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Numerical Study on Hydrodynamic and Heat Transfer Performances for Panel-Type Radiator of Transformer Using the Chimney Effect

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The naturally cooled panel-type radiators are widely used for transformer heat dissipation. However, their poor heat transfer performance also restricts the overall performance of the transformer. The chimney effect can improve the airflow rate due to the thermal pressure difference between the air inside and outside the flow channel, which is widely used to improve the flow and heat transfer of natural convection. In order to improve the heat transfer performance of panel-type radiators under natural convection, a novel radiator is developed, where wind deflectors are added at both lateral sides of the radiator, and a chimney structure is added on the top of the radiator to extend the chimney channel. Then, the fluid flow and heat transfer characteristics inside and outside the radiator are studied by numerical simulation. The results show that cooling air would be effectively sucked into the radiator from the bottom due to the pressure difference generated at the inlet and top of the chimney channel. As compared with the traditional panel radiator without the chimney structure, the airflow on the outer surface of the most cost-effective radiator is increased by 19.14 %, the cooling capacity is increased by 14.76 %, and the oil temperature inside the transformer is reduced to 6.72 °C.

1. Introduction

Power transformers are important parts of power networks. In the process of working, the heat loss caused by the winding and iron core will increase the temperature of the whole system. The insulation performance of the transformer may be reduced, and the life of the transformer may be shortened. Therefore, large transformers are often equipped with cooling apparatus (Kim et al., 2018). Considering the typical configuration of the radiator, panel-type radiators are still the most commonly used in oil-immersed transformers for their economy and stability. Fans are always arranged at the bottom or side of the radiator to increase the heat dissipation capacity of the radiator. However, limited by the maintenance of the fan system and additional power consumption, natural convection is considered by enterprises to be a more stable and reliable way of heat dissipation. Natural convection is the outcome of buoyancy-induced flow fields produced by temperature-dependent density gradients. Increasing the surface area of equipment may enhance natural convection heat transfer, but that often raises concerns about the weight and size of the transformer and may end up with a high cost. The lack of driving forces to overcome viscous friction is a more important issue. This means that it is necessary to increase the density difference of the air through ingenious thermal design to increase the driving force of the fluid (Abbas and Wang, 2020). According to the principle of the chimney effect, adding an insulating extension downstream of the heating channel is a feasible way to enhance the natural convection air velocity. In the early years, some scholars studied the enhancement of heat transfer of parallel plate-fin radiators by the chimney effect. Haaland and Sparrow (1983) are the earliest scholars to study the heat transfer between the heat source and air in vertical chimneys. They numerically illustrate a chimneylike flow induced in vertical channels by a uniformly distributed heat source. Auletta et al. (2001) conducted an experimental investigation of adding adiabatic extensions downstream of a vertical isoflux symmetrically heated channel. Depending on different

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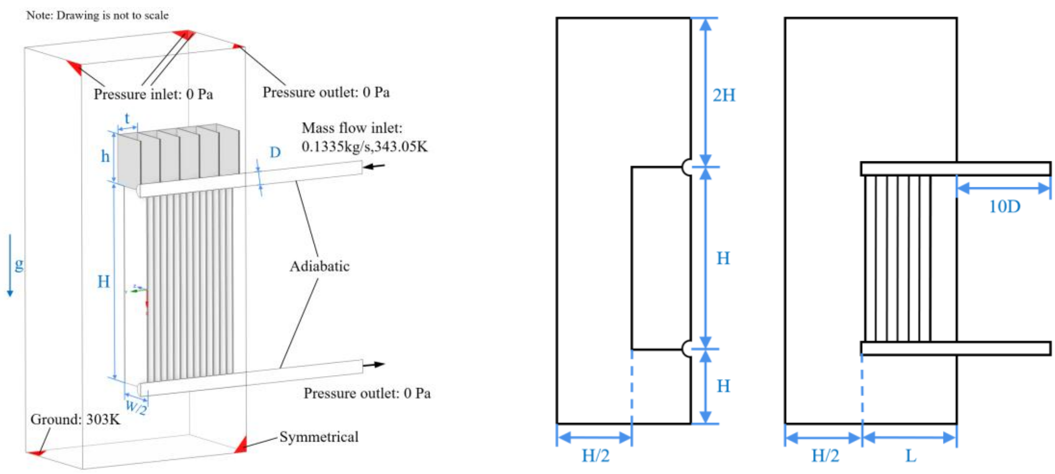
channel configurations, they obtained a 10 - 20 % increase in the average channel Nusselt number. Moon et al. (2015) examined natural convection heat transfer for a finned plate inside a chimney for application in reactor cavity cooling systems. They found that the height and width of the chimney have an important influence on the occurrence and strength of the chimney effect. Recently, Abbas et al. (2020) studied the effect of adding a plastic chimney on the top of an upward horizontal rectangular heat sink under natural convection. And the effect of the chimney's geometric parameters for different fin array dimensions was discussed. They also pointed out that the chimney was only effective when the heat sink was placed horizontally upward. Schwurack et al. (2021) utilised the chimney effect to improve the heat dissipation performance of thermoelectric generators (TEG). They found that the power output of the TEG with chimney channels increased by 46.2 % compared to the traditional passive cooling method with a finned heat exchanger. Besides, the chimney effect is also widely used in solar dryers. Habtay et al. (2021) experimentally investigated the heat transfer performance of a coupled chimney on top of a solar air collector. The experimental results showed that the chimney improves the uniformity of air temperature in the collector and increases its thermal efficiency by 2.7 % ~ 20 %. Lately, the improvement of the natural convection heat dissipation performance of a fully closed cabinet was systematically shown by Fulpagare et al. (2023). Under the redesign of the air flue and the introduction of a new radiator, dual chimneys were formed to separate and facilitate the airflow circulation in the interior and exterior of the cabinet. Generally speaking, the application of the chimney effect is to form a larger temperature gradient in natural convection and then increase the velocity of the fluid.

In the process of working, the heated transformer oil inside the transformer flows into the radiator from the top and flows out from the bottom of the radiator after cooling. As a result, the panel-type radiator for an oil-immersed transformer has a temperature gradient. This kind of radiator can be enhanced its heat dissipation performance through the chimney effect. And the relevant research has not been found. In the present study, the hydrodynamic and heat transfer performances of a novel radiator under natural convection are studied numerically. The radiator adds two wind deflectors to the traditional panel-type radiator to construct the chimney structure. It adds a multi-channel chimney structure on the top of the radiator to extend the chimney channel.

2. Method and simulation

Generally, panel-type radiators used in transformers are made of several steel plates with several grooves by using cold rolling and connected with two collector tubes on the top and bottom. The inner runner of the plate mainly circulates transformer oil, and the external heat is dissipated by air. In the present study, the conjugate heat transfer and fluid flow analysis is carried out to calculate the distribution of velocity and temperature fields for the insulating oil inside a single radiator as well as ambient cooling air outside the radiator. The details of the computational domain and the boundary conditions are shown in Figure 1(a). The computational area is reduced to 1/2 of the actual area by means of a symmetry plane. In addition, according to the research of Abbas et al. (2020), acrylic with good thermal insulation was selected as the material for the defector and chimney.



(a) *(b)*

Figure 1: (a) Computational domain and boundary conditions, (b) position of the radiator with respect to enclosure dimensions

The radiator fins, with sizes *W* (width) × *H* (Height) × *N* (Number), are vertically attached to pipes having a diameter of D. The interval between each set of the fin is 45 mm. What's more, to simplify the calculation, the fins are treated as cuboids with a thickness of 6 mm. According to the principle of Wang (2018), the computational domain for natural convection should contain at least triple the characteristic size of the model assembly in the flow direction and at least half the characteristic size surrounding the assembly. This conclusion was confirmed and adopted by Zhang et al. (2020). The size of the computational domain is illustrated in Figure 1(b).

The simulations were performed using the commercial CFD software Fluent, and the governing equations were discretized with the finite volume method (FVM). The *SST k-ω* turbulence model is adopted for the turbulent flow. And the conservation equations of mass, momentum, and energy of the air domain can be expressed as Eqs.(1)-(3). A Boussinesq approximation is used to take into account the driving force due to a temperature-dependent density, and the thermal expansion coefficient of air is β = 0.0033 K^{-1}. A second-order upwind scheme is used for the convective terms in the momentum, energy, and turbulence equations. In the iterative calculation process, the final residual of the calculation is less than 10^{-5}. The COUPLED algorithm was used for the velocity-pressure coupling technique to obtain the solution.

$$\frac{\partial}{\partial x_i}(\rho u_i) = 0 \tag{1}$$

$$\frac{\partial}{\partial x_i}(\rho u_i u_j) = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_i}\left[\mu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} - \frac{2}{3}\delta_{ij}\right)\right] + g(\rho-\rho_0) - \frac{\partial}{\partial x_i}(\rho \overline{u_i' u_j'}) \tag{2}$$

$$\frac{\partial}{\partial x_i}(\rho u_i c_p T) = \frac{\partial}{\partial x_i}\left(\lambda \frac{\partial T}{\partial x_i}\right) \tag{3}$$

Here, u, P, T, and x in Eqs.(1)-(3) represent the velocity, pressure, temperature, and coordinate direction. Symbols ρ, μ, λ, c_p, and g represent the density, viscosity, thermal conductivity, specific heat of fluid, and gravitational acceleration, and δ_{ij} is the Kronecker delta.

As for insulating oil, the calculated results differ by only 0.15 % compared to the turbulence model. The flow and heat transfer are treated as laminar, and the turbulence term in the momentum equation is ignored. For solid regions, the shell conduction model is invoked directly. The radiator wall thickness is taken as 1 mm. Other detailed geometric and physical parameters are shown in Table 1.

Table 1: Main parameters in the simulation

Name	Parameter		Parameter		Parameter	Insulating oil	Air	Steel	Acrylic
	H (mm)	1,200	t_1 (mm)	670	ρ/(kg/m^3)	1,067.75 - 0.6376T	1.17	7,850	1,180
	W (mm)	520	t_2 (mm)	219	C_p/(J·kg^{-1}·K^{-1})	821.19 + 3.563T	1,007	455	1,549
	D (mm)	80	t_3 (mm)	127	λ/(W·m^{-1}·K^{-1})	0.15217 - 7.16 × $10^{-5}T$	0.262	88	0.2
Geometry	N	14	t_4 (mm)	39	μ/(Pa·s)	0.08467 − 4 × $10^{-4}T$ + 5 × $10^{-7}T^2$	1.86 × 10^{-5}		
	L (mm)	725			β/(K^{-1})		0.0033		
	h (mm)	300							

The reference value T_0 = 298 K is taken for the temperature. Correspondingly, the reference air density and dynamic viscosity are ρ_0 = 1.17 kg·m^{-3} and μ = 1.86×10^{-5} Pa·s. Several characteristic numbers used in the present study can be expressed as Eq(4)-(8):

$$h_g = \frac{1}{A_p}\int_{A_p} -\lambda \frac{\partial T}{\partial n} \Big/ (T_w - T_b)\, dA_p \tag{4}$$

$$Nu = \frac{H h_g}{\lambda} \tag{5}$$

$$Q_m = \frac{Q}{m} \tag{8}$$

Where h_g is the average heat exchange coefficient; Nu is the average Nusselt number; Q_m is the cooling capacity per unit mass of chimney; T_w is wall temperature; T_b is the temperature of the fluid near the wall; Q is the cooling capacity of the radiator; H is the characteristic length which is equal to radiator height; A_p is the radiator surface area; m is the mass of chimney.

In this article, the flow and heat transfer characteristics of air are analyzed in the following 6 cases shown in Table 2.

Table 2: The settings of six cases

Case	Settings	Case	Settings
1	Without enhanced heat transfer components	4	With deflectors and chimney (t = 219 mm)
2	With deflectors	5	With deflectors and chimney (t = 127 mm)
3	With deflectors and chimney (t = 670 mm)	6	With deflectors and chimney (t = 39 mm)

3. Grid and model validations

Owing to the use of the laminar flow model, the grid on the oil side of the radiator does not require high resolution. In the present study, the influence of the number of grids on the air side on the solution results is mainly examined. The grids used are polyhedral grids generated with Fluent meshing. The boundary layer grid uses a thin prismatic boundary layer with a near-wall thickness of 0.15 mm, which satisfies the requirements of the SST k - ω turbulence model for the wall grid ($\overline{y^+}$< 1). The results show that a grid-independent solution is obtained when the number of grids is 1.7 × 10^7.

To ensure the validity of the present numerical analysis, validation simulations are first carried out. A panel-type radiator whose size is 520 mm (width) × 2,500 mm (Height) × 30 (Number) is simulated in the natural convection model. For more detailed parameters, please refer to the research of Kim et al. (2018). The simulation results show that the total cooling capacity of a single radiator is 17.15 kW when it works in a steady state. Compared with the 19.57 kW measured in the experiment by them, there is a deviation of 12.35 %. Compared with the 18.25 kW obtained by them through simulation, the deviation is 6.03 %. The results show that the calculation model and method used in this study are reliable.

4. Results and discussion

In this section, the heat dissipation of the basic design, as in case 1, the design with deflectors on both lateral sides, as in case 2, and the design with deflectors and chimney with a single channel, as in case 3, is first analyzed. The temperature distribution contour at two different sides of these three cases is shown in Figure 2.

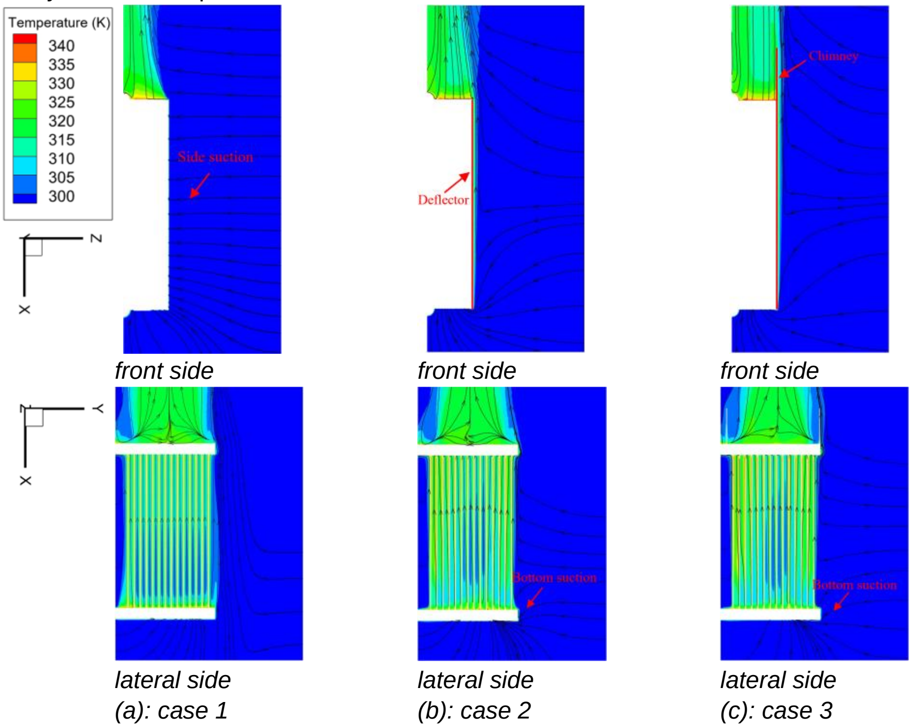


Figure 2: Temperature distributions of different cases at front and side faces (a)case 1, (b) case 2, and (c) case 3

In the working process, the panel-type radiator with a higher temperature will heat the surrounding air, resulting in a density difference in the surrounding air. The cooling air will be sucked into the gap of the radiator fins from the bottom and side. But when the wind deflectors were added on both lateral sides, the side suction of air was blocked. In this case, the radiator and the wind deflectors form a closed chimney structure. Due to the chimney effect, part of the air on the lateral side is driven into the bottom of the radiator, and the other part is taken away directly from the hot air on the top of the radiator. When the top chimney is added, this equates with the extension of the chimney channel. That is beneficial for the bottom suction of air, as shown in Figure 2(c). Besides, it can be seen that as additional components are added, the area of the high-temperature zone on top of the radiator becomes larger and more uniform.

Figure 3 shows the static pressure distribution of different cases on the lateral side. The pressure difference between the air within the fins array and the ambient air around the panel-type radiator drives the air into the fin array. For the basic design in Figure 3(a), the local negative pressure area is only formed near the top of the radiator. When the deflectors are added, the air channel between the radiator forms a large negative pressure area. This can form a greater driving force for airflow from the bottom of the radiator. When the top chimney is added, the local negative pressure area on the top of the radiator increases gradually with the decrease of *t* (the increase in the number of channels). The negative pressure area is mainly concentrated in the middle of the chimney rather than the outermost two channels. That's because the outermost two channels are directly connected to the atmosphere at the bottom.

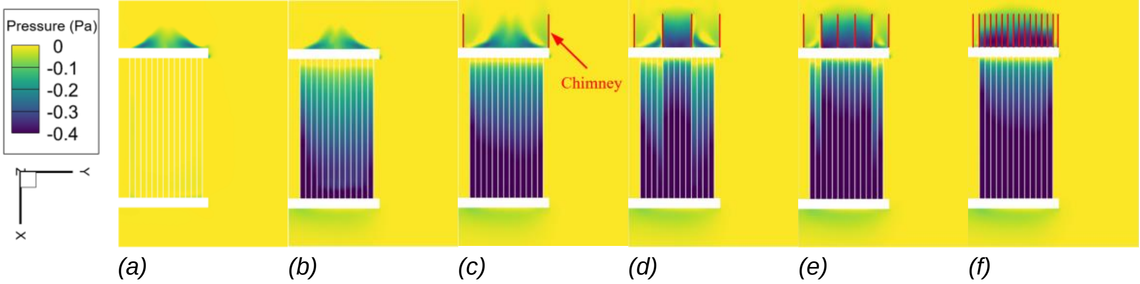


Figure 3: Static pressure distribution of different cases on the lateral side (a)case 1, (b) case 2, (c) case 3, (d) case 4, (e) case 5, and (f) case 6

Figure 4(a) represents the total air intake and their ratio of 6 cases. For basic design, not only the total intake air volume is significantly smaller than that of other cases, but also air absorbed from the side accounts for 72.8 % of the total air intake. This is not conducive to the full contact heat transfer between the air and the radiator, and the side air intake may even prevent the bottom air intake. Comparing cases 3 ~ 6, with the decrease of t (the increase of the number of channels), the total air intake of the radiator increases gradually. A similar result can be seen in Figure 4(b), which shows the h_g and Nu of different cases. As the increase of airflow velocity, the heat transfer between air and radiator is improved. And the heat transfer increases by enlarging the number of channels. Eventually, compared with the basic case, the total air intake in other cases increased by 16.42 %, 19.14 %, 21.53 %, 25.81 %, and 26.21 %, and the heat exchange capacity increased by 10.57 %, 14.76 %, 17.41 %, 18.79 %, 19.22 %. The growth rate of volume flow rate and h_g has slowed down significantly. It can be explained that the pressure loss caused by the channel wall is the main factor in restraining the airflow.

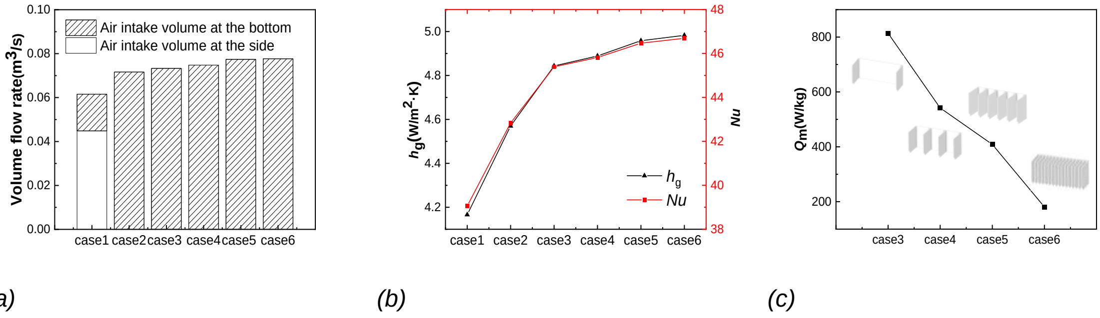


Figure 4: (a) air flow distribution, (b) the h_g and Nu of different cases, and (c) the cooling capacity of different cases

In order to evaluate the economic performance of the chimney, the cooling capacity per unit mass of the chimney of cases 3 ~ 6 is considered in Figure 4(c). The return/input of just increasing the number of channels is lower than expected. Overall, the chimney with a single channel can obtain relatively better-enhanced heat transfer performance and consume less material cost at the same time. With this setting, the temperature of insulating oil at the outlet of the radiator can be reduced by 6.72 °C.

5. Conclusions

In the present study, the effect of the wind defectors added at both lateral sides of the radiator and chimney with several channels added on the top of the radiator is investigated by numerical simulation. The major findings are as follows:

(i) The wind deflector and chimney have significant effects on the flow and heat transfer of the radiator. The radiator fins and the wind deflectors form a closed chimney structure. The chimney on the top of the radiator extends the chimney channel. Owing to the chimney effect, the channel between the fins of the radiator forms a negative pressure zone, which accelerates the flow of air.

(ii) The heat dissipation capacity of the panel-type radiator increases with the increase of the number of chimney channels. And this increase slows down as the number of channels increases.

(iii) The heat dissipation with the best comprehensive performance is case 3 (wind deflectors + the chimney with a single channel). This solution represents a trade-off between the greater driving force and flow resistance of natural convection caused by the chimney. Anyway, under this condition, a 14.76 % increase in heat transfer and a 6.72 °C decrease in the temperature of oil are obtained, which are important improvements in natural convection.

This research shows that the chimney effect can effectively enhance the heat transfer of panel-type radiators in the air-natural convection model. However, more factors of the chimney on the top of the radiator can be considered, such as height, thermal insulation, and view factor. The high-temperature chimney can form a greater pressure difference. It is feasible to study the heat transfer performance of chimneys heated by solar radiation.

Acknowledgements

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