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Numerical assessment of the impact of fin configuration on the cooling performance of a power transformer

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Abstract

In the present work, a three-dimensional model was performed to test a geometry and solar radiation effect on the cooling efficiency of a 250 kilovolt-ampere (kVA) oil-natural-air-natural (ONAN) electrical distribution transformer. The main contribution to the current study is to provide a design that contributes to reducing the temperature of the electrical transformer while maintaining its size equal to the size of a conventional transformer.

Several fin shapes (trapezoidal, wavy, and triangle fins) and other geometric aspects of the transformer were analyzed numerically, using Ansys fluent 22 R1. According to the findings, the trapezoidal fin shape was the most effective in lowering the transformer's average surface and core temperatures, followed by the wavy fins and the triangular fins compared to the traditional transformer shape (straight fins). The surface average temperature drop of the corrugated-finned transformer was 278.15 k compared to the reference transformer, followed by the wavy-finned transformer by 276.15 k, and finally the triangular-finned transformer by 275.15 k. Moreover, the core temperature of transformer with trapezoidal fins dropped by 284.15 k than the core of reference transformer followed by the transformer with wavy fins by 280.15 k and transformer with triangular fins by 278.15 k. The study also showed that the temperature of the surface and the core of the transformer increases with increasing solar radiation, but the effect of high temperature as a result of electrical load is more influential than solar radiation. The results showed a good agreement with previous research.

Keywords: Power transformer; solar radiation; heat transfer; fin geometry

الخلاصة: دراسة تاثير الشكل الهندسي والاشعاع الشمسي على كفاءة التبريد لمحولة القدرة الكهربائية (250) كيلوفولت-امبير ذات التهوية الطبيعية بالأبعاد الثلاثية. تتمثل المساهمة الرئيسية في الدراسة الحالية في توفير تصميم يساهم في تقليل درجة حرارة المحول الكهربائي مع الحفاظ على حجمه مساويا لحجم المحول التقليدي.

أجري التحليل العددي على شكل الزعانف لمحولة القدرة الكهربائية حيث تمت دراسة ثلاث أشكال (الشكل شبه المنحرف, الشكل المموج والشكل المثلث). وجد حسب النتائج ان الشكل شبه المنحرف للزعانف هو الاكثر كفاءة في تقليل متوسط درجة الحرارة لسطح وقلب المحولة. يتبعه الشكل المموج ثم الشكل المثلث مقارنة مع شكل الزعانف القياسي(الشكل المستقيم). لقد انخفضت درجة حرارة سطح المحولة ذات الزعانف شبه المنحرف بمقدار 278.15 درجة كلفن مقارنة بالمحولة التقليدية تلتها المحولة ذات الزعانف المثلثة بمقدار 276.15 درجة كلفن وأخيرا المحولة ذات الزعانف المموجة ب 275.15 درجة كلفن. إضافة, لقد انخفض معدل درجة حرارة قلب المحولة ذات الزعانف شيه المنحرف بمقدار 284.15 درجة كلفن مقارنة بقلب المحولة التقليدية تلتها المحولة ذات الزعانف المثلثة ب 280.15 درجة كلفن ثم المحولة ذات الزعانف المموجةب 278.15 درجة. لقد اظهرت النتائج تقارب كبير مع البحوث السابقة.

1. INTRODUCTION

A transformer is an integral part of electrical grids because of its role in transforming one voltage to another. Power can be transmitted from one electrical system to another with this device. Thus, it is essential for users to have the power transformer in order to make use of electrical power. [1][2]. The transformer produces heat as a byproduct of its regular functioning during the conversion of electrical current. This causes a dramatic rise in the transformer's internal temperature if the excess heat is not dissipated properly. If the insulator fails, the transformer won't last as long. A rise of 8 °C in the insulator's operating temperature, as predicted by the "Mont Singer" calculation, would halve the insulator's expected lifetime in this application [3]. Manufacturers are always looking for ways to improve efficiency without sacrificing weight or size reductions to the transformer system as a whole. In this case, the ratio of heat produced to the total transformer volume rises. Consequently, thermal design is critical and obligatory to maintain an effective, healthy, and dependable continuous power supply. To properly design a transformer system, one must accurately forecast the cooling capacity of the transformer's radiators, regardless of whether the system is an Oil Natural Air Natural (ONAN) or Oil Natural Air Forced (ONAF) configuration [4].

Chereches et al. [5] conducted a numerical parametric analysis to analyze how changing certain variables would affect the efficiency of a transformer's cooling system. The maximum temperature can be reduced by adding an obstacle at the bottom of the transformer since the coolant will then be forced to flow to the area with the highest temperature. The cooling efficiency of radiators used in power transformers with direct-oil-forced and non-direct oil flows was studied by Kim et al. [6]. As the flow rate in the radiator grew, the temperature difference between the top and bottom oils reduced. The large volume flow rate also contributed to an improvement in cooling capacity at higher rates. Using the finite volume approach, Bengang et al. (2017) [7] studied the thermal performance of a 10 kV oil-filled transformer that was cooled in an unorthodox (split) manner. According to their findings, increasing the horizontal distance between the transformer and the radiator causes a temperature drop in the heat spot. The researchers Paramane et al. (2016) [4] evaluated the thermal efficiency (cooling) of a radiator fan component with both the ONAN and ONAF designs. The investigations used five radiators, each 2.5 m high, a total of 27 fins, and two fans, each measuring 1 m in radius. Using the numerical model, the study analyzed how changing the air's flow direction (vertical vs. horizontal) affected the rate at which heat was removed from the system. The thermal performance of the radiator was noticeably impacted by the direction in which the air flowed. In terms of thermal performance, the horizontal airflow direction resulted in a 6.1% increase in the amount of heat lost compared to the vertical airflow direction. Power transformer cooling performance using ONAN was numerically investigated by Anishek et al. [2]. After conducting an optimization study, they found that their suggested radiator design provided 14% more cooling efficiency than the industry standard while using the same amount of raw materials. Using commercial CFD code, Fdhila et al. [8] quantitatively investigated the cooling efficiency of radiators in relation to the number and size of the cooling fans. Using a porous media model, they analyzed the airflow through the radiator. They found that the radiator's cooling effectiveness grew in tandem with the size and number of its cooling fans.

The cooling efficiency of the ONAF systems was 20.1% greater than the ONAN systems. Seong et al. [9] used commercial CFD simulation to conduct a numerical simulation of the fluid flow and thermal performance in the radiator of a transformer. Employing various cooling techniques, researchers evaluated the thermal efficiency of the radiator. They discovered that expanding the length of the radiator was more efficient than increasing the number of fins to enhance cooling efficiency. Using the Finite element method FEM, Tălu [10][11] analyzed the radiator's cooling efficiency for a 630 kVA transformer. They measured the air's temperature at various locations around the radiator. The results showed that a 20° slant between the transformer and radiator's distribution manifold enhanced its cooling effectiveness.

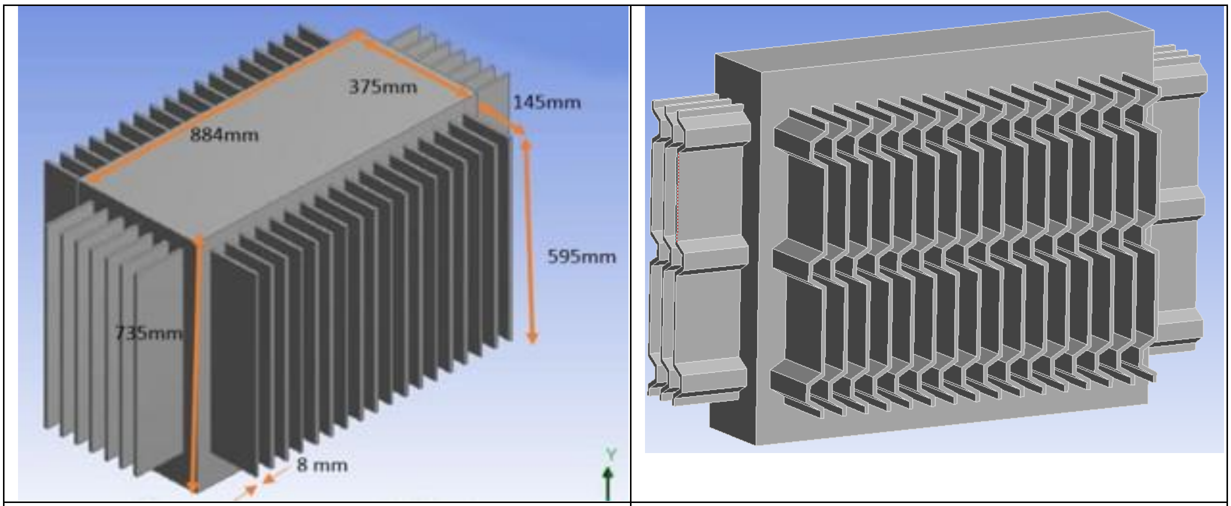
According to the brief analysis above, efforts to increase transformers' thermal performance (cooling rate) have focused on maximizing the natural convection current of the cooling transformer's fluid (oil). However, there has been little research into the possibilities of altering the transformer's geometry, specifically, the fins' shape and design, to increase the cooling rate of the transformer. The current research, however, hopes to address the void by suggesting a novel approach based on the transformer's geometrical design. This was accomplished by using ANSYS Fluent to create a numerical model of the thermal behavior of a 250 kVA, 11 kW oil-immersed transformer and then through experimental validation of that model. Wavy, triangle and trapezoidal are three alternative fin designs that were proposed, evaluated, and compared to the baseline design while maintaining the same operational parameters.

2. PHYSICAL MODEL

The current investigation includes the numerical analysis of the transformers thermal performance across four distinct designs. The 250 KVA electrical transformer was chosen for the study in this work, which is used in the electrical network of Iraq. Diyala State Company manufactured the transformer as a standard transformer with a 250 kV. This transformer was used to compare with the designs proposed in the study.

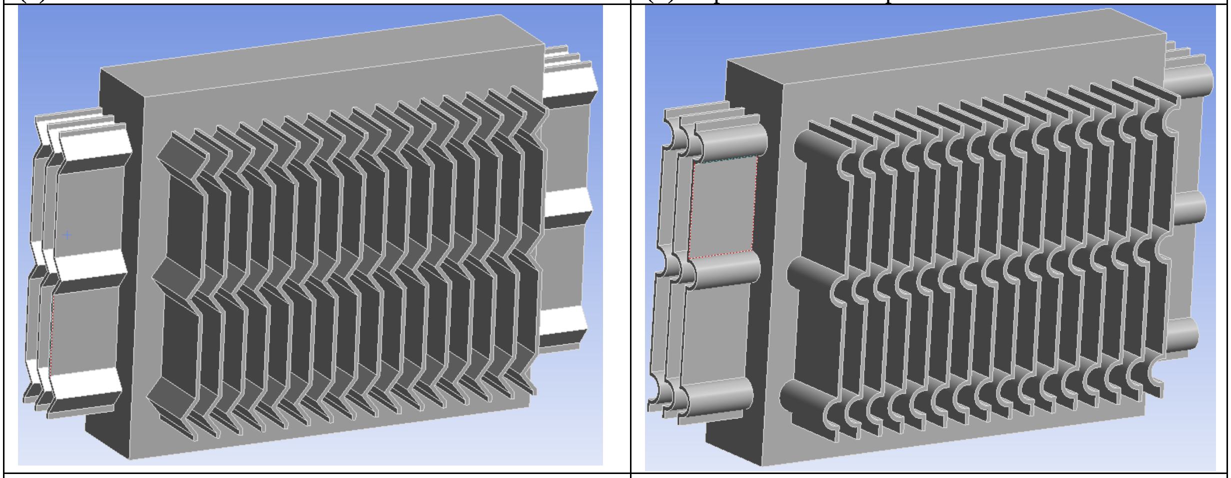
The standard and new designs of the power transformer are shown in **Figure** 1). In the current study, to simplify the solution, only the thickness of the walls was canceled, and the fins were considered to be transformer oil. The transformer designs' overall volume was split in half along symmetrical lines to speed up processing.

Further, the model considered just the oil volume, whereas the core volumes of the metal were disregarded. In order to simplify the solution, it was suggested that the transformer's core be a cube, and its volume was eliminated from the models. Because the numerical study relied on the heat flux on the surface of the transformer core, there is no need to take the transformer core as a solid body because this will increase the number of mesh cells and thus increase the time of the numerical simulation. All case studies were almost identical in terms of their oil volume and exterior surface area for the sake of comparison. Figure 1a) shows the geometrical details of the standard design.



(a)Traditional Power transformer

(b)Trapezoidal finned power transformer



(c)Triangular finned power transformer

(d)Wavy finned power transformer

Figure 1 The design of the electrical transformer with different fins shapes (a)traditional transformer (b)trapezoidal finned transformer (c)triangular finned transformer (d) wavy finned transformer

3. THE BOUNDARY CONDITION

Since the model is closed and the density of transformer oil varies with temperature, thermal transfer of the oil inside the oil tank is accomplished by natural convection caused by buoyancy. When addressing the natural convection issue, FLUENT offers two approaches: one is similar to the Boussinesq technique, and the other is the density definition method. Since the density rarely shifts during natural convection, defining density using the Boussinesq approximation ratio might improve the convergence of the temperature function. This study should use the Boussinesq model since oil density varies somewhat with temperature. For solving the equations presented, density is assumed to be constant; the buoyancy element in the momentum equation is the sole place where density varies with temperature.

4. NUMERICAL MODEL

4.1 Governing equations

Power transformers' coils and cores become warm since they're transforming power, which causes an increase in internal temperature. The oil within the power transformer conducts the heat from the core and coils to the interior walls by natural convection, the oil has a constant specific heat (Cp) 1845 J/kg k, constant thermal conductivity 0.145 W/m k, constant viscosity 1.06 Kg/m s and a boussinesq density 885 Kg/m^3. The created heat is subsequently rejected from the outside surfaces to the neighbouring environment via fins (radiation and convection). The power transformer model may be solved by using the governing equations (1) continuity equation,(2) momentum equation and (3)energy equation [12],[13]:

$$\nabla \cdot \vec{V} = 0 \tag{1}$$

$$\rho\left(V \cdot \nabla \cdot \vec{V}\right) = \nabla p + \nabla \cdot \left(\mu\, \nabla \cdot \vec{V}\right) + \frac{\rho - \rho_\infty}{\rho_\infty} g \tag{2}$$

$$\rho C_p (V \cdot \nabla T) = k \nabla^2 \cdot T \tag{3}$$

Where:
V is the velocity of flow m/s
ρ is the density Kg/m^3
P is the pressure Kg/m s
μ is the dynamic viscosity N s/m^2
g is the acceleration of gravity m/ s^2
C_p is the specific heat J/kg k
T is the temperature K
K is thermal conductivity W/m k

4.2 Numerical solution

CFD is resolved in (ANSYS/FLUENT) utilizing the Finite Volume Method (FVM). The governing equations are solved using the first-order upwind technique, and the segregation is solved using the algebraic form. The SIMPLE process was used to analyze the velocity-pressure coupling scenario, which included solving the continuity equation. In order to guarantee a high level of accuracy in contrast to the power transformer's practical specification, the convergence criteria employed for the momentum and energy equation solution residuals is fewer than 10^{-6}.

4.3 Grid Independence Test

After the geometry has been constructed, the mesh has been generated, and the boundary conditions have been given, many meshes must be inspected to find a good grid system. The term "grid independence test" (GIT) describes this procedure. The simulation of the issue with a dense mesh takes a long time, and the results are inaccurate with a low-density mesh. In order to save simulation time, the GIT guides grid density. Both low and high density meshes provide inaccurate results during simulations of the issue. GIT's specification of the grid's sufficient density allowed for faster simulations.

Because the research design is symmetrical to make the simulation process easier and faster, the typical model employed half of an electrical transformer to build the grid. The number of cells in each of the four grids constructed ranges from 2360098 to 5359411. Mesh components in this model were polyhedral, as illustrated in **Figure**). After the Third grid, the solution is no longer reliant on the volume mesh, as shown in “Table 1” which displays the average transformer surface temperature for the various mesh. For this reason, the Third mesh will be utilized for the rest of the solutions.

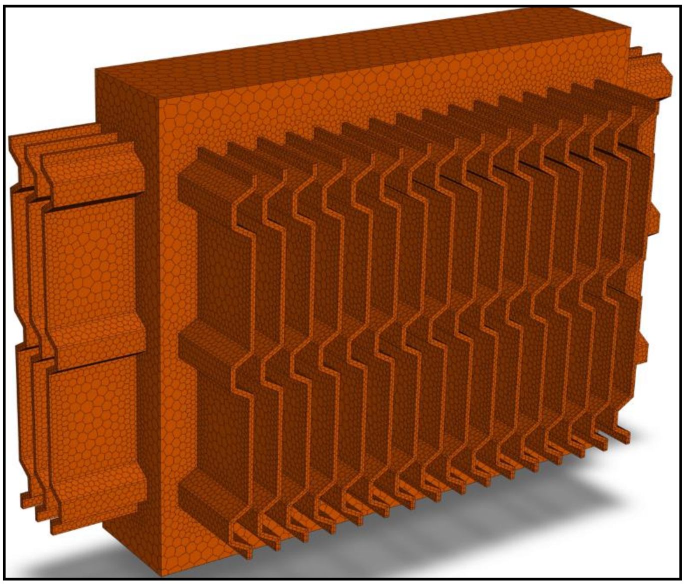


Figure 2 mesh of the trapezoidal fins design of the half electrical transformer (3D).

Table 1 Mesh independent study

Mesh cell size (mm)	**Mesh**	**Surface average temperature (K)**
25	Mesh 1 (2360098 elements)	338.45
20	Mesh 2 (2490993 elements)	340.95
15	Mesh 3 (2963467 elements)	341.55
10	Mesh 4 (5359411 elements)	341.65

5. RESULTS AND DISCUSSION

5.1 Validation study

The model described in [14] was used to verify the numerical model’s accuracy. This rectangular-finned electrical transformer (100 KVA) was used to validate the numerical model findings and assess the software’s efficacy. As can be seen in **Figure**), when using an external temperature range of 298 k to 328 k to determine the mean temperature of the oil, the model’s findings match the data. The acceptable agreement between the preset model’s findings and those for [14] is shown in **Figure**), along with an error ratio of (0.03).

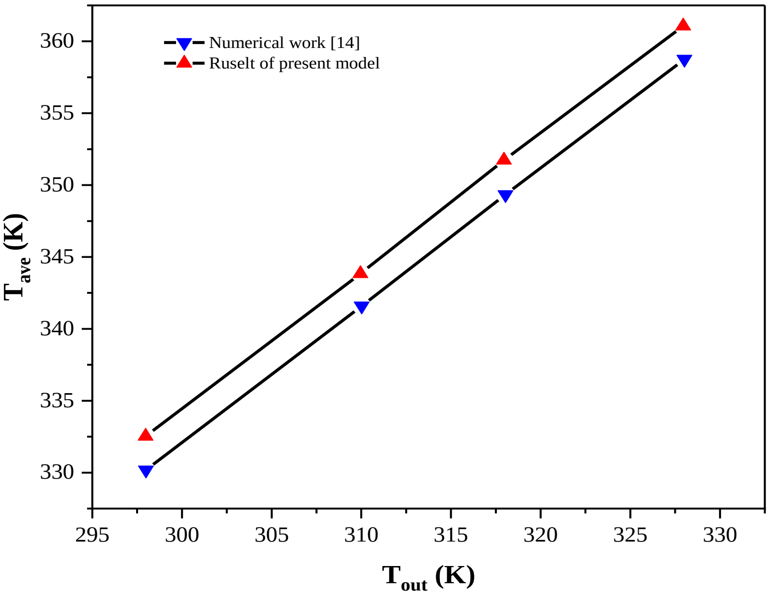


Figure 3 Comparison between the present numerical result and results of [14]

As previously mentioned, the maximum hot spot temperature should be lowered to improve the transformer's performance and lifespan. The temperature at which the transformer is operating will serve as the basis for comparing the conventional design with the suggested designs for the transformer. The transformer system's reaction to the solar load was analyzed in the present part using the Ansys software. Assuming that the transformer was not electrically loaded, sun insolation was measured using fluent over the duration of a day. Results are shown in **Figure** 2). As can be predicted, the impact of the solar load is the highest on the reservoir temperature and the lowest on the core when no other sources of heat production are present. These findings indicate that any simulation that disregards the impact of the solar would result in an incorrect estimation of the temperatures of the transformer components.

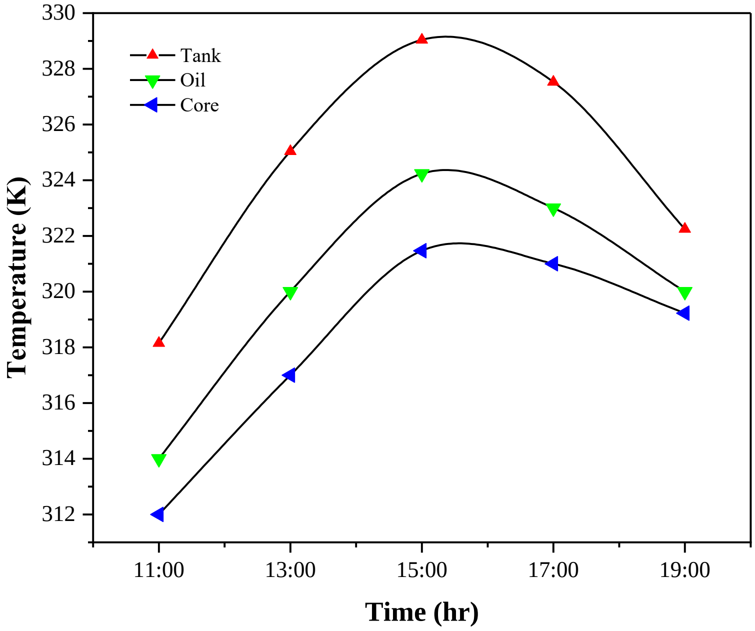


Figure 2 Effect of fin shape and solar radiation on the transformer surface temperature with no load.

5.2 The geometrical effects of fins

The research is conducted using the code program (FLUENT/ANSYS 2022 R1). The power transformer's model utilizes the power transformer's actual dimensions and the maximum heat losses from the power transformer's coils and core. The research used the meteorological conditions of Al-kut, Iraq, on July 1, as shown in Figure **3**, with a temperature of 318.15 K.

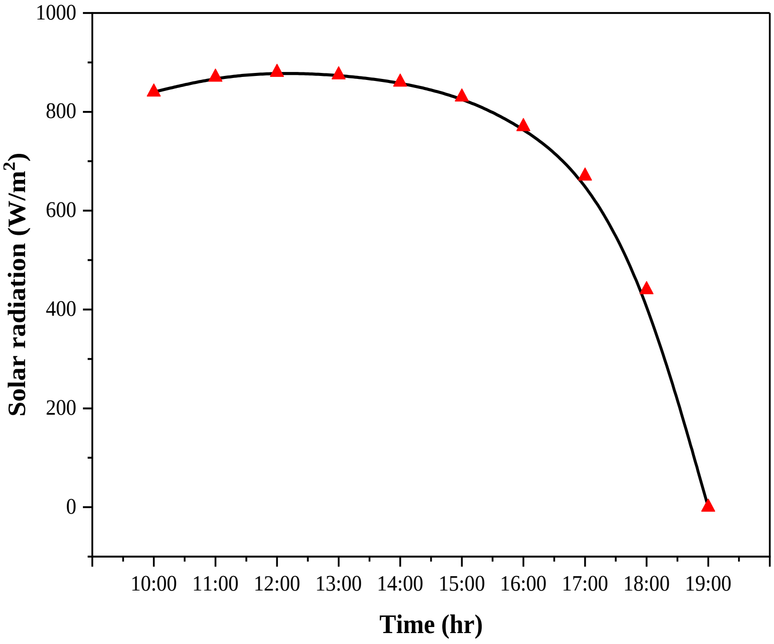


Figure 3 solar radiation measurement on July 1 in al-kut city.

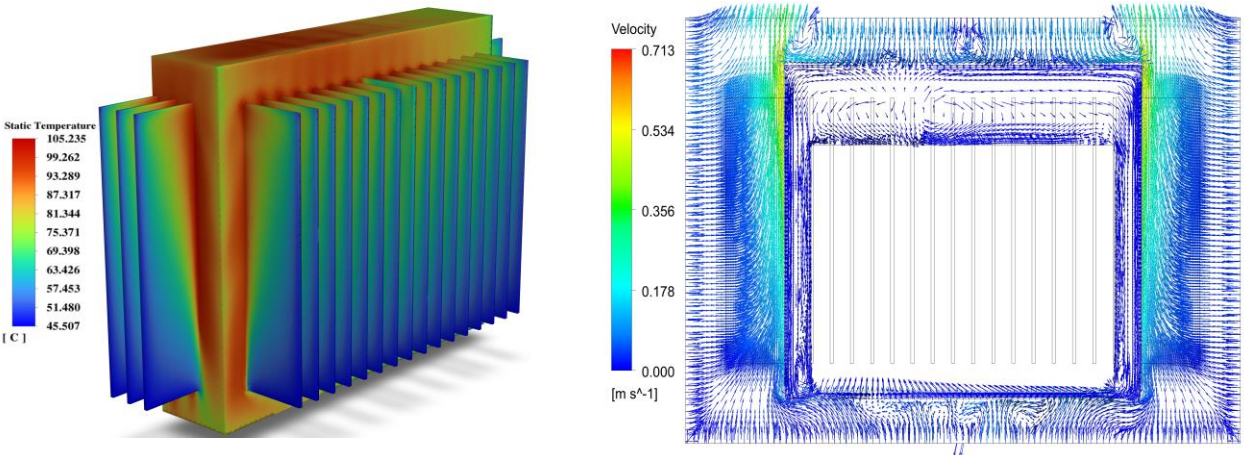
5.3 Effect of different fins configurations

Four different transformer designs had their thermal and flow behavior quantitatively analyzed. There have been a variety of fin configurations, including those with straight edges, trapezoids, triangles, and waves. In this study, the straight fins design of the power transformer is chosen as a reference point against which various designs can be compared and contrasted regarding their thermal performance; in **Figure** (6), the full computational domain that corresponds to the transformer, together with a vector and surface temperature contours, can be seen. As seen in "Figure (6)", the temperature profile of each investigated transformer design varies with transformer height. The surface temperature is coldest near the base and slowly increases as one travels higher. Because of the buoyancy force action, the heated (low-density) oil will rise to the surface. Furthermore, heat dissipation rises to the surrounding air as natural convection currents travel through a system.

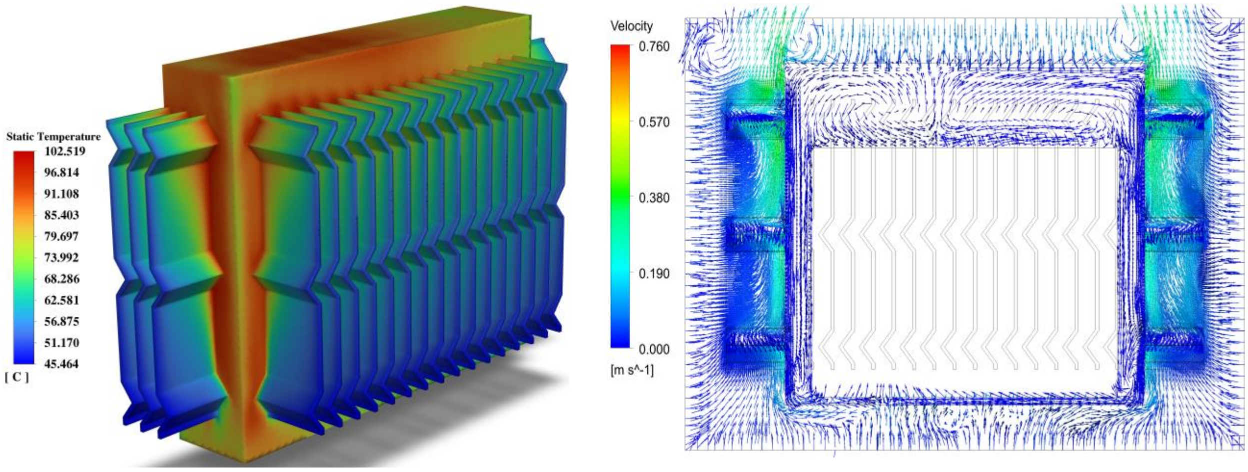
Hence, the top of the surface is where the temperature is the highest. **Figure** (6) indicates that the temperature contour for the straight-finned transformer is higher than for other types. The main reason is that straight fins have a smaller surface area than other designs. As a result, less heat is transferred from the power transformer's core to the surface using a straight-fin transformer than other fin configurations. **Figure** (6) further reveals that the trapezoidal finned power transformer has the lowest temperature distribution, followed by the wavy and triangular finned power transformers. The oil in this design's transformer is plentiful, as it cools the transformer's core and facilitates the rapid dispersal of any generated heat across the massive fin area.

Also, the vector's shape reveals that the air velocity between the trapezoidal fins is the highest, followed by the air velocity between the wavy fins, the triangular fins, and the straight fins. Furthermore, the vector contour demonstrates that vortices are more commonly detected in the oil of a power transformer with a trapezoidal-shaped fin than with the other fin shapes.

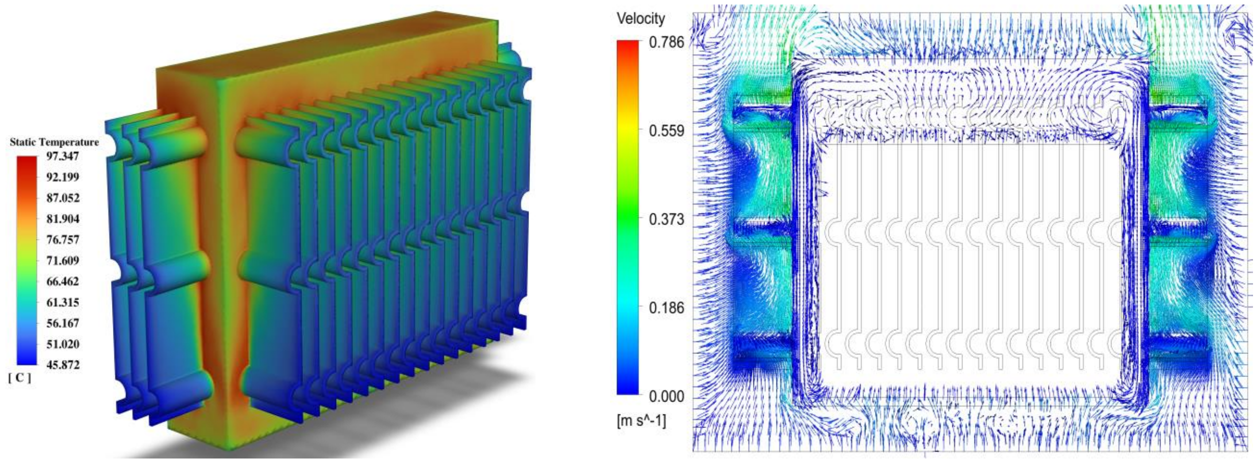
The influence of solar arrays supplied directly to an electrical transformer’s body will adversely affect its performance, as it will increase the temperature of the coils, core, oil, and body. The effects of transformer load and solar radiation on the surface of the power transformer are shown in **Figure** 5). **Figure** 5) shows that the surface temperature of the power transformer of various fin shapes gradually rises with the passage of the operating time. Moreover, “**Figure** 5)” shows that the surface temperature of the power transformer with trapezoidal fins is lower than the surface temperature of other power transformers. Concerning the influence of solar radiation on the surface temperature of the transducer, it is shown that the maximum surface temperature of all forms of fins is at 4 pm. The reason for this is that the effect of the transformer load is predominantly on the temperature distribution, so the impact of solar radiation is not clearly shown in **Figure** 5). In addition, it is noted that the surface temperature of the power transformers stabilizes approximately after 4 pm and then gradually decreases due to the decrease in the effect of solar radiation. **Figure** 6) shows the effect of electrical load and solar radiation on the power transformer’s core. It is clearly observed that the temperature of the transformer core has the same behavior as the surface of the power transformer. Furthermore, when compared to the standard transformer, the average surface temperature drop for the transformers with corrugated, wavy, and triangular fins was 278.15, 276.15, and 275.15 K, respectively. In addition, the transformer with trapezoidal fins had a 284.15 K lower core temperature than the reference transformer, while the transformer with wavy fins had a 280.15 K lower core temperature, and the transformer with triangular fins had a 278.15 K lower core temperature. Therefore, the revised designs are superior to the ones originally offered (straight fins shape). Since the number of fins was kept the same, this finding suggests that the transformer’s shape significantly impacts enhancing heat transfer. The recommended features, notably the transformer’s trapezoidal fins, helped boost the rate at which heat is released into the environment. Because of this, heat is dissipated more efficiently over the transformer’s surface area rather than concentrated in the central fins.



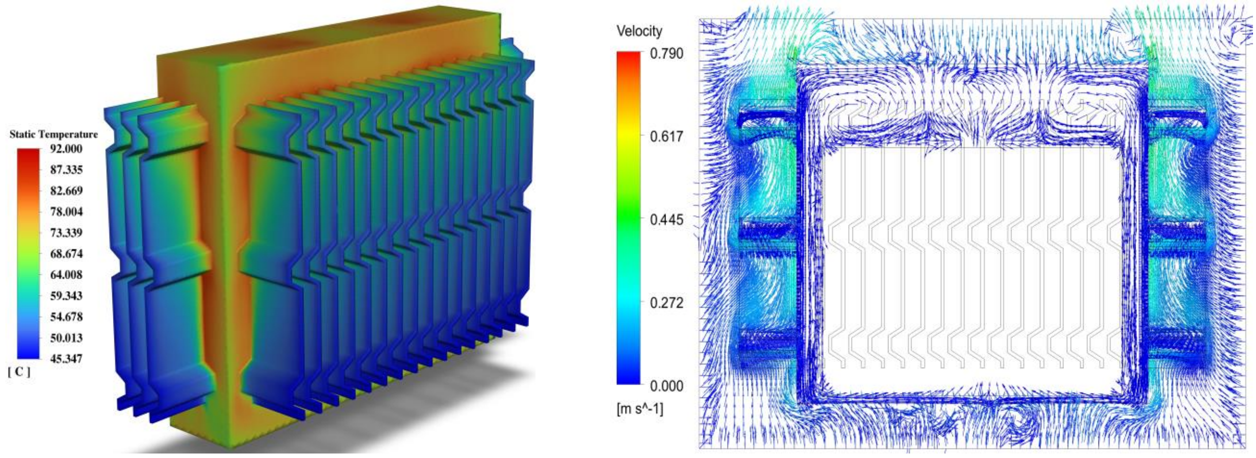
(a)Standard power transformer



(b)Triangular finned power transformer



(c)Wavy finned power transformer



(d)Trapezoidal finned power transformer

Figure 4 Temperature and vector contours of the power transformer at different studied designs.

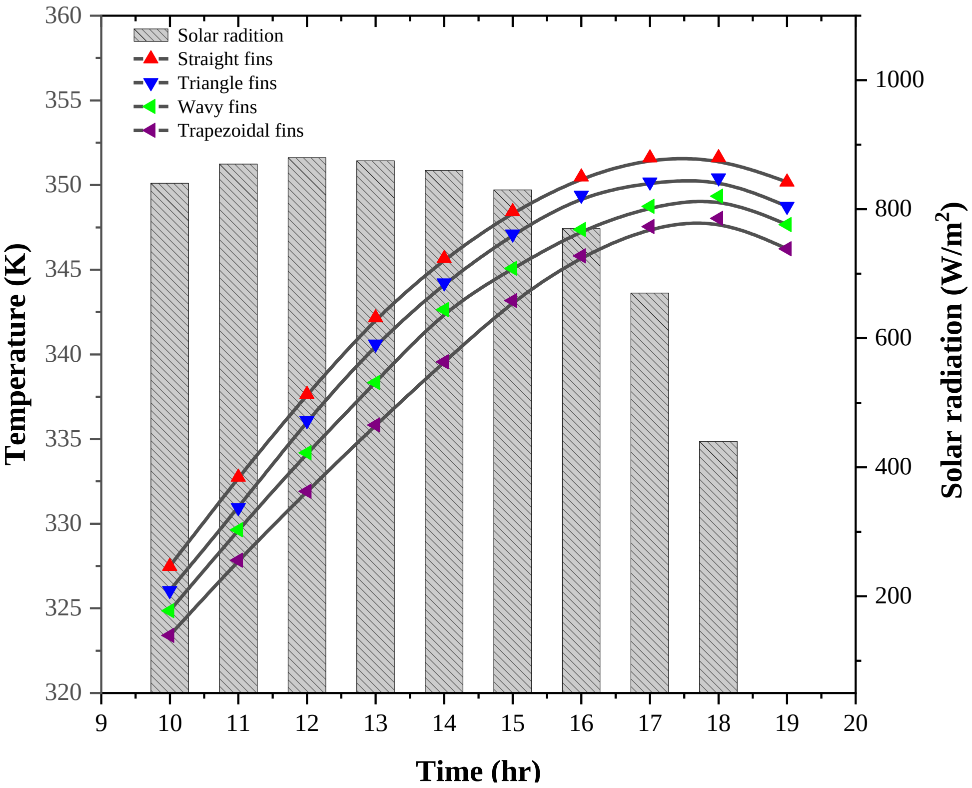


Figure 5 Effect of fin shape, transformer load, and solar radiation on the transformer surface temperature.

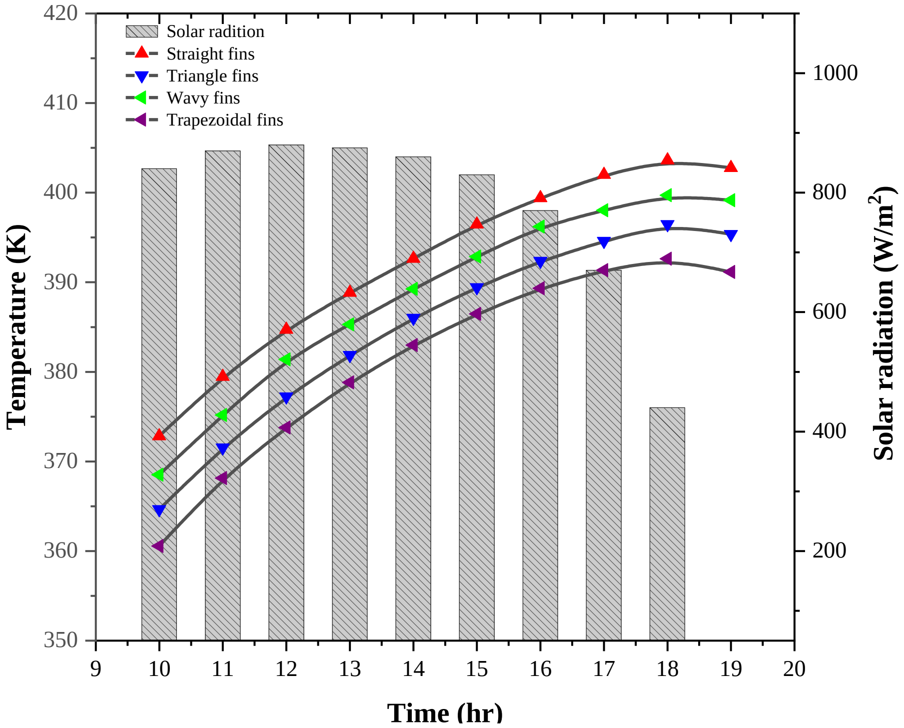


Figure 6 Effect of fin shape, transformer load, and solar radiation on the transformer core temperature.

6. CONCLUSION

This study used a three-dimensional model to examine the effect of geometry and solar radiation on the cooling efficacy of an oil-natural-air-natural (ONAN) 250 kilovolt-ampere (kVA) electrical distribution transformer. The primary contribution of this study is a design that contributes to lowering the temperature of an electrical transformer while keeping its overall size comparable to a conventional transformer.

The transformer's fin shapes (trapezoidal, undulating, and triangular fins) were numerically analyzed. Trapezoidal fin shapes were the most effective at reducing the transformer's average surface and core temperatures, followed by wavy fins and triangular fins compared to the conventional transformer shape (straight fins). Compared to the reference transformer, the corrugated-finned transformer's surface average temperature dropped by 278.15 K, the wavy-finned transformer by 276.15 K, and the triangular-finned transformer by 275.15 K. In addition, the core temperature of the transformer with trapezoidal fins was 284.15 K lower than the core of the reference transformer, followed by the transformer with wavy fins by 280.15 K and the transformer with triangular fins by 278.15 K. The study also revealed that the temperature of the transformer's surface and interior increases with increasing solar radiation, but the electrical load has a greater impact on temperature than solar radiation. The results demonstrated a significant correlation with prior research.

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