SEMARAK ILMU PUBLISHING

Semarak Engineering Journal

Journal homepage:
https://semarakilmu.my/index.php/sej/index
ISSN: 3036-0145

Optimizing Transformer Thermal Performance: Insights from Experimental and Analytical Study

Azhar K. Azeez[1,*], Ibtisam A. Hasan[1], Mohammad J. Mohammad[1]

[1] Electromechanical Engineering Department, University of Technology, Baghdad, Iraq

ARTICLE INFO

Article history:
Received 20 July 2025
Received in revised form 29 November 2025
Accepted 10 December 2025
Available online 25 December 2025

Keywords:
Thermal behavior; horizontal tubes; air speed analysis; FLUENT; practical implementation; hot spot temperature

ABSTRACT

This research investigates the thermal dynamic processes found in transformers, which are the backbone of the network. The design concept makes a radical change to traditional transformer geometry by using a new channel to optimize heat rejection. This design aims to improve the overall performance of this important electric machine. The depth of the analysis is clearly seen in the detailed analysis made to evaluate the indirect one of the integrated cooling channels in the transformer tank. Additionally, the velocity air flow in the ducts and their influence on the dynamic temperature were carefully studied. This study used advanced ANSYS simulation and compared it with experimental work to determine the best solution. This article will help understand the thermodynamic distribution and control strategy of transformers. By proposing avant-garde interventions, the aim is to improve the overall performance and security of critical applications, while at the same time creating a solid foundation for the development of efficient energy conversion. The results of this study go beyond the current topic and provide valuable information that will influence future developments in technology. Where the percentage reduction of hot spot temperature is about 6.4%.

1. Introduction

In the contemporary age, electricity serves as the bedrock of societal advancement. However, the intricate journey of delivering electricity to end-users poses a formidable challenge, encompassing multifaceted stages of production, transmission, and subsequent distribution [1,2]. Transformers play a crucial role in mitigating losses incurred during power transmission and distribution by modulating voltage levels while reducing transmission currents. Nevertheless, the transfer of voltage between windings inevitably results in losses, including both "no-load" and "on-load" losses [3]. Iron loss, also referred to as "no-load" loss, is caused by eddy currents created during the hysteresis phenomena [4]. Power is lost because of the transformer's magnetic material going through cycles of magnetization and demagnetization. “load” loss is related to the square of the current and is due to copper [5]. The cumulative cross-sectional resistance added to the winding’s current causes this

* *Corresponding author.*
E-mail address: eme.22.21@grad.uotechnology.edu.iq

https://doi.org/10.37934/sej.11.1.150166

resistance. Due to the process of turning electrical energy into heat in a transformer, the system endures some tension, which elevates the insulating oil's temperature to a maximum. The lifetime of a transformer and its operational efficiency can be influenced by stress and temperature fluctuations; therefore, prudent energy management reaches its peak in terms of significance [6-8].

In order to maintain this efficiency and reliability, fluctuations in the transformer must be well regulated. It achieves this by transferring the insulating oil, which has a cooling function to absorb and then dissipate the heat it forms. Additionally, the temperatures in the vicinity are also managed. By installing electric fans in the generator design, the surrounding temperatures are controlled through cooling . Radiators absorb and dissipate the heat generated to ensure the ideal operating conditions are met, which in turn prevents overheating. The transformer system's complex aspects are illustrated in Figure 1 below. A complete understanding of losses and thermal dynamics is required to optimize the performance and lifespan of transformers for various applications.

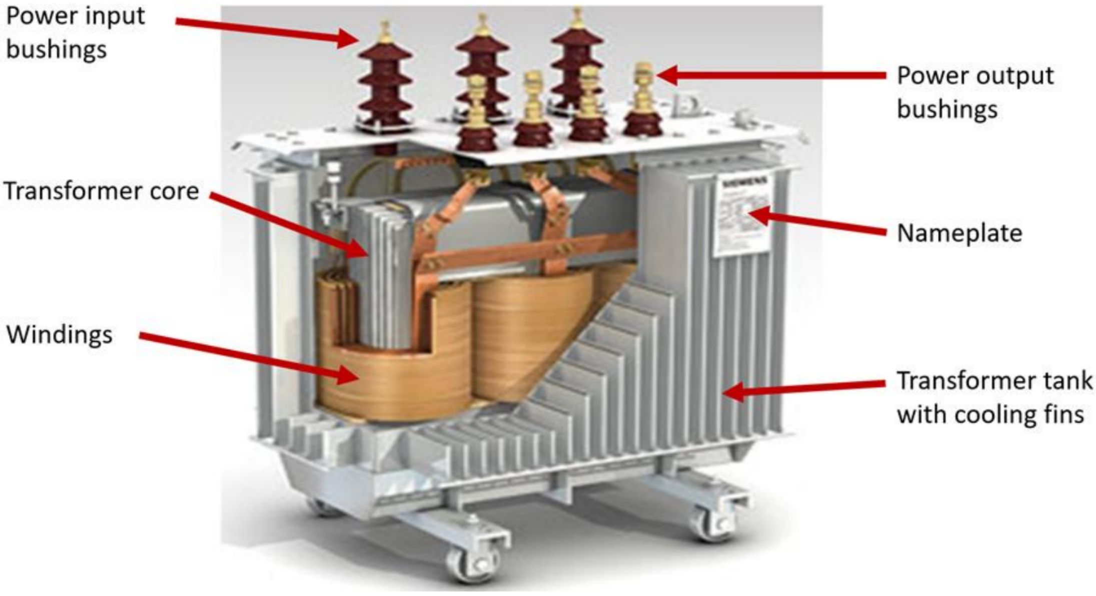


Fig. 1. Parts of transformer [17]

There are many studies conducted in the field of transformer technology focusing on improving heat transfer and cooling systems. A notable study of this is the study conducted by Nelson Moraga and colleagues [9], which presented a new method of using heat pipes to enhance the cooling process of oil-immersed power transformers. Their research has shown that incorporating heat pipes into transformer cooling systems is effective, as evidenced by comprehensive modeling studies and rigorous experimental verification. Heat pipes are used to reduce temperature, especially in important active parts in transformer. These results are important because maximum temperatures in these components can hinder functionality and cause premature deterioration. In addition to demonstrating the efficiency of heat pipes for cooling, Moraga et al. emphasize how important they are for extending the life of critical transformer components. The efficient way to improve the longevity and overall efficiency of energy converters is to use heat pipe technology as auxiliary equipment in cooling processes.

Furthermore, Rafid *et al*., [10] integrate a ground air heat exchanger to enhance the cooling of power transformers (250 kVA), resulting in temperature reduction across various transformer components, including oil, core, and coils. Talib *et al*., [11] implement a thermosyphon to lower oil temperatures and enhance heat transfer, yielding substantial improvements in convection coefficients for both low and high voltage scenarios. Additionally, Manmohan Prajapati and A. Pachori [12] investigate the effectiveness of incorporating water coolant within a three-cooling system, demonstrating reduced evaporation and maintained lower temperatures in both water and transformer oil. Ongoing efforts involve prototyping this cooling system to regulate transformer winding temperature, prolong oil-paper insulation lifespan, and bolster power transformer durability.

The optimization of cooling processes is paramount in preserving the expected 40-year lifespan of new transformers and extending their operational longevity. Niu Wenhao [13]; explores the implementation of a Loop Heat Pipe (LHP) cooling system, determining optimal design parameters through rigorous testing. This system has proved successful in operation for three years, highlighting its efficiency in urban substations while addressing cooling and noise concerns. Similarly, using a laboratory transformer as a test subject, Nurin Ainanie Azizie *et al*., [7] used vegetable oil as a substitute for mineral oil to improve transformer cooling due to its cost-effectiveness and superior thermal properties. This study shows that palm oil-based nanofluids with moderate concentrations of zinc oxide improve thermal conductivity by up to 59.5%, enhancing insulation and cooling properties. Muhammad Zakir Md Yasin *et al*., [14] used COMSOL Multiphysics software to simulate transformer oil aging, reducing costs compared to experimental testing. The simulation provided accurate insights into oil degradation and was validated with empirical data, demonstrating its reliability. This study highlights the efficiency and cost-saving potential of simulation tools in the electrical power industry.

A thorough grasp of transformer geometry leads researchers to use the finite element approach as a dependable thermal behavior prediction tool. The use of the well-known finite element algorithm-based program ANSYS Fluent makes it easier to estimate overall performance and conduct thorough analyses of transformer components. Initial research endeavors to improve cooling system performance by the incorporation of air channels into transformer tanks and the enhancement of airflow. To improve cooling system performance even more, air speed controllers must be designed and implemented in later phases.

1. Mathematical Model

The heat generated within the transformer's active components is the focus of the thermal model used in this study. This heat, which is mostly produced by electrical and magnetic losses, comes from the iron core and winding surfaces, and then enters the surrounding oil. As a medium for heat dissipation, the oil transmits heat through the tank walls and into the surrounding air [15].

The primary sources of heat generation during transformer operation originate from electrical and magnetic losses, predominantly within the active components of the transformer [16]. Heat transfer from the surfaces of these active components (core and windings) to the oil occurs through convection. The film coefficient necessary for this calculation is determined using established formulas. For laminar flow over the vertical surfaces within active parts, the Nusselt number equation is applied, as outlined below [17,18].

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

The Rayleigh number (based on the constant heat flux) is formulated as following[19]:

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

Where δ is:

$$\delta = \frac{b-a}{2} \quad (3)$$

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

$$Nu_m = 0.61\, Ra_{hf}^{0.2} \quad (4)$$

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

$$Nu_m = 0.35\, Ra_{hf}^{0.2} \quad (5)$$

The mean film coefficient for each case is [20]:

$$h_m = \frac{Nu_m . k_{oil}}{\delta} \quad (6)$$

The determination of heat transfer resistance from the lid (top cover of tank) to the surrounding environment can be derived using equations tailored for the horizontal plane. Specifically, when the hot plane is oriented upward, the corresponding equation is expressed as follows [21]:

$$Nul = 0.54 * Ral^{\,0.25} \quad for\ 10^4 < Ral < 10^7 \quad (7)$$

$$Nul = 0.15 * Ral^{0.25} \quad for\ 10^7 < Ral < 10^9 \quad (8)$$

The average convection coefficient between the heat generated source and the cover (hs-c) can be determined using equations applicable to horizontal plates heated from below. The average Nusselt number for this scenario can be calculated using the following:

$$Nus_c = 0.069 * Ras_c^{\,0.33} * Pr^{0.074} \quad for\ 3 * 10^7 < Ras_c < 7 * 10^9 \quad (9)$$

To ascertain the thermal resistance between the spaces among the fins and the environment, Equation (11) is employed. Additionally, to compute the convection thermal resistance value for the outer wall surfaces, equations pertinent to vertical planes can be applied [22]

$$Nufs = \left(0.825 + \frac{0.387 * Ra^{1/6}}{\left[1 + \left(\frac{0.942}{Pr}\right)^{\frac{9}{16}}\right]^{\frac{8}{27}}} \right)^2 \quad \text{for } 10^{-1} < Rafs < 10^{12} \quad (10)$$

The average Nusselt number for the fins can be calculated by the following [20]:

$$Nuf = 0.861 * Raf^{0.2364} \quad (11)$$

In this study, a system incorporating horizontal copper tubes (with a diameter of 9 mm and thickness of 1 mm) was employed for heat transfer purposes. Air was actively directed into these heat transfer tubes via an inlet section and subsequently expelled into the surrounding atmosphere.

The heat transfer process involves the transmission of heat from the transformer oil to the tubes, which is then dissipated by the airflow circulating within.

Figure 2 depicts the heat transfer process through the tubes. The heat transfer to a fluid flowing within a tube can be quantified by the increase in fluid energy, expressed by the following equation [23][24]:

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

The Reynolds and average Nusselt number are [25]:

$$NuD = \frac{h * D}{k} = 0.023 * \ Re^{\frac{4}{5}} * \ Pr^{\frac{1}{3}} \tag{13}$$

$$Re = \frac{\rho * u * D}{\mu} \tag{15}$$

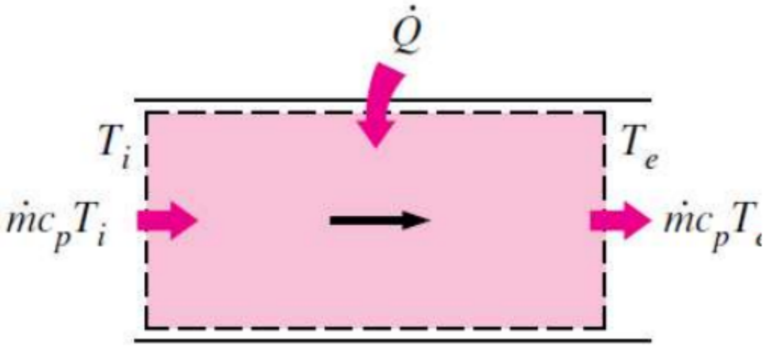


Fig. 2. Heat transfer through tubes

2. Tank Design Improvement

This paper introduces modifications to transformer geometry aimed at enhancing the heat transfer mechanism and consequently improving the conventional transformers performance. The proposed design primarily targets facilitating heat transfer from the active components to the oil, and subsequently to the surrounding air. This is achieved by integrating tubes within the oil-filled tank, enabling airflow ranging from 1 to 8 m/s. Copper tubes, selected for their high thermal conductivity, have a diameter of 1 cm to avoid interference with the fins. A total of eleven tubes were strategically positioned, with two vertically placed above each coil to enhance heat dissipation and cooling. The remaining nine tubes are evenly distributed in two rows over the iron core, aligned with the oil's circulation path. Figures 3 and 4 visually depict the arrangement and number of tubes, while Figure 4 provides their dimensions and a 3D model of the system.

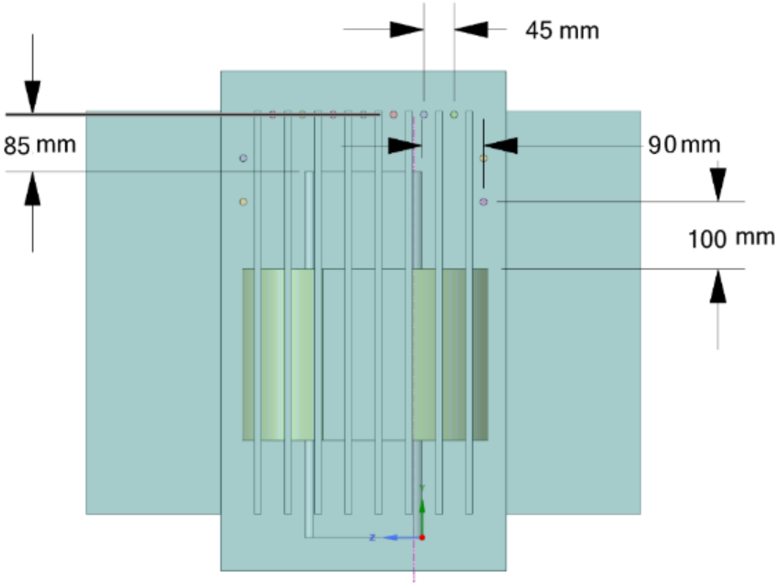


Fig. 3. The arrangement and number of tubes with dimensions

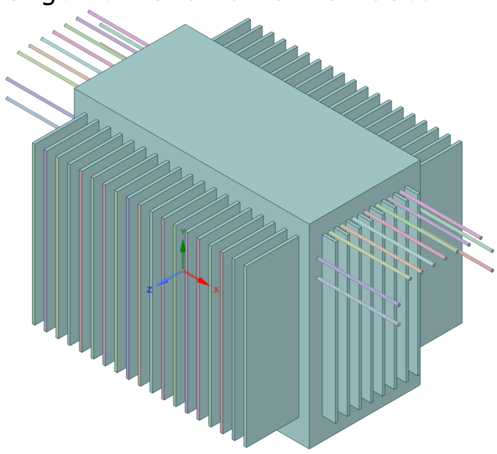


Fig. 4. Suggested transformer with tubes

The model's governing equations can be summarized as follows [26,27]

Mass conservation

$$\nabla \vec{V}=0 \tag{16}$$

Momentum conservation

$$\rho(\vec{V}.\nabla)\vec{V}=-\nabla P+\mu\nabla^2\vec{V}+\rho\beta\vec{g}(T-To) \tag{17}$$

Energy conservation

$$\nabla.(\rho\vec{V}CpT)=\nabla.(k\nabla T) \tag{18}$$

3. Exploratory Investigations

The testing procedure was thoughtfully created, including a methodical sequence of clearly defined stages necessary to conduct an exhaustive evaluation of the distribution transformer's thermal performance.

The distribution transformer model must be painstakingly prepared in the first step. Conventional cores and windings were swapped out for specially designed heaters that were placed thoughtfully inside the transformer tank to maximize safety and improve the experimental setting. By simulating heat transfer through oil, these heaters are designed to compensate for the heat generated inside transformers resulting from power loss. Heaters are regulated by a power regulator to vary the amount of heat generated, simulating actual load changes and realistic operating conditions. Maintaining the validity and safety of the study is made possible thanks to this modification, which replicates the conditions of dynamic loading.

after filling the tank with oil and heaters immersed. The system is operated and monitored. The system is an experimental setup that attempts to faithfully simulate the actual heat generation of the transformer. A seven-hour simulation was conducted to simulate the normal transformer testing period. This allowed the oil temperature to gradually rise until it reached a stable state in the last hour of the test. The hot spot of a transformer system is precisely determined from continuous readings taken during this time, allowing a comprehensive knowledge of its thermal behavior and determination of maximum temperature This configuration gave important insights into temperature dynamics by mimicking real-world conditions, as seen in Figure 5.

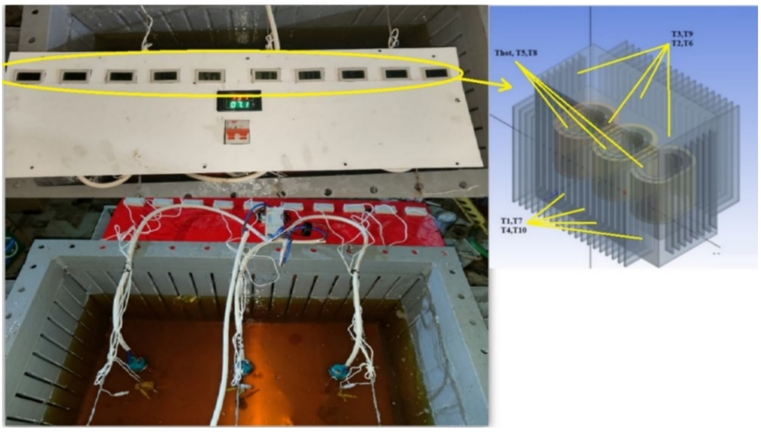


Fig. 5. Test without pipes and location of thermocouples

Buoyant force propels hot oil through the transformer, interacting with fins engineered for efficient heat exchange. In this study, air is introduced into pipes within the transformer tank, inducing convection and facilitating heat transfer from the oil. Initially, heat is conducted from the oil to the inner surface of the tubes, followed by forced convection transmitting the heat to the air along the tube walls. The compressor plays a pivotal role in propelling air into the pipes. Figure 6 illustrates horizontally placed tubes amidst fins within the transformer tank, optimizing heat exchange. This arrangement enhances system thermodynamics, as depicted in Figure 7, which showcases the experimental setup.

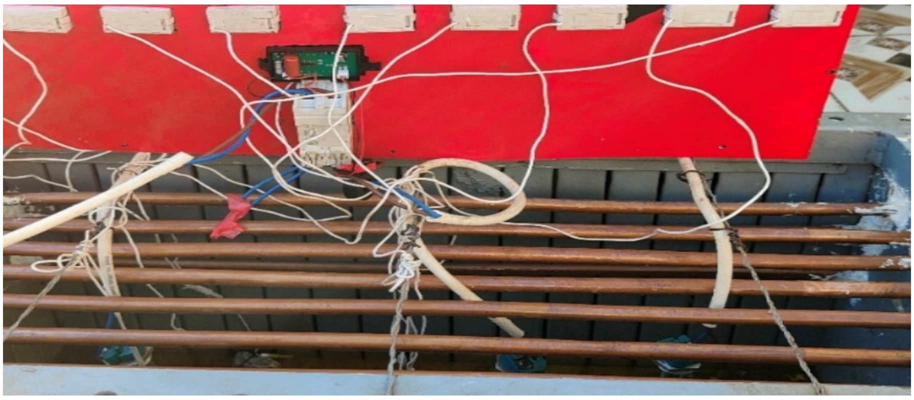


Fig. 6. Pipes connection

Fig. 7. The transformer tank with pipe immersed in oil

This setup uses air pushed in conjunction with heated oil's natural circulation to create forced convection. Important parts include oil circulation, forced convection and conduction heat transfer, and pipes that are placed thoughtfully inside the transformer body to maximize heat exchange efficiency. These coaxial accessories' exact design makes it easier to collect thermal energy from transformer oil efficiently, which improves heat dissipation efficiency. This developed procedure involves the safe integration of cooling tubes within the tank to enhance heat transfer performance.

Copper tubes with a diameter of 1 cm were carefully selected for the experimental setup because of their excellent thermal conductivity, which is extremely important for efficient heat exchange. These requirements have been carefully designed to serve their purpose in the experiment. Pipes made of copper were used because of its high thermal conductivity and high response to changing temperatures. The location of the pipes was not arbitrary. The strategy for distributing the pipes inside the tank was carefully considered as part of a well-thought-out plan to reduce the harmful effects to ensure the successful and efficient operation of the system. The necessary precautions were taken to reduce magnetic interference and electrical contact with the active components of the transformer.

The designed dimensions of the transformer allow a distance of 2 cm between the tank and the active part so as not to interfere between them.

During the design process and passing the pipes through the tank, care was taken to maintain this distance and not exceed it. Because the hot oil was rising to the top of the tank due to its low density, which is inversely proportional to the temperature, pipes were placed in the upper part of the tank. This design is intended to enhance system reliability while protecting test equipment from electromagnetic interference. By meeting stringent performance standards, this high-quality design not only enhances the efficiency of power transfer, but also supports the reliability and overall safety of its test setup. A high-capacity centrifugal fin is carefully used to regulate the airflow in these tubes.

When the designated places in the tank are dug for installing pipes, the tank is connected to the blower. After filling the tank with oil, the heater is activated to initiate the experimental process.

4. Results and Discussion

The findings obtained from the simulation will be expounded upon to determine the optimal combination of tube quantity and air velocity aimed at minimizing the costs associated with practical experimentation. In Figure 8, the correlation between the number of tubes and the hotspot temperature is illustrated, revealing a consistent inverse relationship. The deliberate augmentation in the number of tubes aligns with Newton's law of heat transfer, enhancing the interface between tube airflow and transformer oil and increasing the surface area for heat exchange. Utilizing 11 tubes, the maximum quantity to maintain a 2 cm distance from the tubes to the critical components as per [28], strategically enhances heat transfer efficiency.

To assess the impact of air velocity on the hotspot temperature, experiments were conducted across speeds ranging from 1 to 8 m/s (Figure 9). A clear correlation is observed, where an increase in velocity correlates with a reduction in hotspot temperature. However, beyond 6-8 m/s, the temperature decrease stabilizes due to the irregular heat distribution induced by turbulence. The energy demand to sustain higher velocities may outweigh the cooling benefits, necessitating a judicious balance. Extensive simulations and experiments inform the selection of the optimal velocity, aligning enhanced convective heat transfer with practical system feasibility and energy efficiency considerations.

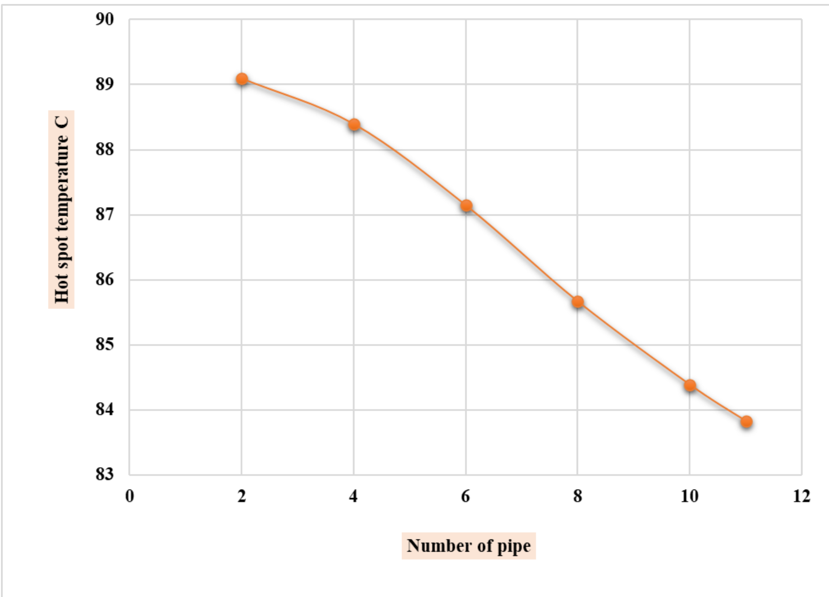


Fig. 8. The relationship between number of pipe and hot spot temperature

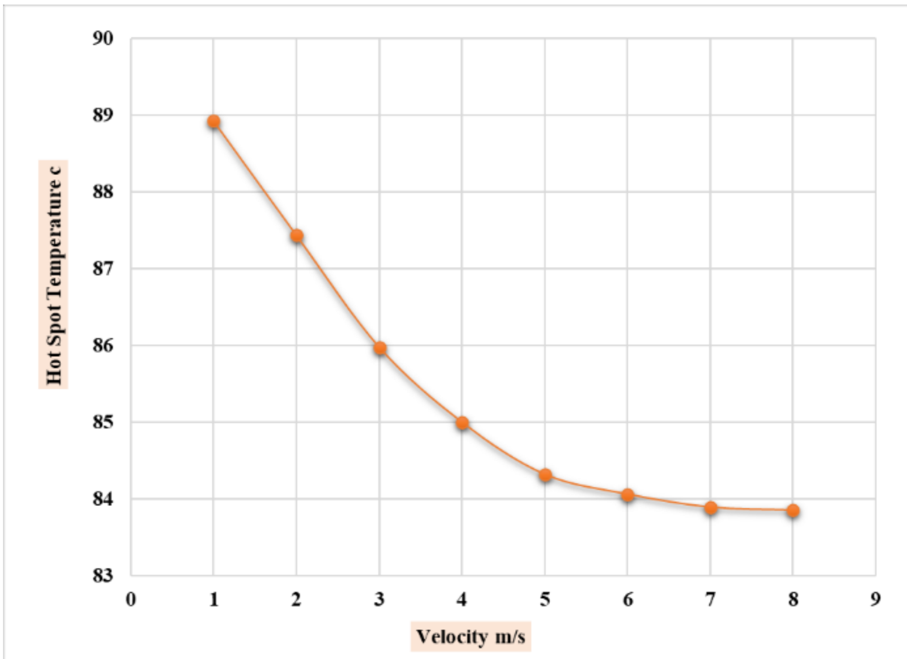


Fig. 9. The relationship between velocity and hot spot temperature

The subsequent section presents outcomes derived from analytical modeling utilizing artificial neural networks. In this methodology, the input dataset comprises two pivotal variables: ambient temperature (T_amb) and power losses (P_losses), while the desired output is the top oil temperature. The dataset, meticulously collected in June 2023 within a clear climate setting, was restricted to the time frame of 8 am to 4 pm.

A detailed representation of the temperature distribution within active components at a speed of 6 m/s is given in Figures 10, 11, and 12. It was shown that the effect of different speeds on temperatures gradually decreases with increasing speed, especially hot spots. The process was done using the ANSYS approach. Increasing air velocity increases the cooling system's ability to dissipate heat due to the Reynolds number and thus its relationship to the heat transfer coefficient, which will increase directly with increasing velocity, which in turn allows heat to be transferred more effectively from the transformer's internal parts, such as the core and coils. As a result, these dynamics promote a consistent temperature distribution throughout the transformer, enhancing the thermal balance of the surrounding environment.

In addition to improving overall cooling performance, high air velocity addresses possible cooling deficits in regions vulnerable to localized overheating at low air velocities. By taking this preventative action, local point of contact risks is successfully reduced, protecting the transformers' stability and longevity. A deeper look reveals that the rate of temperature decline steadily stabilizes as the air velocity surpasses 6 m/s , validating earlier findings and highlighting the need for a well-rounded strategy to enhance cooling in this situation.

The velocity distribution of air in the pipes is depicted in Figure 13. Analyzing pipe sections showed an amazing phenomenon, a particular pattern in the fluid velocities distribution. The tube's center line is precisely where the greatest velocity is located, and it increases progressively

The decline in velocity towards tube boundaries is attributed to increased resistance from adjacent layers, resulting in a significant velocity gradient across the tube's cross-sectional area. Observations indicate that when air enters at a certain speed, its velocity increases upon exiting the tube, gaining heat from the surrounding hot oil. Consequently, the air heats up, and its molecules gain kinetic energy, leading to an increase in average distance between them. This expansion results in decreased air density and increased air volume. According to the continuity equation in fluid dynamics, based on the conservation of mass and velocity must remain constant along the flow path in a closed environment. Therefore, the increase in velocity compensates for the decrease in density.

Figure 14 illustrates the temperature distribution of air at the input and output pipes at 6 m/s. This figure reveals the temperature distribution pattern of air through the pipe, where temperatures near the pipe wall are higher than those in the center. This discrepancy arises due to various interrelated factors governing heat transfer and fluid dynamics. Near the pipe wall, a thin layer called the thermal boundary layer forms, where the slower-moving fluid experiences increased contact with the wall, resulting in higher temperatures. This layer results from friction between the liquid and the wall, causing the temperature to gradually rise from the center towards the wall. Additionally, the fluid velocity profile plays a pivotal role; the highest fluid velocity occurs in the center, promoting more efficient heat dissipation and thus lower temperatures in this region. As the fluid moves towards the wall, its velocity decreases due to the non-slip condition, resulting in lower heat dissipation compared to the center. As a result, fluid moving more slowly at the wall experiences increased contact time with the tube surface, facilitating enhanced convective heat transfer and raising temperatures near the wall. Overall, this distribution creates a distinct temperature profile, with higher temperatures near the pipe wall and lower temperatures in the center, depicting an equivalent temperature profile along the pipe cross-section.

Regarding the tank and a slice of the upper layer of oil, Figure 15 illustrates the temperature distribution for the same velocity. The temperature distribution for the tank ranges from the coldest area, the bottom of the transformer, to the highest point located on the upper cover. This gradient occurs because heat generated inside the transformer rises to the top of the tank, where it accumulates. The top of the tank typically exhibits the hottest temperatures as it collects rising, less dense, and heated oil. As the heated oil ascends and accumulates at the top, it displaces cooler oil downward. Consequently, the bottom of the tank, where the cool oil s

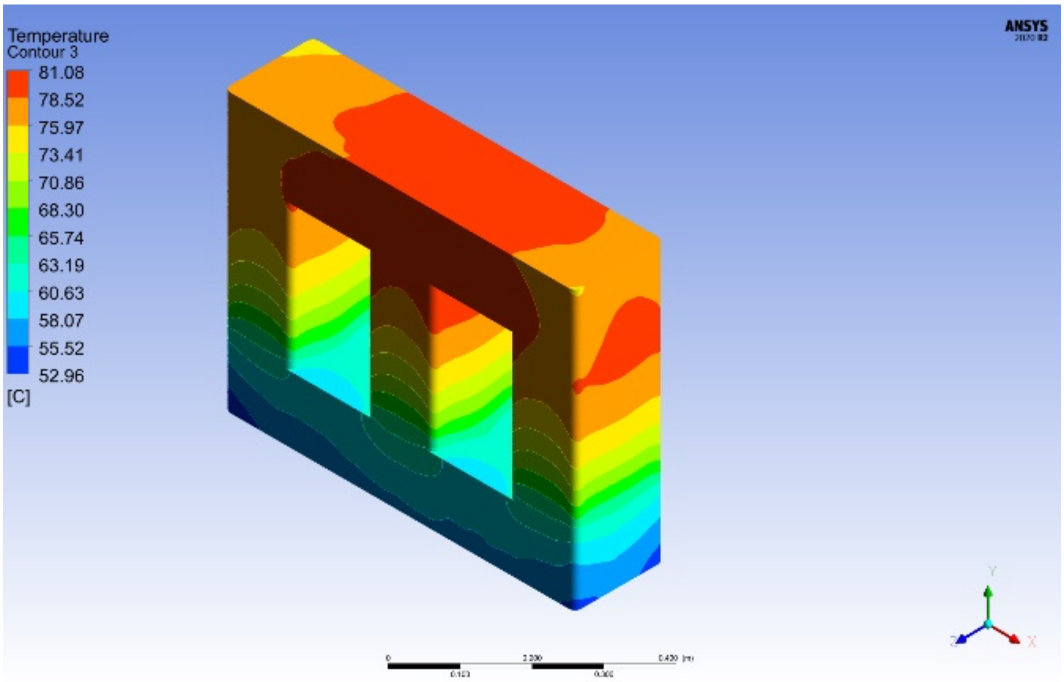


Fig. 10. The transformer core temperature distribution at air velocity 6m/s

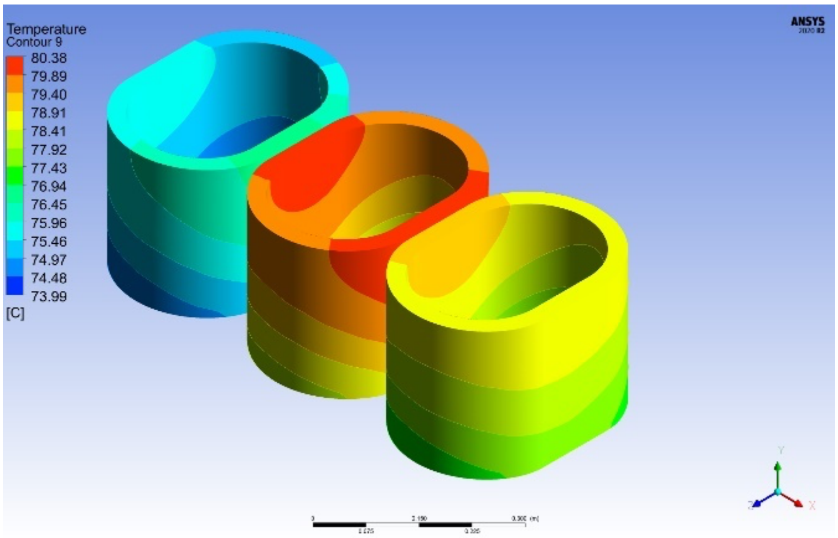


Fig. 11. The temperature distribution in primary winding at air velocity 6m/s

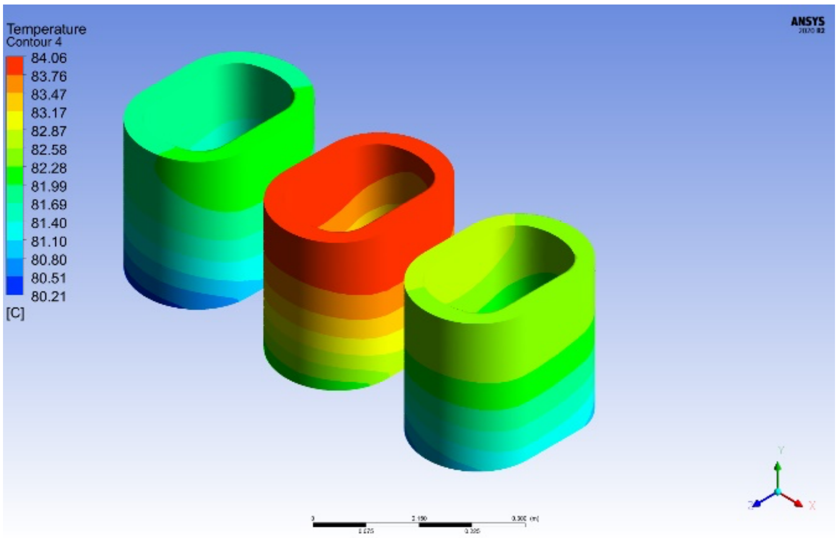
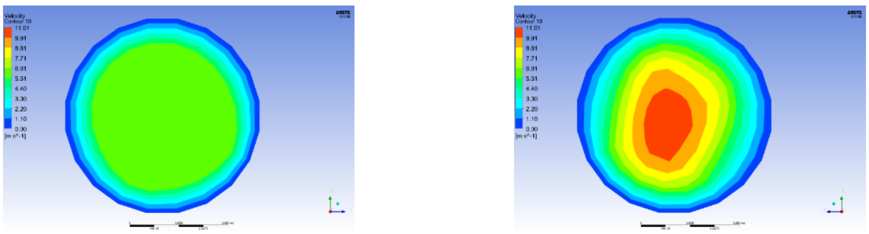
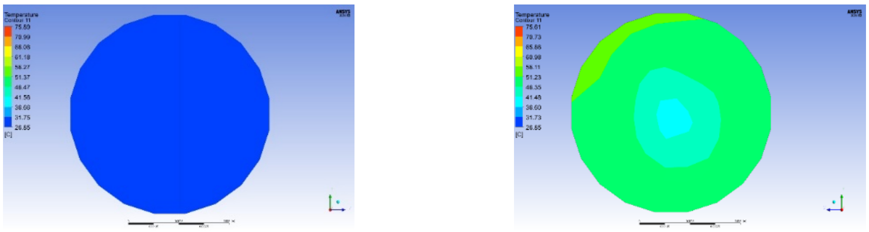


Fig. 12. The secondary winding temperature distribution at air velocity 6m/s



Input Air Output Air

Fig. 13. Velocity Distribution Contour of Air at Input and output Pipe at air velocity 6m/s



Input Air　　　　　　　　　　Output Air

Fig. 14. Temperature Distribution Contour of Air at input and output at air velocity 6m/s

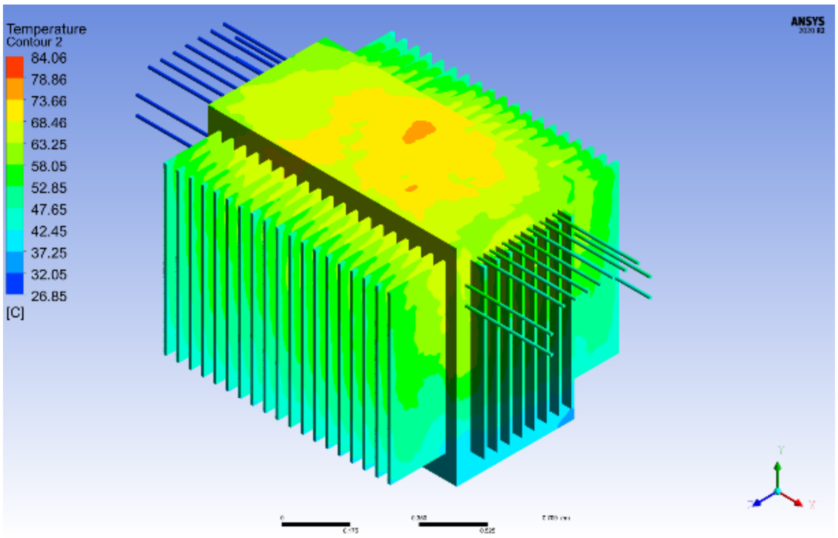


Fig. 15. Temperature Distribution through tank at air velocity 6m/s

A comprehensive database comprising 382 data points, encompassing both input and output data, has been meticulously compiled.

In June 2023, experimental data was collected to evaluate the initial performance of a transformer prior to any modifications. Operating continuously at full capacity for seven hours, the transformer reached a stable state, and its performance was compared with real-world results from Al-Wazyriah Company. Subsequently, deliberate load variations were introduced to provide insights into the transformer's response to dynamic scenarios, simulating real-world conditions. Graphical representation unveiled a gradual temperature increase during continuous operation, closely aligning with Al-Wazyriah's outcomes and validating the model's accuracy. The consistent findings corroborate the proposed model's reliability in simulating and predicting the transformer's behavior, thereby bolstering confidence in practical applications and future research endeavors.

Figure 16 shows a ninety °C hot spot temperature, and Figure 17 shows how load fluctuation affects the top oil temperature, a crucial control parameter. The temperature increase that was seen when the load was changed emphasizes how dynamically load variations and thermal response interact. The complex link between load dynamics and temperature changes is made clear by the higher internal temperatures that arise from higher power dissipation under rising loads.

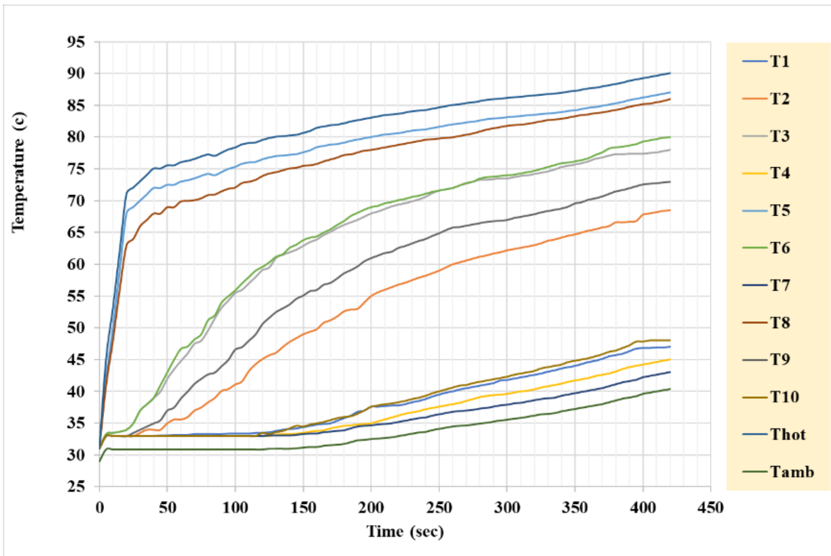


Fig. 16. Temperature at many locations in transformer oil with time

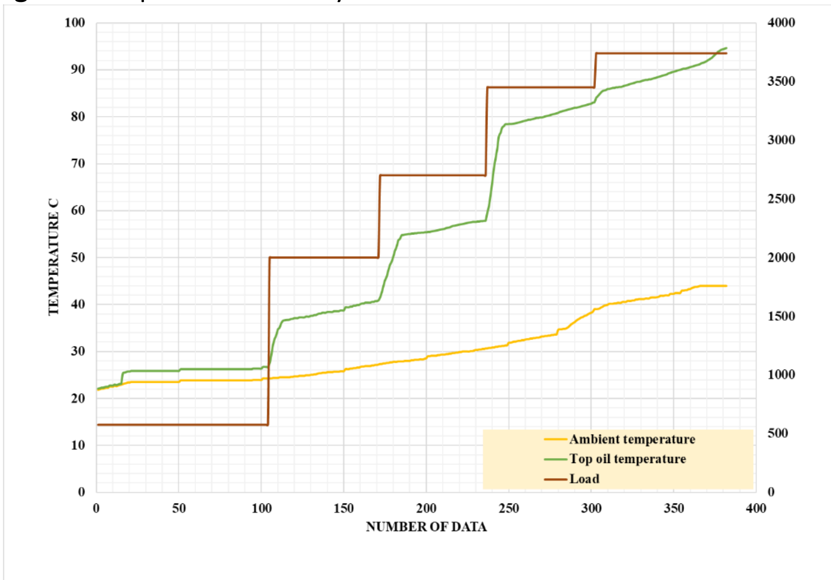


Fig. 17. Top oil, ambient temperature, and load with time

Empirical results obtained from operational testing performed on the fan at a range of speeds, from 1 to 8 m/s, are shown in Figure 18. Measurements of the hot spot and the top oil temperatures were taken at the same time. Interestingly, a pattern is observed when the fan speed increases, the temperature gradually decreases and stabilizes above a velocity of 6 m/s. This observed phenomenon indicates that the centrifugal fan is effective in reducing the temperatures of the oil and active parts of the transformer and that there is an ideal operating range that helps in achieving a stable thermal condition where the stability point starts above 6 m/s.

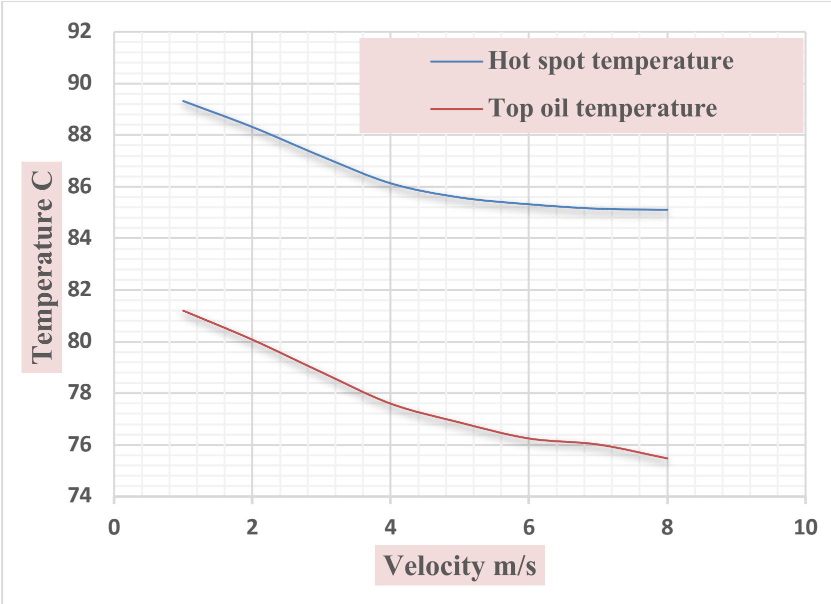


Fig. 18. Experimental hot spot and top oil temperatures with respect velocity

3. Conclusion

This study provided several perspectives on the behavior of transformers under different operating conditions. Through data collection and analysis, including experimental verification and numerical modeling, I was able to gain a basic understanding of the thermal performance of the transformers. Experimental results showed how heat dissipation efficiency can be improved using cooling strategies, such as forced convection through air circulation and microchannels. In addition, the study included the effect of varying air speed and varying load on temperature distribution within the converter, providing important insights for improving cooling system design. The results also showed that adding air ducts and increasing air speed enhances heat transfer, leading to improved cooling system performance. Furthermore, experimental validation of our model demonstrated the reliability and suitability to actual datasets for predicting transformer behavior. Thus, these results provide transformer technology researchers with valuable information that will help them develop more efficient and reliable transformer systems. Future studies could focus on improving innovative cooling technologies and examining the long-term performance of transformers under different operating conditions.

Nomenclatures.

D: Diameter m
g: gravity m/sec2
Q: Heat rate W
Ra: Rayleigh number
Re: Reynolds number
Te: Exit air temperature from pipes K
Ti: Inlet air temperature into pipes K
U: Velocity m/sec
cp: Specific heat J/k. K
h: Heat transfer coefficient W/m2 .K
k: Thermal conductivity W/m .K
m: Mass flow rate kg/sec
NuD: Nusselt number
Pr: Prandtl number
δ: thickness of coil m
β: thermal expansion coefficient K-1

References

[1] Abd Aziz, Azmi Murad, Mohd Aizam Talib, Ahmad Farid Abidin, and Syed Abdul Mutalib Al Junid. "Development of power transformer health index assessment using feedforward neural network." *J Adv Res Appl Sci Eng Technol* 30, no. 3 (2023): 276-289. https://doi.org/10.37934/araset.30.3.276289

[2] Mohmad, Azlan, Mohd Hatta Mohammed Ariff, Mohd Ibrahim Shapiai, and Mohd Solehin. "Investigation of the Influence of Non-Routine and Derived Features in the Development of Early Detection Model for Transformer Health Index Classification." *Journal of Advanced Research in Applied Sciences and Engineering Technology* 39, no. 2 (2024): 141-152. https://doi.org/10.37934/araset.39.2.141152

[3] Rommel, D. P., Dario Di Maio, and Tiedo Tinga. "Transformer hot spot temperature prediction based on basic operator information." *International journal of electrical power & energy systems* 124 (2021): 106340. https://doi.org/10.1016/j.ijepes.2020.106340

[4] R. S. Rajendran, "Design of Distribution Transformer Health Management System using IoT Sensors," no. December, 2022. https://doi.org/10.36548/jscp.2021.3.005

[5] E. Mezura-montes and R. Escarela-perez, "Using Evolutionary Algorithms," pp. 1–16, 2023.

[6] Danishmal, Massoud, Abdulilah Rasoly, Hashmatullah Zeerak, and Sayed Ahmad Zamir Fatemi. "Analyzing Power Losses in Ghazni City's Electricity Distribution Network and Strategies for Minimizing Them." *International Journal of Electrical Components and Energy Conversion* 9, no. 1 (2023): 1. https://doi.org/10.11648/j.ijecec.20230901.11

[7] Azizie, Nurin Ainanie, Nuriziani Hussin, Hana Abdull Halim, and Muhamad Irwanto. "Experimental Investigation on Thermal Conductivity of Palm Oil and Zinc Oxide PFAE-based Nanofluids." *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences* 108 (2023): 93-102. https://doi.org/10.37934/arfmts.108.1.93102

[8] Mohd Aszwan Jimal, Nur Aqilah Mohamad, Ahmad Razani Haron, Pungut Ibrahim, Herwansyah Lago, Chai Chang Yii, Hazlihan Haris, Hazwan Horace, Markus Diantoro, Megat Muhammad Ikhsan Megat Hasnan, "Investigation Seebeck Effect of Industrial High Voltage Transformer Oil Towards Industrial Insulator Oil Condition Detection", Journal of Advanced Research in Applied Mechanics 115, Issue 1 (2024) 131-140. https://doi.org/10.37934/aram.115.1.131140

[9] Rosas, César, Nelson Moraga, Valeri Bubnovich, and Rodrigo Fischer. "Improvement of the cooling process of oil-immersed electrical transformers using heat pipes." *IEEE transactions on power delivery* 20, no. 3 (2005): 1955-1961. https://doi.org/10.1109/TPWRD.2004.838625

[10] Hannun, Rafid M., Salman H. Hammadi, and Mohammed H. Khalaf. "Heat transfer enhancement from power transformer immersed in oil by earth air heat exchanger." *Thermal Science* 23, no. 6 Part A (2019): 3591-3602. https://doi.org/10.2298/TSCI171231116H

[11] Farge, Talib Z., Sahar R. Al-Sakini, and Aseel A. Isael. "Enhancement Cooling System Of Three-Phase Distribution Transformer (250 Kva) By Using Thermosyphon." *Journal Of Engineering And Applied Sciences* (2019).

[12] Manmohan Prajapati, A. P. "Advance Cooling Technique of Large Power Transformer and Impacts of Cooling On the Age of Transformer." *International Journal of Electrical and Electronics Research* 3, no. 2 (2015): 651-661.

[13] Wenhao, Niu, Zhang Guoqiang, Li Kang, Li Ning, Jin Chengxiang, Bai Zhongdong, Xu Zihong et al. "Research and development of a low-noise power transformer with loop heat pipe cooling system." In *2016 IEEE International Conference on High Voltage Engineering and Application (ICHVE)*, pp. 1-4. IEEE, 2016. https://doi.org/10.1109/ICHVE.2016.7800703

[14] Md Yasin, Muhammad Zakir, Nor Hafizah Ngajikin, Siti Hajar Aminah Ali, Muhammad Sazlan Abdul Kadar, Nurfatihah Che Abd Rashid, Mohd Aizam Talib, and Noran Azizan Cholan. "Modelling a D-shaped Sensor for Transformer Oil Refractive Index Detection." *Journal of Advanced Research in Applied Mechanics* 114, no. 1 (2024): 43-50.

[15] Mikhak-Beyranvand, Morteza, Jawad Faiz, and B. Rezaeealam. "Thermal analysis of power transformer using an improved dynamic thermal equivalent circuit model." *Electric Power Components and Systems* 47, no. 18 (2019): 1598-1609.

[16] Luo, Chuan, Chuan Li, Xiaorong Wan, and Zhengang Zhao. "Convective Heat Transfer Coefficient of Insulation Paper–Oil Contact Surface of Transformer Vertical Oil Channel." *Coatings* 13, no. 1 (2023): 81. https://doi.org/10.3390/coatings13010081

[17] Hasan, Ibtisam A., Sahar R. Fafraj, and Azhar K. Azeez. "Theoretical temperature distribution investigation in electrical transformer by using nano-technology." *Engineering and Technology Journal* 34, no. 12 (2016): 2282-2295. https://doi.org/10.30684/etj.34.12A.11

[18] Azeez, Azhar K., Ibtisam A. Hasan, and Mohammad J. Mohammad. "Improving the thermal performance of transformer oil by modifying fin shapes." In *AIP Conference Proceedings*, vol. 3002, no. 1, p. 070034. AIP Publishing LLC, 2024. https://doi.org/10.1063/5.0205921

[19] Wu, Juzhen, and Kanghang He. "Calculation and research of hotspot temperature analysis of converter transformer." *AIP Advances* 14, no. 7 (2024). https://doi.org/10.1063/5.0209804

[20] Jadoaa, Ameer A. "A Numerical Study on Laminar Free Convection between Vertical Flat Plates with Symmetric Heating." *Tikrit Journal of Engineering Sciences* 19, no. 2 (2012): 37-49. https://doi.org/10.25130/tjes.19.2.05

[21] Taheri, Ali Asghar, Ali Abdali, and Abbas Rabiee. "Indoor distribution transformers oil temperature prediction using new electro-thermal resistance model and normal cyclic overloading strategy: an experimental case study." *IET Generation, Transmission & Distribution* 14, no. 24 (2020): 5792-5803. https://doi.org/10.1049/iet-gtd.2020.0457

[22] Ruan, Jiangjun, Yongqing Deng, Daochun Huang, Cihan Duan, Ruohan Gong, Yu Quan, Yuanchao Hu, and Qingyu Rong. "HST calculation of a 10 kV oil-immersed transformer with 3D coupled-field method." *IET electric power applications* 14, no. 5 (2020): 921-928. https://doi.org/10.1049/iet-epa.2019.0469

[23] Jowsey, Mohamad Hafzan Mohamad, Natrah Kamaruzaman, and Mohsin Mohd Sies. "Heat and flow profile of nanofluid flow inside multilayer microchannel heat sink." *Journal of Advanced Research in Micro and Nano Engineering* 4, no. 1 (2021): 1-9.

[24] Y. A. Cengel, Heat and Mass Transfer, 3rd Editio. y McGraw-Hill Education, 2011.

[25] D. P. D. THEODORE L.BERGMAN, ADRIENNE S. LAVINE, FRANK P. INCROPERA and School, Fundamentals of Heat and Mass Transfer, Seventh. JOHN WILEY & SONS, 2011.

[26] Ali Shokor Golam, "Evaluation of the Electrical Power Transformer Fins Design Technology: Numerical Analysis and Experimental Validation", Journal of Advanced Research in Fluid Mechanics and Thermal Sciences 117, Issue 2 (2024) 131-146. https://doi.org/10.37934/arfmts.117.2.131146

[27] Elfaghi, Abdulhafid MA, Alhadi A. Abosbaia, Munir FA Alkbir, and Abdoulhdi AB Omran. "CFD simulation of forced convection heat transfer enhancement in pipe using Al2O3/water nanofluid." *Journal of Advanced Research in Numerical Heat Transfer* 8, no. 1 (2022): 44-49. https://doi.org/10.37934/cfdl.14.9.118124

[28] R. N. Al-Dulaimi, principle of electrical transformers. 2020.