VERTICAL AND HORIZONTAL POWER TRANSFORMER RADIATOR FANS RELIABILITY COMPARISON IN ONAF COOLING METHOD

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In this paper, the cooling of the power transformer radiators using the natural oil-air forced method will be investigated. A comparison between the two modes of cooling fans known as vertical and horizontal placement will be carried out too. In this study, four groups of radiators, each comprises of 14 fins and three fans with a diameter of half a meter have been used. Three fans will be used under the radiator (vertical) once and in one side of the radiator (horizontal) once again. The comparison results show that the horizontal mode has better heat transfer than the vertical mode. In addition, by disconnecting the internal fan, it can be shown that some points exist for the vertical mode which can help the cooling enhancement. With the optimal location of vertical fans, the heat transfer has been enhanced, compared to a horizontal one. It will also be determined that by disconnecting the side fans, the vertical mode will have a low reliability, but the horizontal mode will show a good heat transfer in any cases. By disconnecting one of the fans in the vertical mode, a vast part of radiators will not be considered.

Keywords: Power Transformer, Radiator, Fan, Oil Forced Air Natural (ONAF) Cooling

1. Introduction

The basis of the transformer's work is the principle of energy transferred by magnetic induction from one circuit to another. When one of the transformer’s windings is powered from the alternating current source, the alternating magnetic field will be existent in the transformer core. Alternating magnetic field lines are called fluxes that circulate in the core. The energy losses are proportional to the load. These losses are converted to heat and lead to increase in the transformer temperature which needs to be cooled. All losses that occur in the core, winding, and other insulations that occurs inside the transformer due to voltage and loading, turn into heat. The effective operation of the transformer and the efficient lifetime of the materials depend directly on the operating temperatures. External cooling can include heat exchangers, radiators, fans and oil pump. In power transformers, cooling is performed by circulation of the oil between the active sections and the external radiators of the transformer tank [1]. Power transformers usual cooling methods are: Oil Natural Air Natural (ONAN), Oil Natural Air

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Forced (ONAF), Oil Forced Air Natural (OFAN) and Oil Forced Air Forced (OFAF). In this paper ONAF cooling method is proposed that is less investigated in the previous works.

In [2], the solid insulation hot spot is measured using simple measurable quantities for ONAN cooling method, in which windings and core assembly are equipped with 112 sensors. In [3], a method for calculating the oil temperature inside the transformer is presented based on a hydraulic model. Furthermore, the temperature distribution in each conductor of the coil and the oil temperature in each oil duct are provided. In [4], using hydraulic theory and measured data in large-scale models, a technique for calculating the oil flow velocity in transformer cooling ducts is presented via directed oil forced cooling method. In [5], thermal modeling of power transformer disc windings and the insulating system is considered, and the influence of the effective parameters on transformer cooling is investigated. In [6, 7], a numerical method is proposed based on the heat transfer theory using finite element method, which requires solving the heat transfer equations. In [8], a simplified thermal equivalent circuit for oil-immersed transformer is presented, which is based on electrical circuit laws. In [9], a study has been conducted on the heat transfer and fluid flow in a step-down transformer. In this numerical modeling, the effect of volumetric flow rate changes and boundary conditions on fluid flow and temperature distribution in the transformer is investigated. The effect of different parameters on the disc winding temperature distribution of a sample transformer is investigated in [10]. In [11], the oil natural convection inside several distribution transformers is numerically modeled and simulated. In this paper, a simplified model with reduced computational time has been developed which can predict the oil flow and temperature distribution inside the transformer. In [12], a numerical simulation is presented to improve the heat transfer in a power transformer via the elevation difference between the center of the windings and the radiator center (thermal head). Considering the heat transfer and the fluid flow, the theory analysis and simulation calculations have been used to change the structure of the radiator plate, where the angle of 13 to 20 degrees between the canal and duct has the highest efficiency. In [13], the optimal design of the duct shapes is provided in order to obtain the maximum heat transfer. In reference [14], the power transformer radiator optimal design with ONAN cooling is investigated and simulated for determining cooling capacity. In [15], power transformer radiators thermal modeling in a porous medium is performed using CFD. In reference [16], the cooling performance of an oil transformer radiators is evaluated using directed and non-directed oil forced cooling method. In [17], an oil distribution transformer with two different core materials, silicon and amorphous, is considered, taking into account the comprehensive structure and the details of the transformer including radiators, core, windings, oil tank, and etc. Moreover, in this paper, after transformer electromagnetic simulation, a numerical analysis is presented for the transformer thermal analysis, which includes the coupling between the thermal field, the fluid flow and the electromagnetic field.

In [18], a numerical study has been performed on the fan airflow using ONAF cooling method in a 25 MVA transformer, and the thermal performance of the radiators has been studied in two sections: (1) the effect of horizontal and vertical air blowing direction in two fans with two different velocities (2) the effect of one of the fans displacements in horizontal direction. Vertical direction of the fans has a lower efficiency in the heat transfer of the radiator set in comparison with that of the horizontal direction, and also more air is dissipated or lost around it. As a result, the heat transfer rate in horizontal mode blowing is 7.2% and 6.7% more than that of the vertical mode with two different fans. In [19] as in the previous reference, a study has been conducted on ONAF and also ONAN cooling methods. In this paper, a study is carried out on 5 groups of radiators with 2.5 meters height and two fans with one meter diameter, where the simulation and test results has been well-matched. A numerical study has been also carried out on the horizontal airflow effect in comparison with the vertical mode. The significant effect of airflow direction on the amount of oil flow and temperature distribution inside the radiators along with a 6.1% higher heat transfer is reported for the horizontal direction compared to the vertical direction. In [20], a study has been carried out on fluid flow and heat transfer using numerical simulation of the velocity and temperature distribution for the oil inside the radiator and the cooling air outside the radiator. Furthermore, the cooling effect of the fan locations, underside and right side of the radiator, and the oil flow rate in natural and forced modes on the radiator performance has been investigated. The heat transfer rate of the horizontal forced model is 103% more than the natural model, and is 6.69% more than the vertical mode, which shows a large difference between the horizontal-forced cooling and the natural cooling.

Although some papers have performed the power transformer radiators thermal analysis, but as mentioned in the previous section, many of these papers and references have investigated only ONAN or OFAN cooling methods, or they have not evaluated power transformer radiators with full details and only a simple model of them is considered without making use of CFD for thermal analysis. On the other hand, in none of the previous references, the fan disconnection or the reliability issue is discussed. In the electric power industry, the power transformer cooling by means of radiators is usually performed using two methods: 1. Placing the fans horizontally (alongside radiators). 2. Placing the fans vertically (below radiators). Therefore, in this paper, the power transformer cooling method and also comparison of the two methods for placing the fans, are considered. Moreover, the fans placement optimal points and the reliability of the two methods are investigated.

2. Radiators modeling

In this paper, Ansys Fluent 19 software is used to simulate the model. The considered transformer consists of 4 radiators, and each of them contains 14 ducts. Each duct has a height of 2.6 m, width of 0.52 m and thickness of 2 mm. The three fans have also diameters of 0.5 meters and each radiator has two pipes in diameter of 8 cm. The oil moves into the ducts from the top of the radiator by means of pipes, and after the cooling operation, will move out from the pipes located at below of the radiator and will be transferred to the transformer. Fig. 1 shows the geometry and computational domain of the problem. The computational domain length is 6.5 meters in the horizontal direction and the width and the height are 2.1 and 5.4 meters, respectively. Figs. 2 and 3 show the fans placement in both horizontal and vertical modes. In the case of horizontal placement of the fans in Fig. 2, three fans are located alongside the radiator. The center of the first fan is placed at a distance of 0.45 meters from the top of the radiator, and the next two fans are placed at a distance of 0.85 meters (the distance between the centers of the fans) from each other respectively. The fans vertical placement is also depicted in Fig. 3. In the vertical mode, each fan is placed in such a way to include two radiators and to be exactly placed in the middle of the two radiators. According to the very large dimensions and the geometry complexity, a great number of elements and nodes are required. For this reason, tetrahedral elements and the maximum number of three boundary layers have been used for radiators. Fig. 4 shows the slice of the radiators network meshing. In Fig. 4, the nodes number is 1700000 which is suitable for solving this problem according to the large size of the problem and the complexities of the solution.

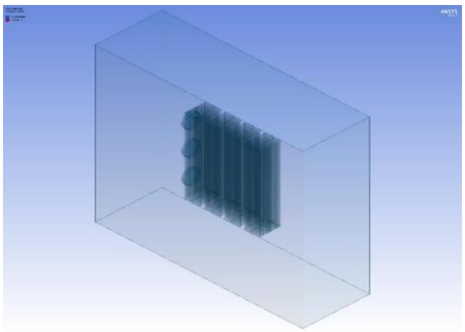


Fig. 1. The geometry and computational domain of the problem

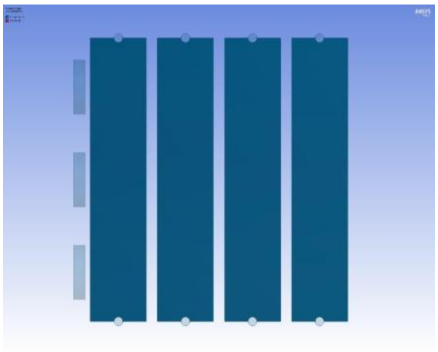


Fig. 2. Placing the fans horizontally

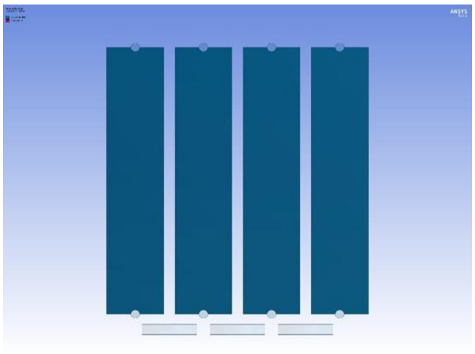


Fig. 3. Placing the fans vertically

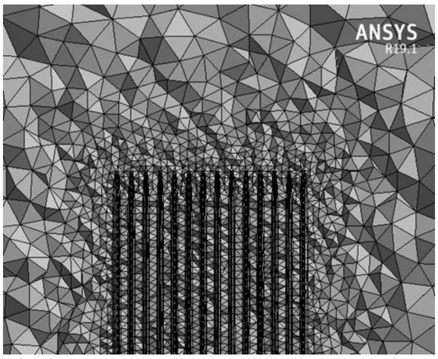


Fig. 4. Inner mesh from the geometry

3. Governing equations and boundary conditions

Determining boundary conditions is a sensitive issue in numerical simulation of the fluid flow and its proper definition is of vital prominence. The ambient temperature is selected 50 °C according to the transformer characteristics and the references. The inlet and outlet of the walls which are in line with the fans are considered as pressure-inlet and pressure-outlet with the pressure of zero Pascal. The remaining walls are considered symmetrical. According to the assumptions of the References [13] and [18], temperature variations at the radiator surface can be considered almost linear. On the other hand, all the walls of the fans are considered adiabatic. The governing equations for solving this problem are Navier-Stokes incompressible equations. The Navier-Stokes and energy equations are solved numerically through finite element or finite volume method. This kind of solution technique is known as the conjugate heat transfer analysis. The Navier-Stokes equations consist of fluid momentum sets of equations and fluid continuity equations. The form of these sets of equations along with the heat equation for an incompressible fluid is expressed as follows:

$$\frac{\partial V_x}{\partial x}+\frac{\partial V_y}{\partial y}+\frac{\partial V_z}{\partial z}=0 \qquad (1)$$

$$\eta\left(\frac{\partial^2 V_x}{\partial x^2}+\frac{\partial^2 V_x}{\partial y^2}+\frac{\partial^2 V_x}{\partial z^2}\right)-\rho\left(V_x\frac{\partial V_x}{\partial x}+V_y\frac{\partial V_x}{\partial y}+V_z\frac{\partial V_x}{\partial z}\right)-\frac{\partial p}{\partial x}=0 \qquad (2)$$

$$\eta\left(\frac{\partial^2 V_y}{\partial x^2}+\frac{\partial^2 V_y}{\partial y^2}+\frac{\partial^2 V_y}{\partial z^2}\right)-\rho\left(V_x\frac{\partial V_y}{\partial x}+V_y\frac{\partial V_y}{\partial y}+V_z\frac{\partial V_y}{\partial z}\right)-\frac{\partial p}{\partial y}=0 \qquad (3)$$

$$\eta\left(\frac{\partial^2 V_z}{\partial x^2}+\frac{\partial^2 V_z}{\partial y^2}+\frac{\partial^2 V_z}{\partial z^2}\right)-\rho\left(V_x\frac{\partial V_z}{\partial x}+V_y\frac{\partial V_z}{\partial y}+V_z\frac{\partial V_z}{\partial z}\right)-\frac{\partial p}{\partial z}=0 \qquad (4)$$

$$k_f\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}+\frac{\partial^2 T}{\partial z^2}\right)-\rho c_p\left(V_x\frac{\partial T}{\partial x}+V_y\frac{\partial T}{\partial y}+V_z\frac{\partial T}{\partial z}\right)=0 \qquad (5)$$

Where V_x is the fluid velocity in x direction (ms^{-1}),V_y is the fluid velocity in y direction (ms^{-1}),V_z is the fluid velocity in z direction (ms^{-1}), p is the pressure inside the fluid ($kgm^{-1}s^{-2}$)T is the temperature (K), η is the fluid dynamic viscosity ($kgm^{-1}s^{-1}$), ρ is the fluid density (kgm^{-3}), c_p is the fluid specific heat capacity ($Jkg^{-1}K^{-1}$), k_f is the fluid thermal conductivity ($Wm^{-1}K^{-1}$) , and k_s is the thermal conductivity of the solid parts ($Wm^{-1}K^{-1}$). Considering that the fan flow speed is about 7 m / s, it can be assumed that the fluid is incompressible, and the problem can be solved in steady state. SIMPLE algorithm has been considered for the type of solver and the second-order discretization has been used to solve the energy equation. The K-ε model, which is a valid model for solving turbulent flow, is used to solve turbulent flow equations. According to the large scale of geometry and mesh, a system with 8 GB of memory and a 2.4 GHz processor has been used to solve the problem. The computational time for each simulation lasts about 13 hours.

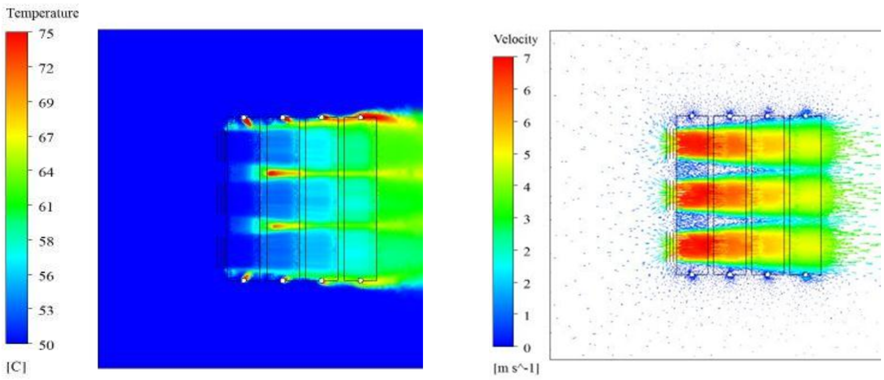
4. Simulation

This section is dedicated to simulating and comparison of the cooling results obtained from horizontal and vertical placement of the fans. First, the radiators are cooled by three fans and then by two fans (with disconnecting of one of the fans), and after that the fans placement is evaluated.

4.1. Cooling with three fans

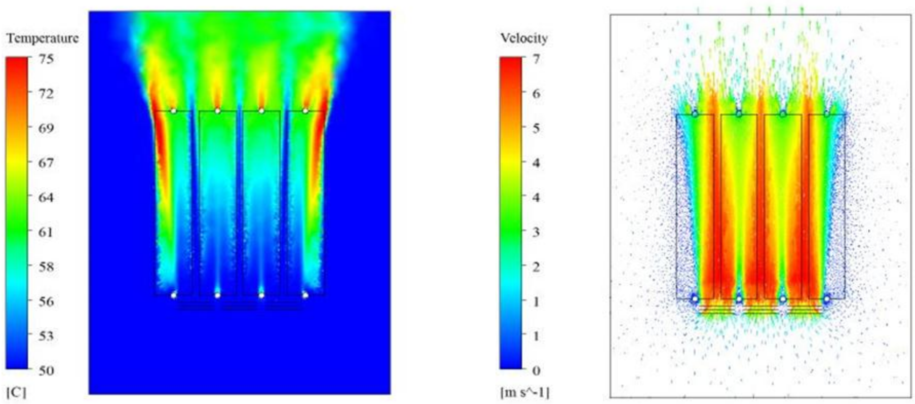
Figs. 5(a), 5(b), 6(a) and 6(b), show the temperature contours and the velocity vectors at a central plane (passing through the fans) along with the radiator overall design, respectively. Fig. 5 shows the fans horizontal placement and Fig. 6 shows their vertical positioning. As can be observed in the figure, the heat is transferred to the right in the horizontal mode and is transferred to the top in the vertical mode, and the horizontal mode heat transfer is more uniform than that of the vertical mode. In Fig. 5(a), in the horizontal mode, as the radiator is located closer to the fans, the temperature will be lower. In this regard, if the radiator assembly is divided into three top, middle and bottom sections, these three parts will have a temperature of 56.9, 55.7 and 53.7 degrees Celsius, respectively. In Fig. 6(a), in the vertical mode, there is an enhanced cooling at the bottom points of the radiator, since the top, middle and bottom parts of the radiator have a temperature of 61.9, 56.6 and 51 degrees Celsius, respectively. In tables 1 and 2, the temperature values are expressed in all three parts for each radiator in horizontal and vertical modes. The heat transfer for the horizontal mode is 56 kW, while it is 51.4 kW for the vertical mode. This difference indicates 8.9% superiority for the horizontal mode compared to the vertical mode. The significant issue in the vertical mode is the temperature of the two side radiators (1 and 4), which is higher than the two middle radiators (2 and 3). The low temperature of the two middle radiators in the vertical mode is due to the fans placement, since all the three fans cool the two middle radiators. Furthermore, in the vertical mode, the middle fan cools the radiators 2 and 3, and the side fans also contribute in a part of these two radiators cooling. Hence an enhanced cooling is performed in the two middle radiators. In the horizontal mode, the radiators which are closer to the fans are cooled better. Nevertheless, in this case, the temperature at the radiator surfaces is more appropriate than the vertical mode. This is due to the same sections that each fan sees in its direction and it is slightly weaker only at the points between the two cooling fans.

According to Figs. 5(b) and 6(b) velocity vectors, the velocity value in the horizontal mode is high at first and then it decreases gradually. The air flow rate, with the exception of the radiator top and bottom points, and also the points between the two fans, have an appropriate encompassing in the radiators which are close to the fan, so there is a better heat transfer as well. In the vertical mode, the maximum air flow speed is at the bottom part of the radiator and close to the fan, which gradually decreases. The air flow is mostly focused on the two middle radiators, while the air flow does not cover all the sections of the two side radiators (1 and 4.). The two middle radiators also benefitted from their side fans, in addition to making use of the middle fan, which causes better heat transfer and lower temperature in these two radiators.



(a) (b)

Fig. 5. (a) Temperature contour, (b) Velocity vector for horizontal mode using three fans



(a) (b)

Fig. 6. (a) Temperature contour, (b) Velocity vector for vertical mode using three fans

Table 1

Radiators temperatures in degrees Celsius for horizontal mode using three fans

Radiator Number / Position	1	2	3	4
Up	50.9	57.8	59	60
Center	49.5	56.8	57.7	59
Bottom	49.2	53	56.2	56.5

Table 2

Radiators temperatures in degrees Celsius for vertical mode using three fans

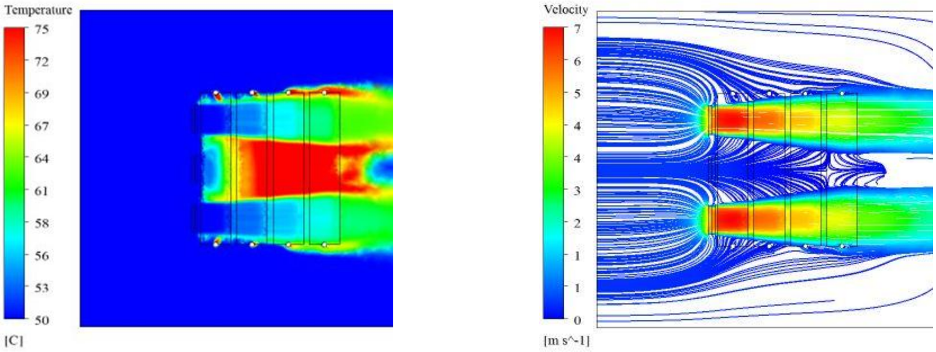
Position \ Radiator Number	1	2	3	4
Up	66	58	58.5	65.2
Center	58	54	54.6	60
Bottom	52	50	51	53

4.2. Cooling performance using two fans

In this section, the system cooling performance using two fans or the system behavior by the disconnection of one of the fans is investigated. Meanwhile, the reliability of the two systems and the optimum point of the fans vertical placement are also examined. Next, by disconnecting one of the fans, the strengths and weaknesses of both vertical and horizontal modes will be compared and the heat transfer rate will be also calculated.

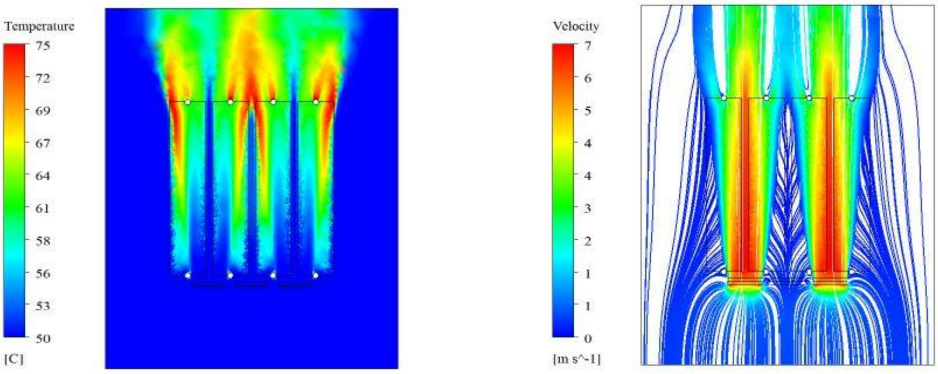
4.2.1. The middle fan disconnection

The heat transfer rate in this case is 40.2 kW for the horizontal mode and 39.4 kW for the vertical mode. In the case of disconnecting the middle fan, it is observed that the horizontal mode has only 2% better performance in comparison with the vertical mode which is reduced by 6.9% compared to the case of using three fans. In fact, the reason for the enhanced performance of the vertical mode in this case is the optimum point for placement of its two fans. Figs. 7(a) and 7(b) illustrate the temperature contour and stream lines for the fans horizontal mode, and Figs. 8(a) and 8(b) show the temperature contour and stream lines for the vertical mode with disconnecting the middle fan. By disconnecting the middle fan in the vertical mode, each of the two other fans cools a part of their alongside radiator. The stream lines and temperature contours in the vertical mode indicate that uniform amount of air is blown into each section of the radiator. The temperature in the middle of the radiator assembly has been higher. By disconnecting the middle fan (compared to the case of using three fans), a part of the two radiators (2 and 3) is ignored. In the horizontal placement of the two fans, it can be observed that the middle section of the radiator assembly is ignored, so the heat transfer rate is significantly reduced compared to that of the vertical mode. Therefore, it can be expressed that the condition improvement in the vertical mode compared to the horizontal mode is due to the accurate placement of the fans. However, in this situation (disconnection of the middle fan), the heat transfer rate of the horizontal mode is slightly better than that of the vertical mode, which indicates the low superiority of the fan horizontal placement in the case of disconnecting the middle fan.



(a) (b)

Fig. 7. (a) Temperature contour, (b) Stream lines for the horizontal mode in the case of disconnecting the middle fan (using two fans)

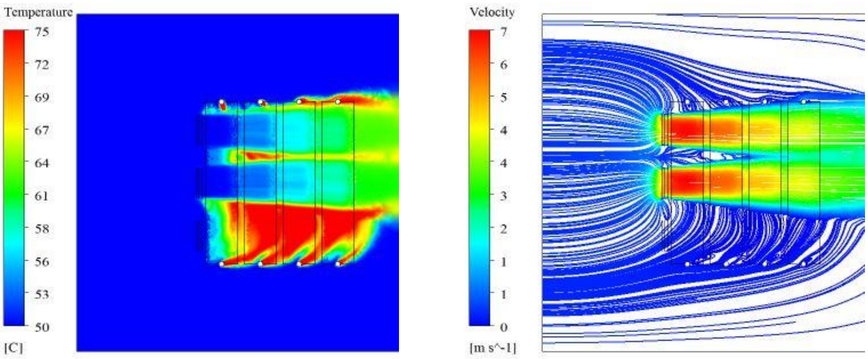


(a) (b)

Fig. 8. (a) Temperature contour, (b) Stream lines for the vertical mode in the case of disconnecting the middle fan (using two fans)

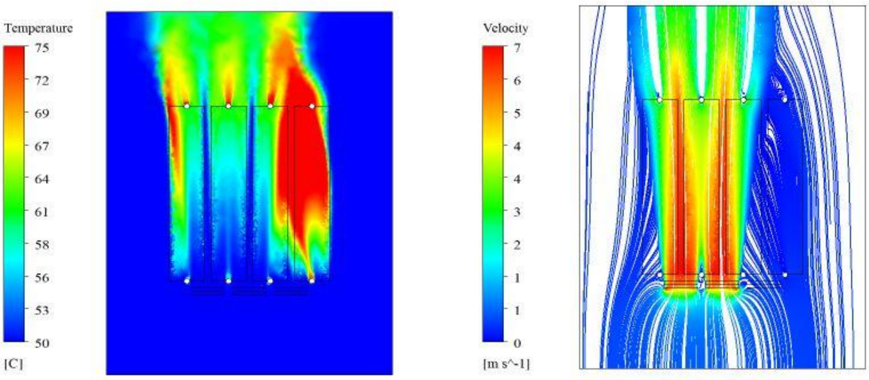
4.2.2. The side fan disconnection

By disconnecting one of side fans, the heat transfer rate is 40.7 kW in the horizontal mode, and 36.7 kW in the vertical mode. Therefore, the horizontal mode has 10.9% better heat transfer rate in comparison with the vertical mode. Figs. 9(a) and 9(b) show the temperature contour and stream lines for the horizontal mode, and Figs. 10(a) and 10(b) show the temperature contour and stream lines for the vertical mode in the case of disconnecting the side fan. As it is evident from these figures, the radiator No. 4 and a part of the radiator No. 3 are not cooled in the case of the side fan disconnection in the vertical mode, but in the horizontal mode, each fan cools a section of each reactor uniformly. Therefore, by disconnecting the side fan, the horizontal mode will have more reliability, which can be notable for designers. It can be even concluded that if there is a set containing 5 radiators with 28 ducts (which is usually used in very large transformers), then for the selection between the horizontal and the vertical modes for cooling applications, the more reliable one will be the horizontal mode. Because in the event of one of the fans disconnection in the vertical mode, a large part of the radiators will not be considered.



(a) (b)

Fig. 9. (a) Temperature contour, (b) Stream lines for the horizontal mode in the case of the side fan disconnection



(a) (b)

Fig. 10. (a) Temperature contour, (b) Stream lines for the vertical mode in the case of the side fan disconnection

Table 3

Comparison of the heat transfer rates in horizontal and vertical modes with other references

Previous References / Heat Transfer(kW)	Proposed	Ref.[17]	Ref.[18]	Ref.[19]
Horizontal Mode	56	73	46.24	223.06
Vertical Mode	51.4	68.1	43.58	209.08
Horizontal Superiority Percentage	8.9%	7.2%	6.1%	6.69%

5. Verification and validation

In reference [18], four radiator groups, each of them consists of 14 ducts, are used. The mentioned reference model has three fans with diameters of half a meter, possessing two different speeds. The number of meshes in the reference simulation is considered to be two million. In the mentioned paper, the attempt has been to make a comparison between the horizontal and vertical placement of the fans. The obtained heat transfer results for the two modes shows the superiority of 7.2% and 6.7% for the horizontal mode compared to the vertical mode. In Reference [19], again, five groups of radiators, each of them consists of 27 ducts, are used. The number of the fans is considered to be two with a diameter of one meter in this case. The results obtained from the comparison between two modes of horizontal and vertical placement indicate a superiority of 6.1% for the horizontal mode compared to the vertical mode. Furthermore, Reference [20], in addition to cooling procedure illustration of the power transformer radiator, and mentioning the difference between the natural and forced cooling of the airflow, compares the radiators cooling performance in the vertical and horizontal placement of the fans. This reference uses 5 groups of radiators, each of them consists of 30 ducts, and the assembly possesses three fans with a diameter of 0.6 m. The obtained results show 6.69% superiority for the horizontal mode compared to the vertical mode. In fact, the common point of all the three mentioned references, in addition to the cooling illustration of large-scale radiators, is the comparison between the horizontal and vertical placement of the fans, in which the results indicate the superiority of the horizontal mode compared to the vertical mode. Table 3 shows the comparison between the proposed results and the results of the mentioned references.

6. Conclusion

In this paper, in addition to investigation of the cooling performance of ONAF method, a comparison was made between two usual cooling modes. By placing three fans vertically and horizontally, it was concluded that the horizontal mode has a better heat transfer in comparison with the vertical mode. The heat transfer rate is 56 kW for the horizontal mode, while it is 51.4 kW for the vertical mode. This difference represents 8.9% superiority for the fans horizontal mode compared to the vertical mode. Moreover, the reliability of the power transformer radiators cooling system in the case of disconnecting one of the fans was investigated, which resulted in the following conclusions:

-By disconnecting the middle fan in both vertical and horizontal modes, the heat transfer rate is reduced compared to the case in which three fans are used. The heat transfer rate is 39.4 kW in the vertical mode and 40.2 kW in the horizontal mode, which indicates 2% superiority of the horizontal mode. By disconnecting

the middle fan in the vertical mode, each of the two other fans cools a part of their alongside radiator. In fact, the reason for the improved performance of the vertical mode in this case is the optimum point for placement of its two fans.
-By disconnecting the side fan, the heat transfer rate in the horizontal mode possesses so less variations compared to the case of disconnecting the middle fan, due to the fact that all of the radiators are encompassed by air flow. By disconnecting the side fan, the radiator is not cooled in its direction in the vertical mode, which shows its unreliability. Therefore, in the case of one of the fans disconnection in the vertical mode, a large part of the radiators will not be considered. The heat transfer rate is 36.7 kW in the vertical mode and 40.7 kW in the horizontal mode, which indicates that the heat transfer rate in the horizontal mode is 10.9% higher than the vertical mode.

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