HEAT DISSIPATION PERFORMANCE ANALYSIS AND STRUCTURAL PARAMETER OPTIMIZATION OF OIL-IMMERSED TRANSFORMER BASED ON FLOW-THERMAL COUPLING FINITE ELEMENT METHOD

by

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In this paper, a coupled flow-thermal field simulation model is established based on the parameters of the transformer. Then the distribution of the flow and thermal fields are obtained. The results show that oil backflow occurs to varying degrees at the top and bottom of the transformer. In addition, with the formation of backflow, the hot spot temperature of the transformer increases. Through the combination of orthogonal experiments and finite element method, the geometric structure of winding oil passage is selected as the optimization variable. The law between the winding structure and the maximum temperature is acquired by means of range and variance analysis, and the optimal parameters are obtained. The hot spot temperature is reduced by 34.27 K compared to the pre-optimization period, which is a guideline for the design of transformers.

Key words*: transformer, flow-temperature field, orthogonal experiment, oil backflow, oil channel*

Introduction

As an important equipment in the power system, transformer plays the role of voltage transformation in the links of power generation, transmission and distribution. In the actual operation process, The transformer often burns down. The relevant research reveals that high temperature rise of winding is one of the main reasons. According to GB/T 1094.7-2008 load guidelines for oil-immersed power transformers [1], the aging rate of the transformer will be doubled with the increase of 6 °C in temperature. For oil-immersed transformer, its overall structure is complex. The winding heat dissipation process is complex, involving heat conduction, heat convection and heat radiation [2]. Therefore, it is overwhelmingly important to accurately acquire the temperature rise distribution of the transformer winding and to carry out the optimization research of the structural parameters of the winding. At present, there are quite a few researches on the winding temperature of oil-immersed transformer. Among them, the most widely used is the empirical model of transformer winding hot spot temperature recommended by IEEE STD C57.91-1995 [3]. In order to obtain the hot spot temperature of the winding, the model calculates the ambient temperature of oil-immersed transformer, top oil

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temperature and the temperature gradient between the temperature of the winding hot spots. This calculation method is relatively simple, but the error of calculation results is large. In [4], according to the different ventilation and heat dissipation conditions of transformers in indoor and outdoor, the indoor transformer top oil temperature thermal model is proposed, and the outdoor transformer top oil temperature thermal model is compared. In addition, a top oil temperature model based on thermoelectric analogy is proposed [5]. Nevertheless, the heat circuit model cannot accurately obtain the temperature distribution inside the transformer. Thus, it has great limitations in practical application. With the development of numerical analysis methods, a transformer winding temperature calculation model combining analytical method with numerical analysis and calculation was proposed in [6]. In [7], the finite element analysis software ANSYS was used to simulate the temperature field of 160 kVA oil-immersed transformer, and the temperature rise of the winding and oil inside the transformer was obtained. In [8], the finite element method was used to calculate the temperature field of transformers cooled by different oils. In [9], the 3-D temperature field distribution of transformers with and without shields was calculated using the finite element method. The influence of shielding layer on losses and transformer hot spot temperature was studied by comparing hot spot temperature calculated under different conditions. In [10], it establishes the field-path coupling model of the reactor and compares the finite element simulation results with the prototype test to illustrate the accuracy of finite element calculation. In [11, 12], it studied the temperature field of the winding and core of power transformer, respectively by establishing the finite element model. In [13, 14], it analyzed the temperature field of dry-type transformer and piezoelectric transformer through finite element method, and verified the accuracy of the results through prototypical test. Therefore, by using the finite element method to simulate the heat transfer process inside the transformer, the flow-temperature field distribution inside the transformer can be more accurately obtained.

In the practical transformer design, in order to ensure the economic performance of the transformer, it is necessary to accurately obtain the hot spot temperature of the transformer. In [15], a diversity-guided particle swarm optimization algorithm based on attraction-repulsion mechanism is proposed to solve the problem that particle swarm optimization algorithm is prone to prematurity. Furthermore, it is applied to the optimization design of column-type air-core reactor. Nevertheless, this model has the problems of the large amount of computation and long computation time. In [16], the artificial neural network is used to predict the oil surface temperature of the transformer. However, as the neural network adopts the principle of empirical risk minimum, the minimum expected risk cannot be guaranteed. At the same time, the neural network optimization process can rarely guarantee convergence to a certain point, and cannot get the global optimal solution. In [17], genetic programming hot-spot (GP-HS) model is established to predict the hot spot temperature of tractional transformer, but when the load alters greatly, the prediction error is large. In [18], a Takagi-Sugeno based model was established to calculate the hot spot temperature rise of transformer winding. The calculation method is complicated since the parameters of the model are determined by the fuzzy C-means clustering algorithm and the parameters of the model are identified by the weighted least square method off-line. In [19], the hot spot temperature is reduced by adjusting the airway width of the dry-type transformer. However, this method requires doing various parameters tentatively, and the principle is not clear and the calculation is heavy.

In this paper, based on the analysis of transformer loss and transfer of heat, the finite element simulation software COMSOL is used to establish the coupling simulation model of flow-temperature field of oil-immersed step-down transformer. Based on the finite element analysis, the flow-temperature field inside the transformer is obtained, and the influence of different winding oil channel structure design on the distribution of the temperature field is further studied. Through orthogonal experiment, the influence of oil channel parameters on the maximum temperature of transformer is obtained. And the combination of oil channel parameters to minimize the local temperature is determined.

Transformer structural parameters and equivalent model

Basic structure of transformer

The oil-immersed step-down transformer is mainly composed of winding and cores. Among them, the winding consists of primary winding and secondary winding, where each winding is composed of three layers of coils. Each layer of the coil is made of multi-turn metal wire wound, that conductor material is copper. The winding is separated by the vertical oil channel, which plays the role of insulation and heat dissipation.

The 2-D equivalent model

The main parameters of primary and secondary winding of oil-immersed step-down transformer are as follows. The thickness of the winding is 0.058 m and the height is 1.3 m. The turns of the winding coil are 1760 and 168, respectively. In particular, the core is a cylinder with two oil channels in both the primary and secondary winding. The inlet and outlet of transformer oil flow are, respectively located at the upper and lower parts of the transformer oil tank body, and the oil flow inlet radius is 0.03 m. According to the aforementioned structural parameters of oil-immersed transformer, the model is simplified into a 2-D axisymmetric model, as shown in fig. 1.

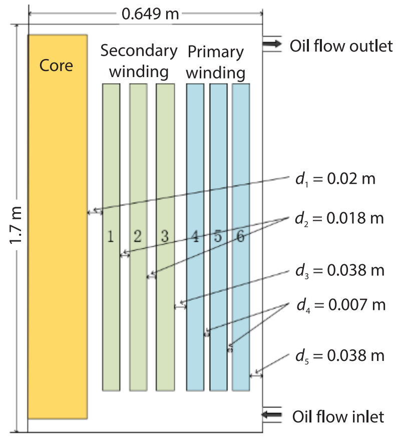

Figure 1. Cross-section of oil-immersed step-down transformer

Temperature field simulation calculation of transformer

Calculation of Loss and Heat Source

In order to accurately calculate the temperature rise of transformer, it is necessary to accurately calculate the loss of transformer. The loss of transformer mainly includes core loss and winding loss [20].

Core loss: the iron loss value of the core material used in this paper at 50 Hz:

$$P_{\text{core}} = k_{\text{core}} G \tag{1}$$

where G is the core weight and k_{core} – the iron consumption coefficient, which generally ranges from 1.1-1.3.

Winding loss: the transformer winding loss mainly includes the resistance loss and eddy current loss. The resistance loss of a single winding coil of the transformer can be expressed:

$$P_{\text{coil,i}} = I_i^2 \frac{2\pi R_i W_i}{\kappa S_i} \tag{2}$$

where $P_{\text{coil},j}$, I_i, R_i, W_i, and S_i are, respectively, the resistance loss, current, radius, number of turns, and cross-sectional area of the coil at the i layer and κ – the electrical conductivity of a metal conductor.

Eddy current loss: the winding eddy current loss of a single-turn wire can be expressed:

$$P_{\text{eddy},i} = \frac{2\pi R_i W_i \kappa \omega^2 a_i b_i}{12}\left(a_i^2 B_{z,i}^2 + b_i^2 B_{r,i}^2\right) \tag{3}$$

where $P_{\text{eddy},i}$ is the eddy current loss of single-turn wire of layer i coil, a_i and b_i are the radial width and axial height of the i layer coil, respectively, and $B_{z,i}$ and $B_{e,i}$ are the axial and radial components of the magnetic induction intensity of the i layer coil at this position, respectively.

According to eq. (3), eddy current loss of transformer winding is related to magnetic induction intensity, and transformer flux density distribution is obtained through simulation, as shown in fig. 2.

According to the structural parameters of transformer winding, combined with the eqs. (1)-(3), the loss of each component can be calculated.

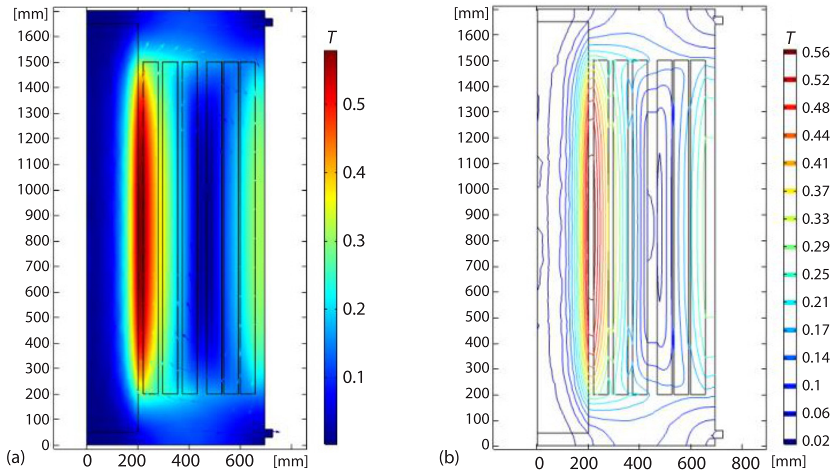

Figure 2. Transformer flux density distribution; (a) flux density distribution at *t* = 0.005 seconds and (b) flux density at *t* = 0.005 seconds

Governing equation

In the actual operation of transformer, the heat generated by winding and core diffuses outward, including heat conduction, heat convection and heat radiation. Heat diffuses from the interior of the windings and cores to the surfaces of the windings and cores by heat conduction. The heat from the surfaces of the windings and cores is then diffused by heat conduction into the transformer oil near the windings and cores. Then, the heat of the transformer oil near the winding and the core diffuses to the inner surface of the tank in a convective heat transfer way. At the same time, there is heat radiation between the winding and the core surface [14].

Material parameter setting

In the simulation of transformer temperature field, parameters of winding metal conductor, core material and flow need to be set. The winding, core and flow area in the model are set according to the parameters of copper, silicon steel and transformer oil, respectively. The material properties of each part are shown in tab 1.

Table 1. Transformer material parameters

Material	Features	Value
Winding (copper)	Thermal conductivity [$Wm^{-1}K^{-1}$]	$1342.77 \cdot 10^6/(3434200 - 391T)$
	Specific heat volume [$Jkg^{-1}K^{-1}$]	385
	Density [kgm^{-3}]	8940
Iron core (silicon steel)	Thermal conductivity [$Wm^{-1}K^{-1}$]	72
	Tpecific heat volume [$Jkg^{-1}K^{-1}$]	446
	Density [kgm^{-3}]	7550
Transformer oil	Thermal conductivity [$Wm^{-1}K^{-1}$]	$0.134 - 8.05 \cdot 10^{-5}T$
	Specific heat volume [$Jkg^{-1}K^{-1}$]	$-13408.15 + 123.04T - 0.33T^2$
	Density [kgm^{-3}]	$1055.05 - 0.58T - 6.4 \cdot 10^{-5}T^2$
	Dynamic viscosity [$kgm^{-1}s^{-1}$]	$91.45 - 1.33T + 0.01T^2$

Boundary condition setting and computational mesh

In the transformer simulation model, the lower side boundary of the oil flow inlet is inflow, with a normal inflow velocity of 1.5 m/s and a temperature of 303.15 K. The upper boundary line of the model oil flow outlet is transformer oil flow out. The left boundary of the whole model is set as the axis of symmetry. The tank boundary of the model, set as thermal insulation, is defined as the environmental parameter (standard atmospheric pressure, room temperature 295.15 K). In order to take into account the speed and accuracy of the simulation calculation of the flow-temperature field, the mesh is relatively dense near the edge of the core, the winding and the fuel tank. Meanwhile, other parts of the mesh are coarser.

Multiphysics field analysis

In order to solve the temperature distribution inside the transformer, the multi-physical field coupling flow chart in this paper is shown in fig. 3.

In this paper, a circuit – magnetic circuit finite element simulation model is established, and the magnetic field distribution and loss distribution of oil-immersed transformer are obtained. On this basis, the finite element simulation model of flow-temperature field is established. The average loss of the transformer in a period is used as the heat source of the transformer and loaded into the fluid-temperature field. At the same time, according to the influence of fluid temperature on the electrical conductivity of the winding, the flow distribution and temperature distribution of the oil-immersed transformer are obtained by two-way coupling.

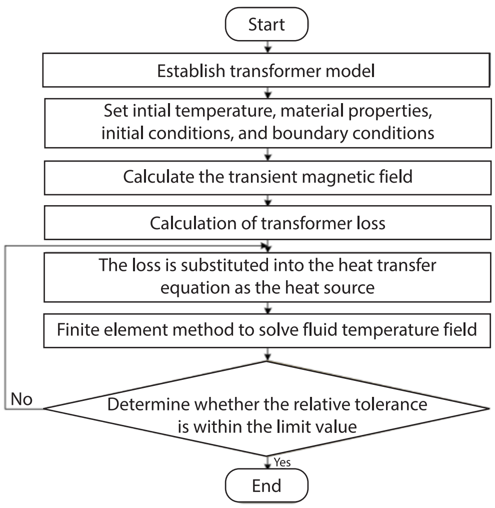

Figure 3. Flow chart of multi-physical field coupling of oil-immersed step-down transformer

Results of numerical simulation

According to the electrical parameters and structural parameters of oil-immersed transformer, and combined with the flow-temperature field simulation method, the simulation model is established. After setting the material parameters, heat source, boundary conditions and meshing of the model, the simulation results of temperature field and flow field obtained are shown in fig. 4.

Figure 4 shows the temperature field distribution of oil-immersed transformer at $t = 10$ hours, and it can be considered that its temperature reaches a stable state. The maximum temperature is 368.38 K, which is located in the fifth layer coil. Because the density of the transformer oil becomes smaller after heating, the transformer oil at a higher temperature will continue to move upward, so the temperature is higher at the upper end of the core and the winding. Moreover, due to the large loss of the primary winding and the limitation of the width of the oil passage, the temperature rise of the primary winding is higher, and the fifth layer winding is located in the middle of the primary winding, far from the tank wall, with poor heat dissipation ability and the highest temperature rise.

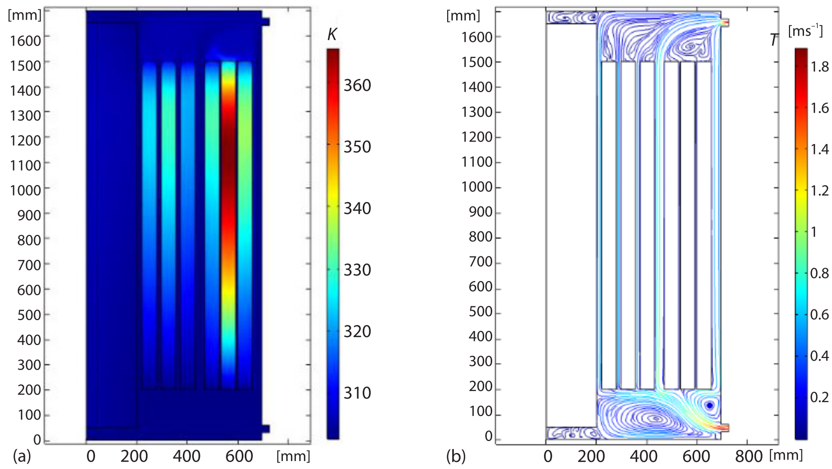

Figure 4. Results of numerical simulation of flow field and temperature field; (a) results of temperature field and (b) results of flow field

In order to analyze the temperature field distribution characteristics of oil-immersed transformer, the temperature distribution results along different paths are extracted, and the selected paths are shown in fig. 5(a).

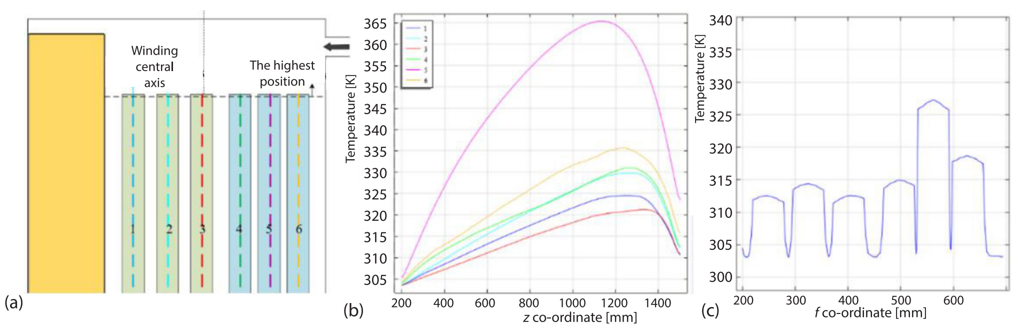

Figure 5. Selection of the temperature distribution; (a) selection path diagram, (b) winding axis temperature distribution, and (c) the highest position temperature distribution

As can be seen from fig. 5(b), on the central axis of the winding, the winding temperature gradually rises with the increase in height, and slightly decreases at the end, mainly because the heat dissipation at the end of the coil is more sufficient. As can be seen from fig. 5(c), the fifth layer coil at the highest position has the highest temperature, and the temperature inside the winding is slightly higher than that outside because the winding side near the oil passage has better heat dissipation.

Mesh independence study

At the same time, mesh independence study is carried out, and hot spot temperatures with different numbers of meshes are given in tab. 2. It can be inferred that when the number of nodes is 30956, the temperature rise reaches a stable value.

Table 2. The hot spot temperature under different meshes

Number of nodes	9688	14892	19641	24738	30956
T_{max} [K]	366.98	367.21	367.84	368.38	368.38

The optimal design of transformer winding structure

According to the aforementioned analysis, the highest temperature rise of oil-immersed transformer winding is mainly concentrated in the winding region. The maximum temperature of the iron core is significantly lower than that of the winding. Therefore, it is necessary to optimize the structural parameters of the transformer winding to reduce the transformer temperature.

Orthogonal experimental design and results of the numerical calculation

Combined with the structural characteristics of the transformer, the structural parameters that may affect the temperature rise of the transformer windings are screened out. It is mainly the distance between the winding and the core, the winding and the winding, the distance between each layer in the oil channels. They are d_1, d_2, d_3, d_4, and d_5, as shown in fig. 1.

The heat source of each part is set to a fixed value because changing the width of oil passage has little effect on the transformer winding loss. Orthogonal experimental design is used to select five factor levels for each parameter, as shown in tab. 3. Orthogonal experimental design is a design method to study multi-factors and multi-levels. It is to select some representative points from the comprehensive test according to the orthogonality, and analyze the results to find the optimal level combination.

Table 3. The orthogonal experimental design structural parameters

Level	Quality characteristics				
	d_1 [mm]	d_2 [mm]	d_3 [mm]	d_4 [mm]	d_5 [mm]
1	16	14	34	3	34
2	18	16	36	5	36
3	20	18	38	7	38
4	22	20	40	9	40
5	24	22	42	11	42

As can be seen from the tab. 3, if each group is tested by permutation and combination, the required number of experiments is $5^5 = 3125$. In order to reduce the amount of calculation, the orthogonal experimental table with five factors and five levels is generated by statistical product and service solutions. Combined with the simulation calculation method of transformer temperature field, the maximum temperature of transformer under different parameters is shown in the tab. 4.

Table 4. Transformer hot spot temperature under different parameters

Case	Quality characteristics					T_{max} [K]	SNR
	d_1	d_2	d_3	d_4	d_5		
1	1	1	1	1	1	379.72	–51.59
2	1	2	2	2	4	370.58	–51.38
3	1	3	3	3	2	365.01	–51.25
4	1	4	4	4	5	355.16	–51.01
5	1	5	5	5	3	348.21	–50.84
6	2	1	4	5	4	344.68	–50.75
7	2	2	5	1	2	380.62	–51.61
8	2	3	1	2	5	370.26	–51.37
9	2	4	2	3	3	365.07	–51.25
10	2	5	3	4	1	355.65	–51.02
11	3	1	2	4	2	352.64	–50.95
12	3	2	3	5	5	345.67	–50.77
13	3	3	4	1	3	380.93	–51.62
14	3	4	5	2	1	382.01	–51.64
15	3	5	1	3	4	365.05	–51.25
16	4	1	5	3	5	365.33	–51.25
17	4	2	1	4	3	353.16	–50.96
18	4	3	2	5	1	345.77	–50.78
19	4	4	3	1	4	381.62	–51.63
20	4	5	4	2	2	371.20	–51.39
21	5	1	3	2	3	370.60	–51.38
22	5	2	4	3	1	365.71	–51.26
23	5	3	5	4	4	356.21	–51.03
24	5	4	1	5	2	345.30	–50.76
25	5	5	2	1	5	381.29	–51.63

The results of numerical analysis

The simulation results are studied by means of range analysis and variance analysis. When considering a factor in range analysis, it is believed that other factors have a balanced impact on the simulation results, so the difference between each factor and each level is caused by the factor itself [21]. The important order of the influence of various factors on the transformer temperature can be obtained by range analysis. The analysis of variance comprehensively considers the influence of each factor on the index. Through the analysis of variance on the obtained data, it is tested whether the two factors have significant influence on the index [22].

Range analysis

Table 4 shows transformer temperatures with different oil passage widths. It can be seen from the table that the width of oil passage has a significant effect on the temperature rise of the transformer. The highest local temperature of the transformer is 382.01 K, and the lowest local temperature is 344.68 K. In order to analyze the influence of transformer oil channel width on transformer hot spot temperature, the statistical analysis and contribution rate of the hot spot temperature parameters are shown in tab. 5.

Table 5. Performance statistics and parameter contribution rates

	d_1	d_2	d_3	d_4	d_5
PS_1	363.736	362.594	362.698	380.836	365.772
PS_2	363.256	363.148	363.07	372.93	362.954
PS_3	365.26	363.636	363.71	365.234	363.594
PS_4	363.416	365.832	363.536	354.564	363.536
PS_5	363.822	364.28	366.476	345.926	366.476
R_j	10.02	16.19	18.89	174.55	17.61
C_{oj}	0.042	0.068	0.080	0.736	0.074

The calculation process of performance statistics (PS) is explained take the performance statistics of d_1, PS_1 (d_1 with factor Level 1), as an example. In tab. 5, the case number is the average temperature of hot spots corresponding to 1, 2, 3, 4, and 5.

The range calculation of each parameter is shown:

$$R_j = \max(PS_a) - \min(PS_a), \;\; a = 1,2,3,4,5 \tag{4}$$

The contribution rate is calculated as shown:

$$Co_j = \frac{R_j}{\sum\limits_{j=1}^{5} R_j} \tag{5}$$

The influence of transformer oil channel parameters on hot spot temperature obtained from tab. 5 is shown in fig. 6.

As can be seen from fig. 6, with the increase of d_3, the hot spot temperature rises in an almost linear relationship. With the increase of d_4, the maximum temperature increases first and then decreases. With the increase of d_2, the maximum temperature first decreases and then increases, indicating an inflection point.

As can be seen from the tab. 5, parameter d_4 has the largest influence on the transformer hot spot temperature, up to 73.6%. The contribution rate of parameter d_1 is the least, which is only 4.2%.

Variance analysis

The signal noise ratio (SNR) of hot spot temperature is calculated by means of variance analysis:

$$SNR = -10\lg\left[T_{\max}^2\right] \tag{6}$$

The SNR calculated according to eq. (6) is shown in tab. 4.

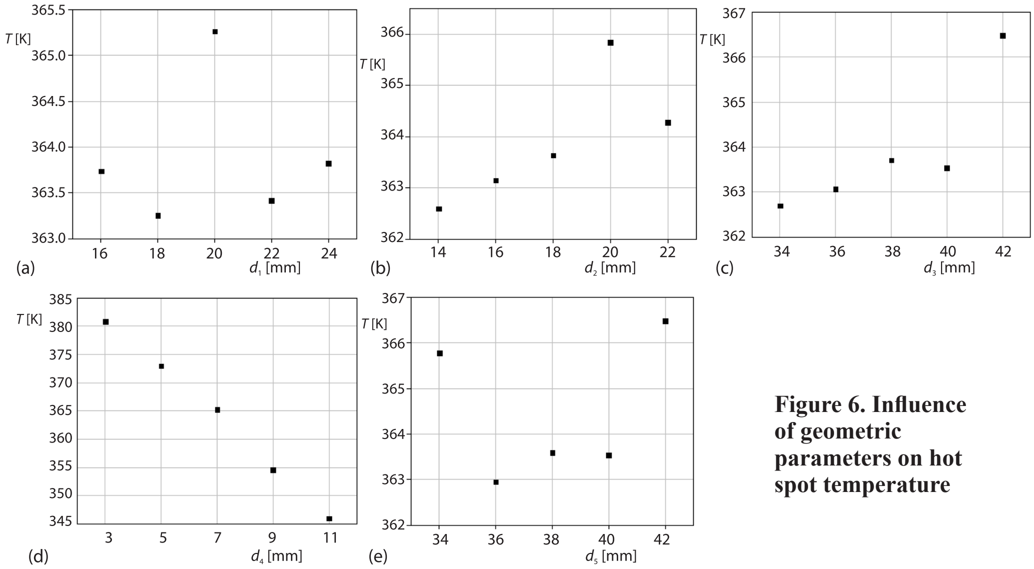

Figure 6. Influence of geometric parameters on hot spot temperature

Table 6. Results of analysis of variance

Source	Sum of squares	DoF	Mean square	F-value	Significant
d_1	0.007	4	0.002	1.167	0.442
d_2	0.017	4	0.004	3.012	0.155
d_3	0.025	4	0.006	4.43	0.089
d_4	2.233	4	0.558	396.29	0.000**
d_5	0.013	4	0.003	2.275	0.223

The significance level p is selected to determine the corresponding critical value to make a judgment on the significance. When significance $p < 0.01$, the factor is highly significant and is denoted as **. When the significance is $p < 0.05$, the factor is significant and is denoted as *. The results of analysis of variance are shown in tab. 6.

As can be seen from tab. 6, the F-value ordering of the five factors is: $d_4 > d_3 > d_2 > d_5 > d_1$. The significance level of d_1, d_2, d_3, and d_5 are greater than 0.05, which makes little contribution the maximum temperature of transformer. At the same time, the significance level of d_4 is highly significant. Therefore, changing d_4 has a significant effect on the maximum temperature of the transformer.

Results of the optimization and verification

Results of the optimization

In order to analyze the influence of different oil channels on temperature, the hot spot temperature of 15 K is taken as the temperature gradient, and the simulation results of the 6th, 10th, 2nd, and 14th experiments in the orthogonal experimental table are compared as fig. 7.

As shown in fig. 7, when the temperature rise of the transformer is the highest, the oil backflow trend at the bottom of the transformer is the same, but the backflow gradually forms at the top of the fifth layer winding as the temperature rises. Therefore, the temperature rise of the transformer is related to the backflow between the oil channels. By changing the geometric parameters of transformer oil channel, the backflow between oil passage can be effectively restrained.

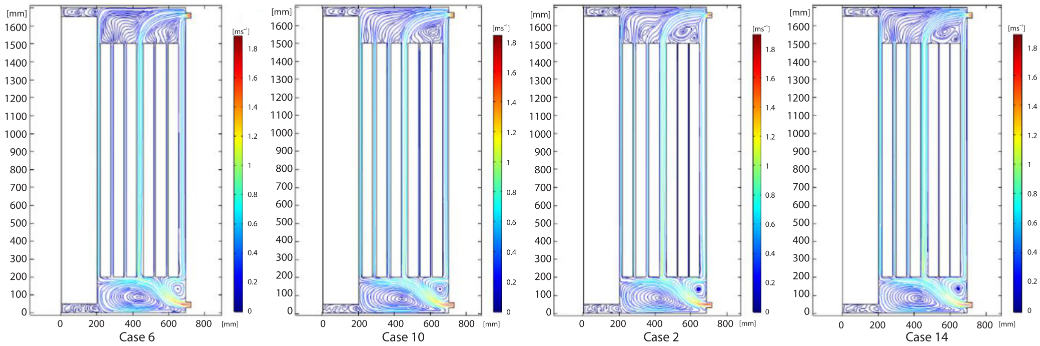

Figure 7. Transformer flow field distribution under different experiments

The width of the oil channel cannot be increased unlimitedly by the volume size of the transformer. The contribution rate of each parameter to hot spot temperature of transformer is obtained by orthogonal experiment. The geometric parameters of the minimum transformer hot spot temperature obtained are shown in tab. 7.

Table 7. Optimal structural parameters

Case 26	d_1	d_2	d_3	d_4	d_5
Value [mm]	18	14	34	11	36

Verification of the numerical simulation

A new set of parameter combinations is obtained according to the optimal structural parameters (Case 26). The hot spot temperature is 334.11 K after the flow-temperature field simulation calculation. As can be seen from fig. 8, the maximum temperature of transformer winding can be reduced when the geometric parameters of transformer oil channel are the optimal combination.

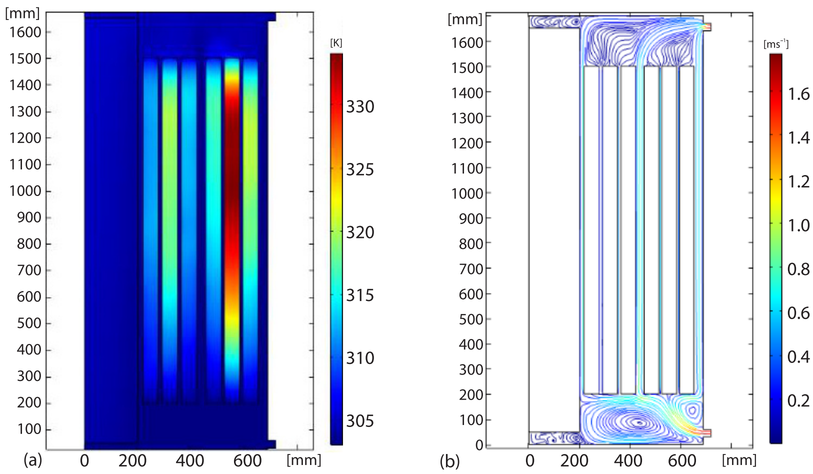

Figure 8. Flow field and temperature field distribution of transformer under optimal geometric parameters; (a) temperature field and (b) flow field

Conclusions

A simulation model of flow-temperature field for oil-immersed transformer is established in this paper. Orthogonal experimental method is used to obtain the influence rule of different winding structural parameters on the hot spot temperature of transformer, and the following conclusions are as follows.

- The detailed flow-temperature field distribution of the transformer is obtained. At the top and bottom of the transformer, there are different degrees of backflow, which is the main reason for the local temperature rise of the transformer.
- The structure parameters of transformer winding have significant influence on transformer temperature. Based on the orthogonal experiment method, the influence rule of transformer structure parameters on the maximum temperature is obtained, among which d_4 has a significant influence on the maximum temperature of transformer, while d_1 has no significant influence on the maximum temperature of transformer. Therefore, attention should be paid to d_4 in transformer design.
- The best combination of oil channel parameters is obtained by analyzing the orthogonal experiment results through range and variance analysis. The results show that the hot spot temperature is down to 334.11 K, decreased to 34.27 K compared with the hot spot temperature before optimization. Therefore, the optimization method can significantly reduce the temperature rise of transformer.

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