial geometry, thereby improving the transformer lifespan and performance. Shiravand et al. [20] studied a physical-thermal model to predict temperature variations inside transformers, considering six thermal points, including radiators. The model incorporates nonlinear thermal resistances to represent conduction, convection, and radiation. Incorporating the thermal points of the radiators improves the accuracy of the model. Comparisons with standard models demonstrated the superiority of the proposed model. It can also be used for fault detection.

In light of Iraq's severe summers, when high ambient temperatures can cause transformer failure and safety hazards, this research tackles the crucial problem of transformer overheating. The objective of this study is to investigate how air tubes affect transformer thermal performance in order to increase cooling effectiveness and lower the possibility of overheating. The finite element technique (FEM), which has shown promise in forecasting thermal behavior and offering insights into component performance, is employed in light of the intricate geometry of transformers. The transformer's thermal performance is modeled and simulated using ANSYS Fluent, a well-known finite element analysis software program that helps with design optimization and production cost reduction.

It is essential to use virtual simulations to evaluate the transformer's internal temperature distribution early in the design process. This is essential to avoid temperature increases that exceed design limitations, which might harm or impair the functionality of this expensive and essential power distribution equipment. The study focuses on certain factors, such as lowering the fin width to reduce the transformer's total size and adding air vents to the transformer tank to boost cooling efficiency and oil flow. The suggested solutions are validated using both experimental and computational techniques, offering a thorough strategy for enhancing transformer thermal performance and dependability.

2. DEVELOPMENT OF THERMAL MODEL

The thermal model adopted in this study emphasizes the heat generated within the transformer's active components and then conveyed from the surfaces of the windings and iron core to the surrounding oil, which subsequently dissipates through the tank walls into the ambient environment [21]. The principal origins of heat generation in an operational transformer stem from electrical and magnetic losses, primarily arising from the active components of the transformer [22]. The transfer of heat from the surfaces of the active parts (core and windings) to the oil occurs through convection. The film coefficient is calculated using established formulas. For laminar flow along vertical surfaces within the transformer (core and coil), the Nusselt number equation is employed as presented below [23, 24].

$$\mathrm{Nu_m} = 0.75\mathrm{Ra_{hf}^{0.2}} \tag{1}$$

The Rayleigh number based on the constant heat flux is formulated as following:

$$\mathrm{Ra_{hf}} = \frac{g.\beta.\rho^2.q_w.c_p.\delta^4}{k_{oil}^2.\mu} \tag{2}$$

where, δ is:

$$\delta = \frac{b-a}{2} \tag{3}$$

While the Nusselt number equation for the upper surfaces (used for laminar and turbulent) is [23]:

$$\mathrm{Nu_m} = 0.61\ \mathrm{Ra_{hf}^{0.2}} \tag{4}$$

And for the lower surfaces (used for laminar and turbulent) is [23]:

$$\mathrm{Nu_m} = 0.35\ \mathrm{Ra_{hf}^{0.2}} \tag{5}$$

The mean film coefficient for each case is [25]:

$$h_m = \frac{\mathrm{Nu_m} \times k_{oil}}{\delta} \tag{6}$$

The amount of heat transfer resistance from above the cover to the environment can be obtained by equations for the horizontal plane. If the hot plane is upward, the equation is as follows [26]:

$$\mathrm{Nu_l} = 0.54\ \mathrm{Ra_l^{0.25}} \text{ for } 10^4 < \mathrm{Ra_l} < 10^7 \tag{7}$$

$$\mathrm{Nu_l} = 0.15\ \mathrm{Ra_l^{0.33}} \text{ for } 10^7 < \mathrm{Ra_l} < 10^{10} \tag{8}$$

The average convection coefficient between the heat source and the cover, hs-c is obtainable by the equations for horizontal planes heated from below. The average Nusselt number for this case can be obtained by the following equation:

$$\mathrm{Nu_{s-c}} = 0.069\mathrm{Ra_{s-c}^{0.33}}.\mathrm{Pr^{0.074}} \quad \text{for } 3*10^5 < \mathrm{Ra_{s-c}} < 7*10^9 \tag{9}$$

To obtain thermal resistance between the fins space with the environment, (11) is used. To calculate the value of convection thermal resistance for the outer wall surfaces, the equations relevant to the vertical planes can be used [27].

$$\mathrm{Nu_{fs}} = (0.825 + \frac{0.387\ \mathrm{Ra^{1/6}}}{[1+(0.492/\mathrm{Pr})^{\frac{9}{16}}]^{8/27}})^2\ 10^{-1} < \mathrm{Ra_{fs}} < 10^{12} \tag{10}$$

The average Nusselt number for the fins according to can be obtained by the following equation [26]:

$$\mathrm{Nu_f} = 0.861\ Ra_f^{0.2364} \tag{11}$$

For this investigation, a system comprising horizontal copper tubes (with a diameter of 9 mm and thickness of 1 mm) was utilized for heat transfer. The air was forcibly directed into these heat transfer tubes via an inlet section and subsequently discharged into the atmosphere. The transfer of heat occurs from the transformer oil to the tubes, which is then cooled by the airflow circulating within.

Figure 2 shows the heat transfer modes in the transformer, and Figure 3 illustrates the process of heat transfer through the tubes. The heat transfer to a fluid flowing within a tube can be quantified by the increase in fluid energy, as expressed by the following equation [28]:

$$\mathrm{Q} = \mathrm{m} \times \mathrm{cp} \times (\mathrm{Te} - \mathrm{Ti}) \tag{12}$$

The Reynolds and average Nusselt numbers are [29]:

$$\mathrm{Nu_D} = \frac{\mathrm{h} \times \mathrm{D}}{\mathrm{k}} = 0.023\ \mathrm{Re^{4/5}} \times \mathrm{Pr^{1/3}} \tag{13}$$

$$\mathrm{Re} = \frac{\rho \times u \times D}{\mu} \tag{14}$$

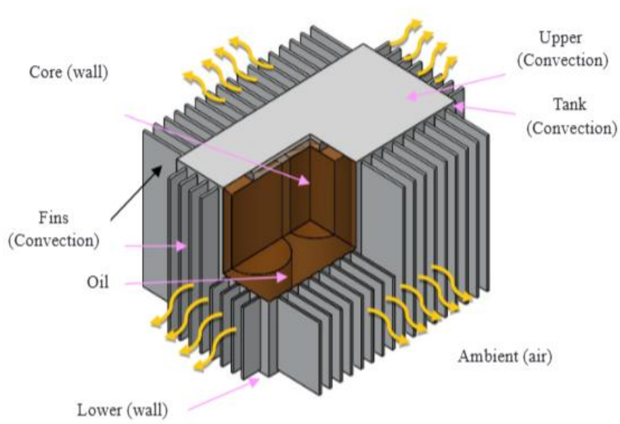


Figure 2. Heat transfer in distribution transformer [30]

The thermal radiation occurring between the surfaces of the active components and the inner surface of the transformer tank, driven by temperature disparities, has been intentionally omitted in this analysis. This decision stems from the relatively low emissivity of the materials utilized for the transformer components. Hence, disregarding this factor does not exert a notable influence on the accuracy of the results obtained [30, 31].

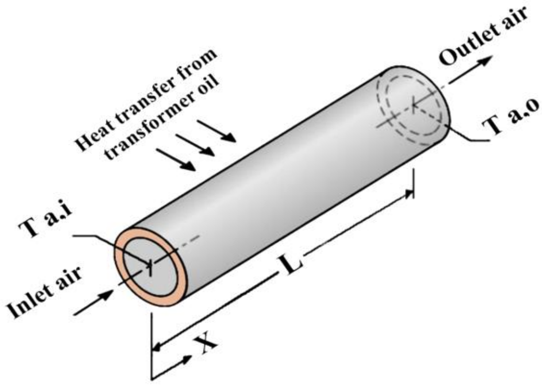
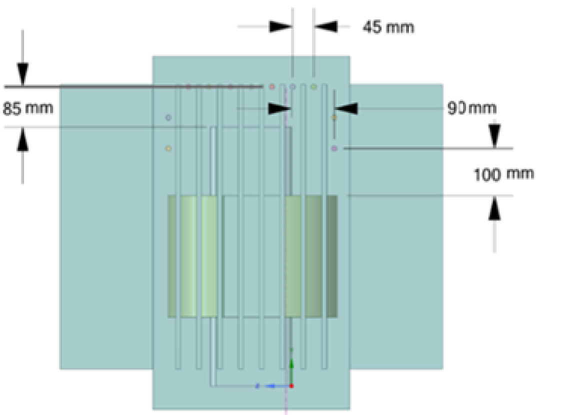


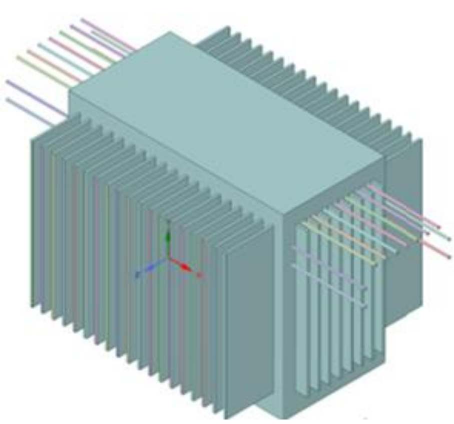
Figure 3. Thermal and mass balance in tubes

2.1 Proposed modified transformer

Various modifications to the transformer's geometry were compared to enhance the heat transfer process and thereby improve the performance of traditional transformers. The proposed designs focused on facilitating additional heat transfer from the active components to the oil and, subsequently, to the surrounding air. Multiple transformer geometries were proposed by incorporating tubes within the oil-filled tank, enabling airflow ranging from 1-8 m/s.



(a) The arrangement and number of tubes with dimensions



(b) Suggested transformer with tubes

Figure 4. Suggested transformer with cooling tubes

Copper tubes were chosen for their high thermal conductivity and a diameter of 1 cm, carefully selected to prevent interference with the fins. Eleven tubes were used to maximize the available surface area without compromising electrical performance. Among these, two tubes were positioned vertically on each side above the coils to enhance heat dissipation and improve cooling, considering the significant heat generation in that region. The remaining 9 tubes were evenly distributed in two rows over the iron core. This strategic placement was based on the oil's circulation from the bottom to the top, carrying away heat generated in the active components. As a result, the oil temperature remains elevated above the iron core, warranting the strategic placement of tubes in this region. For clarity, Figures 4(a) provide a visual representation of the arrangement and number of tubes, while Figure 4(b) illustrates their dimensions and a 3-D model of the system.

In the second scenario, a deliberate and gradual reduction in the length of the fins was methodically executed. This reduction persisted until the original thermal performance was reinstated. Through meticulous numerical analysis, the fin length that would restore an equivalent thermal performance to that of the original transformer design was precisely determined. Consequently, the transformer's size was effectively diminished while rigorously ensuring that its thermal performance consistently adhered to the predefined acceptable limit as stipulated by the relevant standards.

3. SIMULATION METHODOLOGY

To accurately simulate the thermal performance of the distribution transformer, a comprehensive and structured computational methodology was employed. The process encompassed the following key steps.

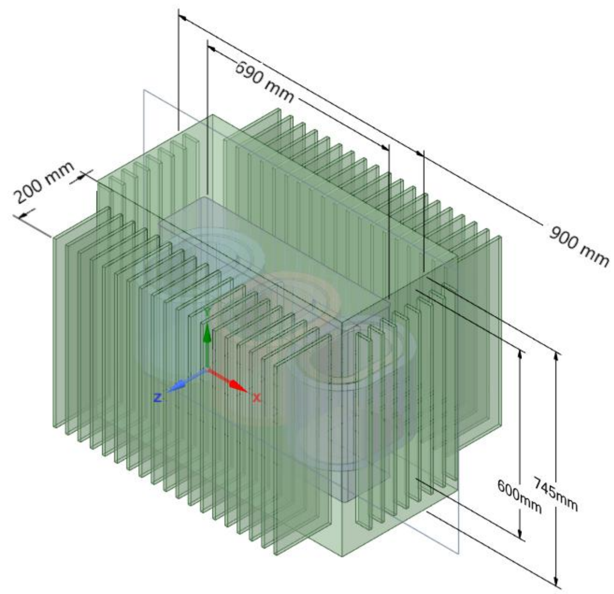


Figure 5. The three-dimensional transformer model

3.1 Model development

A three-dimensional computational model was developed to represent the transformer and its integrated cooling system. The external environment was modeled as static air at atmospheric pressure, emulating the conditions within the test room. Heat generation within the transformer was attributed to the core and coils, while the space between these active components and the tank walls was filled with oil to facilitate heat transfer. Key surfaces identified for effective heat dissipation included the upper part, base, and fins on both sides of the tank. An initial temperature of approximately 32°C was assigned to all parts of the transformer to reflect operational conditions. Figure 5 visually outlines the three-dimensional computational domain designated for this purpose.

3.2 Mesh generation

The computational domain was discretized using a structured mesh to achieve a balance between computational efficiency and accuracy. A mesh independency check was conducted to ensure that further mesh refinement would not significantly alter the simulation results, thereby validating the chosen mesh density. Figure 6 shows the mesh generation.

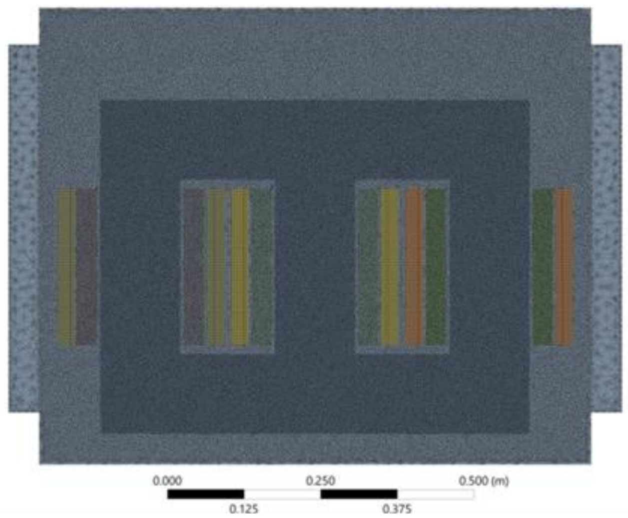


Figure 6. Mesh generation

To streamline the model without compromising accuracy, the following assumptions were made:

i. Exclusion of Rigid Insulation Layers: Rigid insulation layers were omitted to reduce model complexity while maintaining the integrity of the thermal analysis.
ii. Oil Movement Modelling: The movement of transformer oil was modeled based on the buoyancy-driven floating phenomenon, capturing the natural convection effects within the oil.
iii. Negligible Radiation Effects: Radiation was considered negligible compared to convection and was therefore excluded from the analysis.

3.3 Assumptions and governing equations

The simulation employed the fundamental governing equations for continuity, momentum, and energy to accurately represent the static, incompressible flows of oil and air within the transformer system.

Continuity:

$$\nabla . U = 0 \tag{15}$$

Momentum:

$$\nabla . (\rho \vec{U})\vec{U} = -\nabla P + \nabla^2 . (\mu \vec{U}) + g(\rho - \rho_\infty) \tag{16}$$

Energy:

$$\nabla . (\rho C_P \vec{U}\, T) = \nabla^2 . (\lambda T) \tag{17}$$

3.4 Boundary conditions

Boundary conditions were critical for achieving an accurate numerical solution. These included:

i. Ambient Temperature Conditions: The surrounding environment was modeled to reflect the static air conditions at atmospheric pressure.
ii. Heat Generation Rates: Heat generation was attributed to the active components of the transformer, including the core and coils.
iii. Inlet and Outlet Air Velocities: The airflow for the cooling system was modeled to simulate convective heat transfer, ensuring realistic thermal behavior.
iv. Validation with Empirical Data.

The computational model's accuracy was validated through direct comparison with experimental data. This alignment demonstrated the model's reliability and reduced dependence on costly physical testing, making it a robust tool for performance evaluation.

Convective heat transfer was identified as the primary cooling mechanism. The simulation highlighted the tank's fins, upper surface, and base as the critical areas for dissipating heat into the surrounding air. This focus ensured the effective evaluation of thermal performance under realistic operational conditions.

This comprehensive methodology facilitated a precise simulation of the transformer's thermal behavior, offering valuable insights for optimizing design and improving performance under challenging operational scenarios.

4. EXPERIMENTAL MEASUREMENTS

4.1 Losses test

The routine testing for the transformer encompasses a structured sequence of steps as outlined below:

Step 1: Calculation of no-load losses

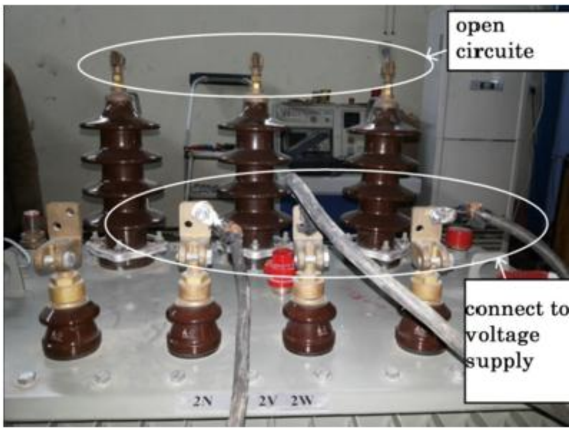
To ascertain the no-load losses, a voltage is supplied to the secondary coils while the primary coils are deliberately left open. The precise measurement of no-load losses is facilitated using the power analyzer PM300.

Step 2: Measurement of load losses

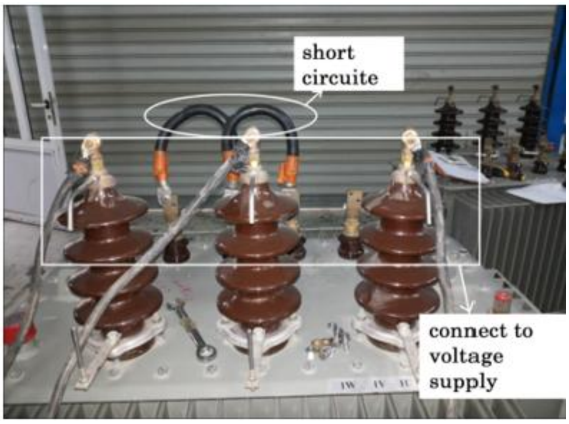
In this pivotal stage, the low-voltage coils undergo a short circuit while the high-voltage coils are energized with a voltage until the rated current is achieved. The power analyzer PM300 is instrumental in measuring the load losses. Figure 7 provides a schematic representation of the connection arrangement for these critical steps.

4.2 Thermal experiments

To assess the "temperature rise" of the transformer, a dedicated test was conducted, meticulously measuring the top oil temperatures and the ambient temperature. This involved strategically placing four thermocouples on the tank's side surfaces at strategic points. Additionally, an extra thermocouple was carefully positioned within the insulating oil through a top tank hole. To accurately gauge the oil's temperature in the surroundings, three containers filled with the same type of transformer insulation oil were meticulously positioned one meter away from the transformer.



(a) Measurement with no load



(b) Measurement with load

Figure 7. Losses measurements in the transformer, (a) Without load, (b) With load

Figure 8. The experimental setup for the temperature rise measurement

Following these preparations, the transformer was put into operation under full load conditions, and temperature readings were diligently recorded hourly for seven hours using a thermometer. Furthermore, the resistance of the coils was measured, an essential step in calculating the transformer's maximum temperature, following the guidelines outlined in the IEC 60076 standard [32]. The specific setup for this crucial test is illustrated in Figure 8.

5. RESULTS AND DISCUSSION

The analyses of this industrial problem have been achieved through experimental tests and then extended for other cases by computational modeling and simulation.

5.1 Validation of the numerical procedure

As most of the analysis cases have been conducted commuting the exploration of transformer thermal dynamics, a meticulous comparative analysis unfolded, aligning experimental data with simulation results via the ANSYS platform. This alignment, as illustrated in Figure 9, signifies the computational model's accuracy in replicating intricate temperature distribution within the transformer. Minor divergences, attributed to procedural nuances per the IEC 60076 standard, affirm the model's robustness. The deliberate exclusion of radiation's influence rested on the low emissivity of the transformer's components [22], reaffirming radiation's negligible impact.

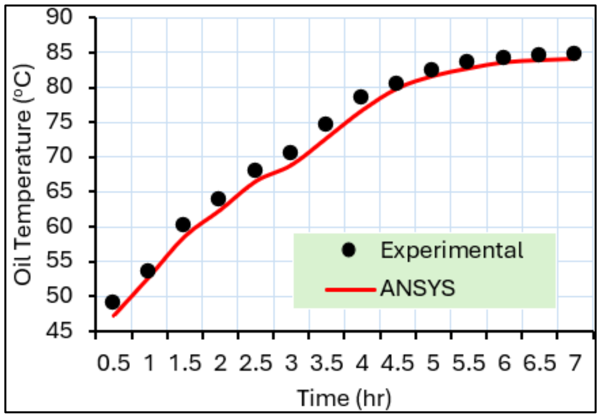


Figure 9. Comparison between the experimental and numerical results of the top oil temperature rise

This strengthens the model's role as a reliable design and testing tool across transformer types, minimizing the need for resource-intensive physical tests in line with modern computational trends.

5.2 Results of cooling system improvement

The study meticulously investigated the influence of air velocity flow inside pipes on the hot spot temperature of a transformer, employing a well-designed range of experimental conditions spanning from 1 to 8 m/s, as shown in Figure 10. A discernible trend emerged, indicating a clear relationship between heightened air velocity and reduced hot spot temperature. This association can be attributed to the velocity-dependent heat transfer coefficient, as elucidated by equation 14, where increased air velocity significantly augments the overall heat transfer process. However, an intriguing observation surfaced when the air velocity exceeded the range of 6-8 m/s. Beyond this threshold, a point of stabilization became evident, underscoring a delicate equilibrium between air velocity and efficient heat dissipation. Initially, heightened air velocity positively impacted convective heat transfer, enhancing the dissipation of heat from the transformer. However, as the velocity further increased, turbulent effects began to manifest. Turbulence, a characteristic of chaotic and unpredictable fluid flow, could potentially compromise the uniform distribution of heat and hinder overall heat dissipation efficiency. This nuanced observation underscores the intricate interplay between air velocity and heat transfer dynamics within the transformer. It suggests that while increasing air velocity would initially enhance heat dissipation, there exists a threshold beyond which turbulent effects might counteract the benefits.

The study alludes to the critical importance of carefully optimizing air velocity in the design of transformer cooling systems. Engineers must strike a balance, seeking to maximize heat dissipation while avoiding the detrimental effects of excessive turbulence, ensuring the transformer operates within safe temperature limits for optimal performance and longevity.

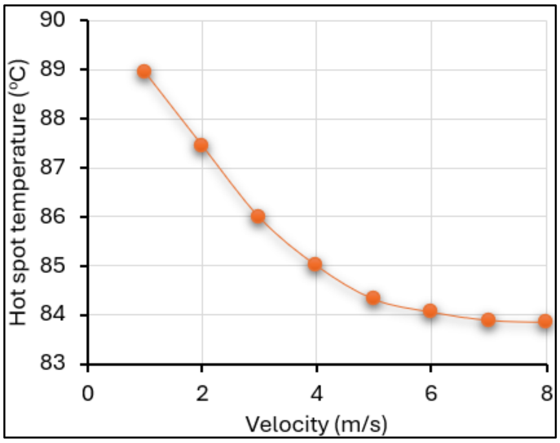


Figure 10. The relationship between inlet air velocity inside pipes and hot spot temperature

The intricacies of temperature reduction with varying velocities were quantitatively unveiled through Figure 11, presenting a reduction ranging from 0.77% to 6.44% with 1 and 8 m/s of air velocity in the cooling pipes, respectively. This reduction holds promise in maintaining the integrity of the insulation, a critical facet in ensuring the efficient operation of the transformer. Notably, within the velocity range of 6-8, a semblance of stability in temperature reduction was observed. This underlines the significance of optimizing air velocity through the tube, necessitating a delicate balance between achieving heightened heat dissipation and making requisite energy investments for the optimal performance of the system.

In Figure 12, a clear correlation between velocity and cumulative heat transfer rate across 11 tubes was underscored, demonstrating a proportional increase with escalating air velocity. These visual representations provided valuable insights into the inverse relationship between hot spot temperature and velocity, a consequence of the interplay between Nusselt and Reynolds numbers (as defined by Eq. (14)). Specifically, heightened velocity corresponded to an augmented heat transfer coefficient, further emphasizing the critical role of air velocity in effective heat dissipation within the transformer system.

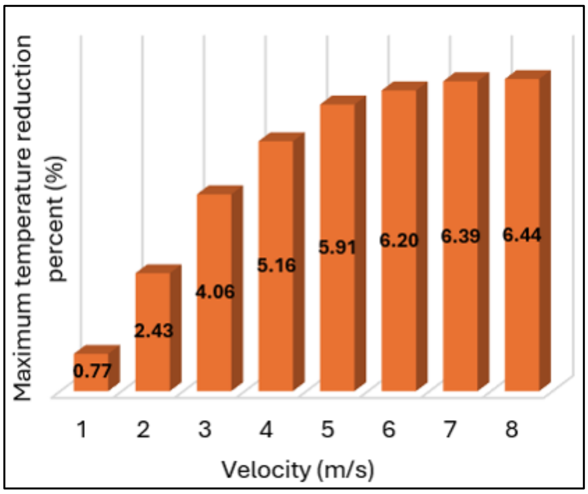


Figure 11. The reduction percentage of maximum temperature with inlet air velocity inside pipes

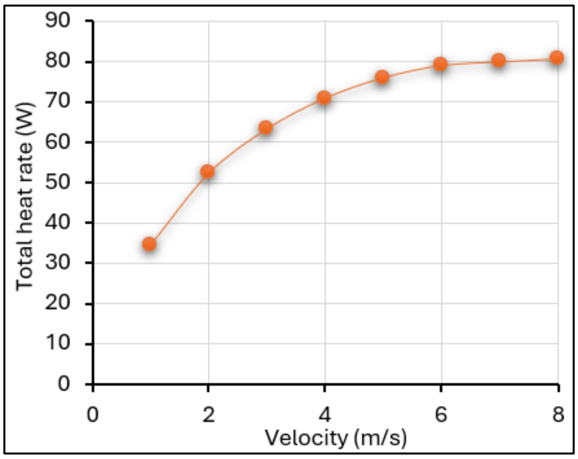


Figure 12. Effect of inlet air velocity on the total heat transfer rate of the cooling pipes

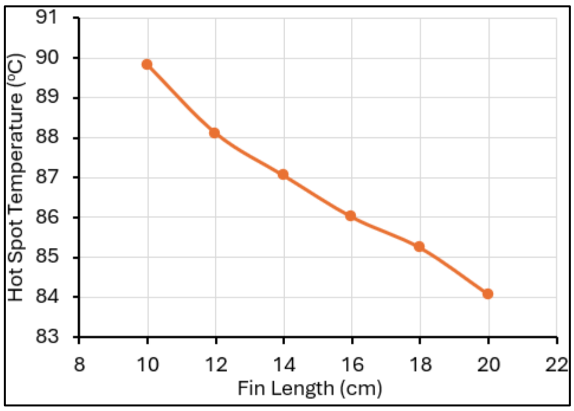


Figure 13. Relation between hot spot winding temperature and fin length

Figure 13 presents the relation between hot spot temperature and fin length. As the fin length was reduced, the hot spot temperature increased until it reached 87°C at a fin length of 10 cm. This temperature remains within the acceptable design limits. The reduction in fin length contributed to a more compact transformer design, which in turn decreased the required volume of insulating oil. This optimization was achieved while maintaining the thermal and electrical performance of the transformer, as the heat dissipation remained within permissible limits, ensuring reliable operation.

5.3 Qualitative analysis based on CFD results

Several factors, including fluid velocity, fluid properties, and the geometry of the system, influence the Nusselt number. Higher air velocity leads to increased turbulence and better mixing of air near the heated surfaces, enhancing convective heat transfer. Turbulence disrupts the insulating layer of stagnant air that usually forms near the heated surface, allowing fresh air to contact the surface and carry away more heat.

Reynolds number, which represents the flow regime (whether laminar or turbulent), is related to air velocity. In the turbulent flow regime, heat transfer is significantly more efficient due to the increased agitation and movement of air molecules, promoting effective heat dissipation. Hence, as air velocity increases, the Nusselt number and Reynolds number increase, resulting in a higher heat transfer coefficient and, consequently, lower hot spot temperatures within the transformer. This relationship displays the importance of optimizing air velocity to enhance convective heat transfer and ensure the efficient cooling of the transformer system.

The study's findings highlight the critical role of air velocity in influencing the transformer's hot spot temperature. Based on the experimental analysis, an inlet air velocity to the cooling pipes of 6 m/s was identified as the optimal value, offering the best cooling performance while maintaining high system efficiency.

The decision to use 6 m/s as the preferred velocity stems from its ability to significantly enhance heat dissipation without inducing excessive turbulence. As observed in the results, increasing air velocity from 1 m/s to 6 m/s led to a continuous decrease in hot spot temperature, attributed to the improved convective heat transfer coefficient. However, beyond 6 m/s, the cooling effect began to stabilize, and further increases in velocity introduced turbulent effects that could disrupt the uniform distribution of airflow and diminish heat dissipation efficiency.

By selecting 6 m/s, the study ensures a balance between effective heat removal and system stability. This velocity allows for sufficient cooling without the drawbacks associated with higher turbulence levels. Thus, maintaining air velocity at this optimal point ensures that the transformer operates within safe thermal limits, enhancing reliability, longevity, and overall performance.

Figures 14-16 illustrate the temperature distribution within the transformer's active components at an air velocity of 6 m/s, providing valuable insights into the thermal behavior under varying cooling conditions. The results demonstrate that at this velocity, the cooling system effectively enhances heat dissipation, maintaining a balanced temperature profile across the transformer's critical regions. The uniformity in temperature distribution indicates an optimal convective heat transfer rate, minimizing localized hot spots and ensuring thermal stability. This observation underscores the efficiency of 6 m/s as the preferred cooling velocity, as it maximizes heat removal while preventing excessive turbulence that could otherwise hinder effective thermal regulation.

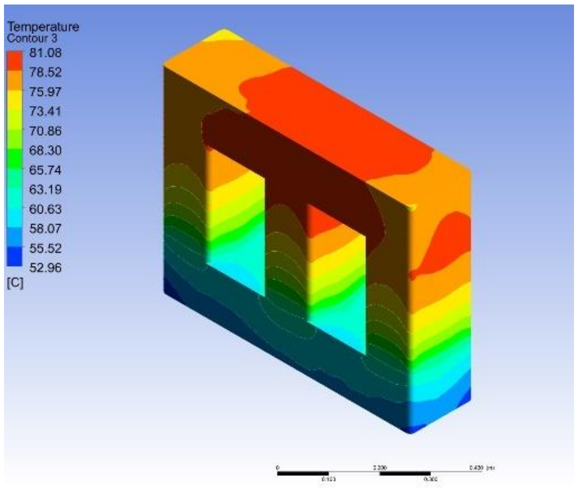


Figure 14. Temperature distribution in transformer core at 6 m/s air velocity

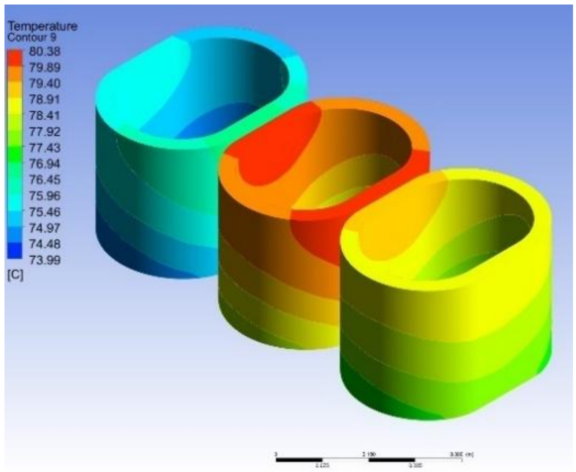


Figure 15. Temperature distribution in primary winding at 6 m/s air velocity

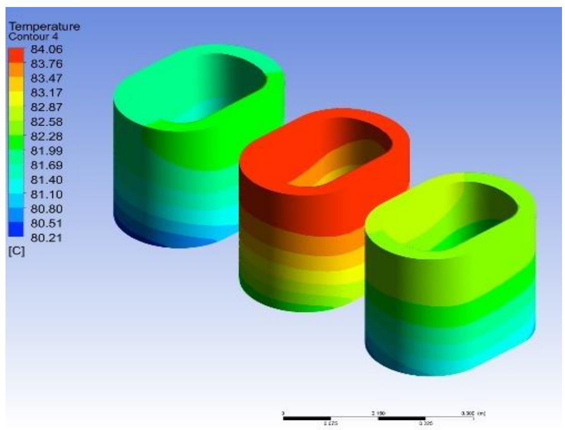
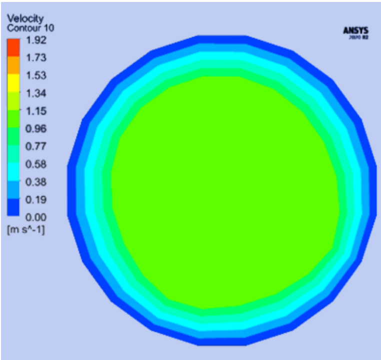
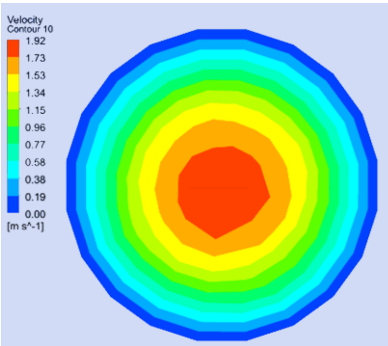


Figure 16. Temperature Distribution in secondary winding at 6 m/s air velocity

Figure 17 presents the velocity distribution contour of air at the inlet, inlet, outlet pipe, and side view through the pipe, respectively, illustrating a characteristic central peak velocity that gradually diminishes toward the inner walls due to the effects of boundary layer formation and flow resistance. This behavior aligns with classical fluid dynamics principles, where velocity gradients emerge as a result of viscous interactions between the airflow and the pipe walls. The observed velocity profile typifies laminar and transitional flow characteristics, depending on the Reynolds number, and highlights the impact of wall friction and turbulence on velocity distribution. Understanding this variation is crucial for optimizing convective heat transfer, as regions of higher velocity contribute to enhanced thermal dissipation, whereas lower velocity zones near the walls may result in localized thermal resistance.



(a) Inlet



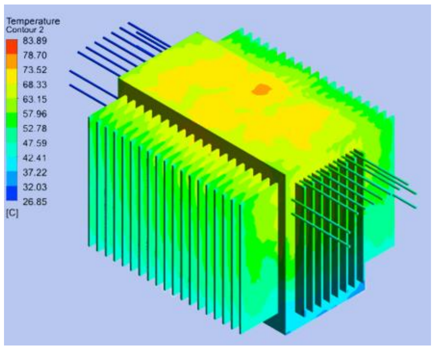
(b) Outlet

Figure 17. Velocity distribution contour of air in the cooling pipe

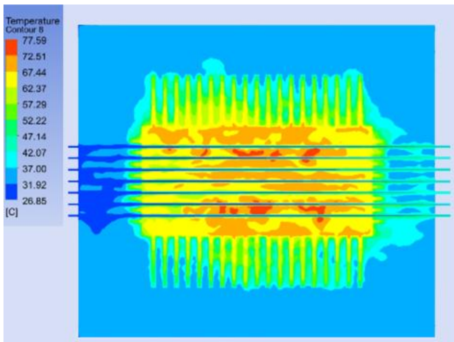
Figures 18(a) and 18(b) depicted temperature distribution in the tank and through the plane, respectively, spanning from the coldest bottom to the hottest upper cover. Convective dynamics within the transformer led to the accumulation of heated, less dense oil in the upper region, displacing cooler oil downwards. As air speed in the pipes surged, temperatures stabilized, signifying an equilibrium in heat dissipation.

Electrical engineers have primarily aimed at optimizing thermal performance through tailored modifications to the tubular structure of transformers. This endeavor includes deliberate adjustments aimed at minimizing the length of heat dissipation fins. In turn, the reduction of the fin size surrounding the converter reduces the size of the transformer, which is the aim of the Iraqi Electrical Equipment Manufacturing Company. This size reduction initiative is driven not only by the imperative to minimize the transformer's physical footprint but also to adhere to stringent insulating oil volume regulations mandated by governing bodies such as the Ministry of Electricity. Notably, this reduction in oil volume carries profound implications for environmental preservation.

Empirical investigations have elucidated a fundamental and quantifiable relationship between precise dimensional adjustments and the transformer's thermal performance. Systematic experimentation has demonstrated a significant reduction in fin width from the initial 20 cm to 10 cm while maintaining the operating temperature at an optimal level of 89.51℃, consistent with pre-optimization benchmarks.

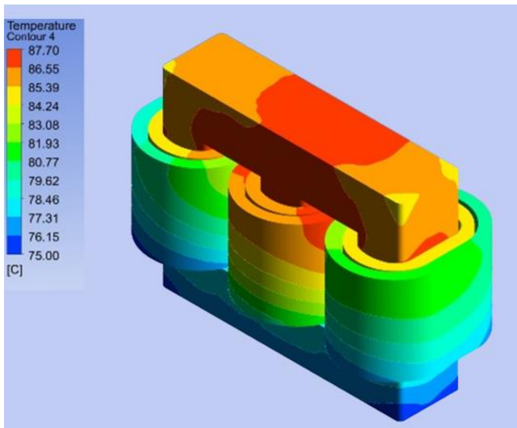


(a) 3D Temperature distribution through the transformer

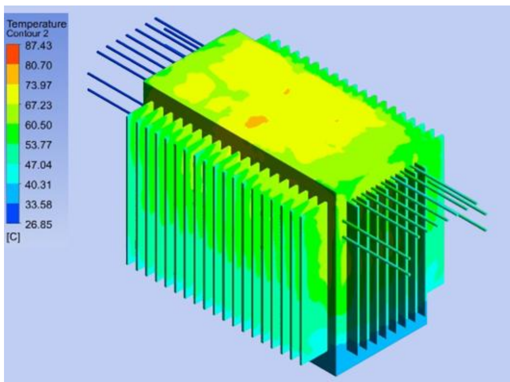


(b) 2D Temperature distribution through a plane at the mid-height

Figure 18. Temperature distribution in the transformer



(a) Active parts of the transformer



(b) Transformer tank

Figure 19. Temperature distribution

Figure 19 presents the temperature distribution in active parts and the tank, respectively. This accomplishment, representing a notable halving of fin size, holds considerable ramifications for transformer design and efficiency. Beyond technical advancements, these findings underscore the critical role such initiatives play in promoting sustainability within the energy sector. By reducing energy consumption, optimizing resource utilization, and concurrently minimizing the environmental impact associated with transformer installations, this research offers a tangible pathway toward a more environmentally sustainable future.

Furthermore, Air cooling, devoid of pollutants, curbs atmospheric harm and minimizes spill risks, safeguarding ecosystems. This shift embodies sustainability, aligning with clean energy goals and reducing carbon footprint. By integrating air-cooled systems, reliance on oil for cooling diminishes, mitigating pollution levels and promoting environmental stewardship.

These results underscored the critical influence of fin size on the transformer's thermal characteristics. By meticulously optimizing the fin design in harmony with operational requisites prescribed by regulatory bodies, the study not only met the requisite thermal benchmarks but also effectuated a profound reduction in the physical dimensions of the transformer unit. This reduction augurs well for resource conservation endeavors, exemplifying the transformative potential of targeted design modifications. Thus, we stand at a transformative juncture where engineering ingenuity, regulatory compliance, and sustainability converge, propelling us into an era of leaner, more efficient power distribution solutions.

6. CONCLUSIONS

This comprehensive study focused on optimizing transformer thermal performance, resulting in significant advancements in cooling efficiency and thermal management. The alignment between experimental data and ANSYS simulations demonstrated high accuracy with a mean 1.03% difference between the experimental and computational results. Moreover, optimizing air velocity within the 6-8 m/s range showed a clear impact in reducing temperatures, highlighting the delicate balance between efficient heat dissipation and optimal energy utilization. The deliberate reduction in fin dimensions from 20 cm to 10 cm played a pivotal role in achieving a substantial temperature drop, reaching the target of 89.5℃. This emphasizes the significant influence of fin size on the thermal characteristics of the transformer. The study also underscores the transformative potential of eco-conscious engineering practices, demonstrating the feasibility of resource conservation while adhering to regulatory standards and thermal performance benchmarks. The numerical results indicate a 0.77% to 6.44% reduction of hot spot temperature in the winding, with 1 and 8 m/s of air velocity in the cooling pipes, respectively, coupled with the fin size reduction. Beyond thermal optimization, this study delves into the intersection of scientific precision and practical engineering, offering insights that lay the foundation for a new era of transformer design. These optimization strategies promise a sustainable future while exemplifying the synergy between innovation and environmental consciousness in redefining power distribution paradigms. Thus, this study stands as a testament to the transformative potential of multidisciplinary research and well-informed design principles.

It is recommended for future research to explore advanced high-conductivity fluids, such as nanofluids or phase-change materials, and optimize fin geometries using additive manufacturing. Additionally, integrating smart thermal management systems and enhancing two-phase flow dynamics could further improve heat exchanger efficiency and miniaturization.

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NOMENCLATURE

Cp	specific heat, J/kg·K
g	gravity, m/s^2
h_m	mean film coefficient, W/m^2·K
k_{oil}	thermal conductivity of oil, W/m·K
L	characteristic length, m
U	velocity, m/s
T_{amb}	ambient temperature, K or °C
T_{sur}	surface temperature, K or °C
T_{oil}	oil temperature, K or °C
$T_{air, in}$	temperature of air inlet pipes, K or °C
$T_{air, out}$	temperature of air outlet of pipes, K or °C

Greek symbols

μ	dynamic viscosity, kg/m.s
ρ	density, kg/m^3
v	kinematic viscosity, m^2/s

Abbreviations

Gr	Grashof number
CFD	computational fluid dynamics
HST	hot spot temperature
Nu_b	Nusselt number for base
Nu_L	Nusselt number for lid, at top wall
Pr	Prandtl number
Ra	Rayleigh number-based heat flux
Re	Reynolds number