# Study on Oil Flow Characteristics and Winding Temperature Distribution of Oil-immersed Transformer

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Received 05 March 2021; Accepted 08 March 2021;
Publication 17 April 2021

## Abstract

The stability and effective functioning of a power grid depend upon the reliability as well as safety prospects of a transformer which is the principal component of the power system. The natural oil circulation in the oil-immersed transformer drifts the oil flow by the change in the density which is again caused by the change in temperature. But the pressure is comparatively low with respect to the oil pump causing the lower down of velocity which in turn dissipates unimpressionable heat. In this paper, a noble attempt has been made to build a natural oil circulation layer-type winding transformer based on a fluid-solid coupling heat transfer model pertaining to the internal temperature field and flow field by using the fluid mechanics' simulation software. In the next stage, the authors have analyzed the temperature distribution, hot

*Distributed Generation & Alternative Energy Journal, Vol. 35_3,* 173–194.
doi: 10.13052/dgaej2156-3306.3531

spot, position condition of the variable winding, the horizontal the oil channel width as well as the temperature of the winding transformer. The paper is of great significance as it examines the influence of the flow characteristics of oil channel on the winding temperature distribution. The outcome can significantly improve the structure of heat dissipation and the operating environment of the transformer.

**Keywords:** Oil-immersed transformer, fluid-structure coupling, horizontal oil channel, winding temperature rise.

## 1 Introduction

Power transformers constitute the most critical power equipment in power systems. The stability of their operating state directly affects the safety of the whole power system. According to statistics, accidents caused by power transformers in the distribution system accounted for 90% [1]. The fault caused by the transformer winding accounts for more than 70% [2–4] attributed to the high frequency of failure. This is because the losses generated during the operation of the transformer will cause the internal temperature of the transformer to rise. In this process, the iron core, the windings, and the internal parts are in a high-temperature condition for a long time. According to the National Standard of the People's Republic of China GB1094.2-2013 [5], for the A Class insulation material used in oil-immersed transformers, the service life of the transformer will be shortened by half for every 6°C increase in the winding temperature in the range of 80°C to 140°C. The windings of the power transformer are mostly pie-type structures, and the horizontal oil channel is the main cooling channel between the windings, and the horizontal oil channel width has a large influence on the convective heat transfer between the transformer windings and the interstitial oil flow [6, 7].

In 2013, Dursun applied fluid dynamics calculation software 'Comsol' to simulate oil-immersed transformer flow field and discussed the influence of transformer oil properties on winding temperature variation is discussed [8]. In 2013, Wang et al. used Fluent to build a two-dimensional model for a non-steering transformer with a vertical oil channel in order to obtain a horizontal oil channel velocity vector [9]. Guo et al. built a two-dimensional model of the oil channel and winding, and changed the vertical oil channel width for calculation and analysis. It was found that the average temperature rise of the winding was significantly reduced when the vertical oil channel width was increased [10]. In 2015, Chen et al. used Fluent to calculate the two-dimensional flow field of the transformer and set a different number of oil baffles for the transformer. It was found that the distribution of the temperature field was ideal when 9 sets of oil baffles were set up [11]. In 2015, Li et al. proposed using the electromagnetic-fluid-temperature coupling method to perform simulation calculations, and the loss of internal heat source was attributed to the fluid-temperature field coupling analysis. The winding calculation model takes the 1/48 3D model of the overall model. The rise in temperature and position of the winding hot spot can be determined by calculating the temperature rise and oil flow distribution of transformer windings through the finite volume method [12]. In 2017, Xu et al. simplified the winding calculation model and calculated its winding temperature using the fluid network method [13].

This paper takes the model of SZ11-10000/35 three-phase double-winding load-regulating power transformer produced by a company in Yunnan as the research object, theoretically analyzes the heat source and the internal heat transfer principle of the transformer, and analyzes the oil flow without an oil channel. The numerical calculation of the temperature distribution of the winding is carried out. Considering the change of the physical property parameters of the transformer oil under temperature change, a numerical model of three-dimensional heat transfer inside an oil-immersed transformer was established. In this research work, the Fluid mechanics' simulation software ANSYS CFX has been adopted for simulation of the heat flow coupling in the winding area of the transformer and analysis of oil flow situation at different width levels. This also measures the impact of the rise of temperature on winding. The fiber winding temperature measurement means (temperature sensor) is used to directly detect the temperature of the transformer winding, and the experimental results are compared with the simulation results to verify the validity of the simulation results.

## 2 Oil-immersed Transformer Structure and Heat Source Analysis

As an important equipment in power transmission and transformation systems, oil-immersed transformers are mainly composed of iron cores, windings, fuel tanks, etc. The structure diagram is shown in Figure 1. When the transformer is functioning, the core and windings generate losses and transfer heat to the transformer oil, so they can be used as a heat source in the internal temperature and oil flow calculation of the transformer [14]. The loss in the transformer consists of the idling loss generated by the iron core and the load

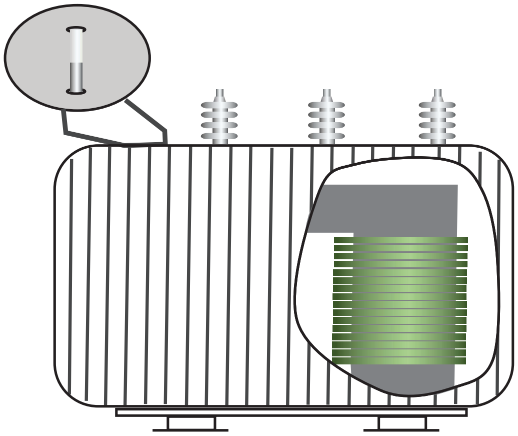


**Figure 1** Oil-immersed transformer structure diagram.

loss generated by the high and low voltage windings, which is expressed by the following formula [15]:

$$P_T = P_L + P_C \tag{1}$$

where $P_T$ is the total loss, $P_L$ is the load loss, $P_C$ is the idling loss.

The idling loss is mainly composed of the hysteresis loss and eddy current loss of the core. Hysteresis and eddy current loss are related to material quality and magnetic density of silicon steel sheet [16]. Hysteresis loss due to hysteresis in ferromagnetic materials during repeated alternating magnetization. Its magnitude is proportional to the square of the maximum magnetic induction density of hysteresis coefficient, alternating magnetization frequency, the core volume and alternating flux. Hysteresis loss can be expressed by the following formula

$$P_h = \gamma f B_{\max}^2 V \tag{2}$$

where $\gamma$ is the hysteresis coefficient of the core material, $f$ is the frequency, $B_{max}$ is the maximum magnetic induction density of the core alternating magnetic flux, $V$ is the total volume of the core.

Eddy current loss is not only related to induced potential and maximum magnetic density, but also to the resistivity and thickness of the silicon steel sheet. Therefore, in the design and manufacture of the iron core, reducing the thickness of the silicon steel sheet can reduce eddy current loss, and the eddy

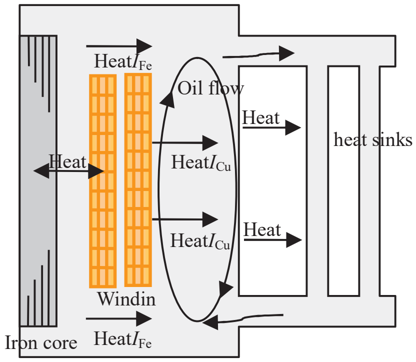


**Figure 2** Transformer structure and heat dissipation diagram.

current loss Pe can be expressed as

$$P_e = \gamma d^2 f^2 B_{max}^2 V \tag{3}$$

where $d$ is the thickness of the silicon steel sheet. Therefore, the idling loss $P_C$ is:

$$P_C = P_h + P_e = \gamma f B_{max}^2 V + \gamma d^2 f^2 B_{max}^2 V \tag{4}$$

The load loss of the transformer, also known as copper loss [17], is the loss generated when the primary and secondary windings respectively flow through their respective load currents. During the operation of the transformer, the load loss is

$$P_D = 3I_{1N_\varphi}^2 r_{1,75^\circ\mathrm{C}} + 3I_{2N_\varphi}^2 r_{2,75^\circ\mathrm{C}} \tag{5}$$

where $P_D$ is copper loss, $I_{1N_\varphi}$ and $I_{2N_\varphi}$ are the phase current of the primary and the secondary winding, respectively, $r_{1,75^\circ\mathrm{C}}$ is the total resistance of the primary winding at 75°C, and $r_{2,75^\circ\mathrm{C}}$ is the total resistance of the secondary winding at 75°C.

Through the analysis of the heat generation and heat conduction of the transformer, both the iron core and the winding generate heat. During this process, the transfer of heat takes place due to conduction and convection. In a similar process, the heat generated by the core and the windings are also transferred to the transformer oil. Then, the heat of the transformer oil is directly transmitted to the air through the tank wall. Similarly, transformer oil brings internal heat to the heat sink fins, which ultimately transfers heat to the air through the heat exchange between the heat sink and the air.

## 3 Fluid-solid Coupling Model of the Oil-immersed Transformer

The oil-immersed power transformer provided by Yunnan Tongchang Electric is used in this study. According to the actual core, winding structure and material parameters of the transformer, the finite element analysis software ANSYS is used to establish the three-dimensional temperature calculation model of the core and winding.

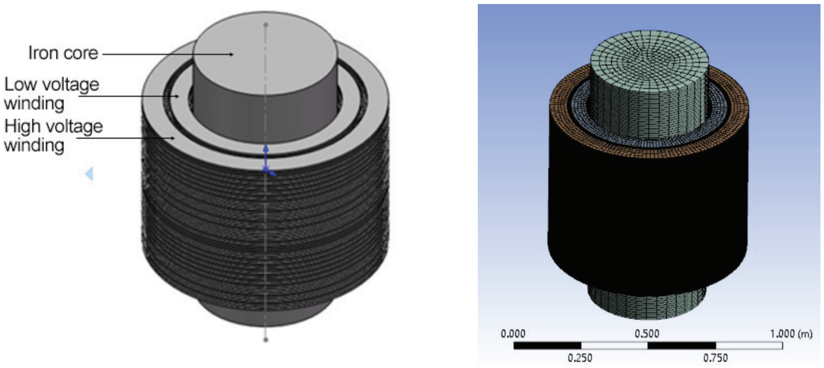
Establishing a three-phase model of the transformer, the core is simplified into a cylinder, the outside is low and high voltage winding, the high-low voltage winding is 55 layers, the winding height of each layer is 7.5 mm, and the oil channel height between each layer 2 mm, the total height of the winding is 520.5 mm. According to the actual parameters of the iron core and the winding the simplified three-dimensional physical model of the transformer. The three-dimensional model is shown in Figure 3(a). The iron core is simplified into a cylinder. The division is divided into grids as shown in Figure 3(b).

**Table 1** Structural parameters of various components of the transformer

| Component | Structural Parameters | |
|---|---|---|
| Iron Core | Diameter | 440 mm |
| | High | 860 mm |
| | Three pillar center distance | 78 mm |
| Low Voltage Winding | Height per pie | 7.5 mm |
| | Total thickness | 56.5 mm |
| | Spacing from the core | 14 mm |
| High Voltage Winding | Height per pie | 7.5 mm |
| | Total thickness | 65 mm |
| | Spacing from the low voltage winding | 20 mm |
| Horizontal Oil Channel | High | 2 mm |

**Table 2** Transformer material properties

| Component | Material | Density ($kg/m^3$) | Thermal Conductivity (W/mK) | Specific Heat Capacity (J/kg K) |
|---|---|---|---|---|
| Iron core | Silicon steel | $7.42 \times 10^3$ | 21 | 485 |
| Low voltage winding | Copper | $8.93 \times 10^4$ | 398 | 386 |
| High voltage winding | Copper | $8.93 \times 10^4$ | 398 | 386 |



(a)Winding, iron core three-dimensional model (b) Meshing results

**Figure 3** Three-dimensional model of the iron core and winding.

The heat loss of each heat source is converted into body load, assume that the loss of the transformer core and winding is evenly distributed, and can be calculated and applied to the iron core according to the volume of the transformer core and the high and low voltage windings. The unit heat loss is 1074 W/m$^3$, and the unit heat loss of the high and low voltage windings is 64875 W/m$^3$.

If you want to accurately obtain the flow state of the transformer oil and the temperature rise of the winding, you need to establish a fluid-solid coupling heat transfer model to resolve the calculation, and the model needs to be simplified [16],

(1) The external environment of the transformer is constant as 25°C;
(2) Iron core and winding are evenly heated;
(3) Ignore the influence of other phase windings on adjacent windings;

The thermal lift force driving the oil circulation in the natural oil cycle is derived from the density change of the transformer oil, and the flow state of the transformer oil almost determines the heat dissipation effect inside the transformer. The material properties of the fluid need to be set before the model is numerically solved. The physical properties of transformer oil vary with temperature as shown in Table 3.

The temperature field of an object is a scalar field. The object temperature is generally expressed as a function of space coordinates and time, which can be expressed in a Cartesian coordinate system [18]

$$T = f(x, y, z, t) \tag{6}$$

**Table 3** Transformer oil physical parameters

| Physical Properties | Fitting Formula |
|---|---|
| Density (kg/m $^3$) | $\rho = -0.58\mathrm{T}+893.09$ |
| Dynamic viscosity (kg/můs) | $\eta = 8 \times 10^{-5}\mathrm{T}^2 - 4.8 \times 10^{-3}\ \mathrm{T}+0.1$ |
| Thermal conductivity (W/mK) | $\mathrm{k} = -8.049 \times 10^{-5}\ \mathrm{T}+0.133$ |
| Specific heat capacity (J/kgK) | $\mathrm{C} = 4.207\mathrm{T}+1763.4$ |

where $x, y, z$ is a space rectangular coordinate; $t$ is time. When the temperature difference exists in the iron core and winding in the solid domain, the microscopic particles undergo thermal motion and heat conduction occurs. In the heat conduction phenomenon, the heat passing through a given section is proportional to the temperature change rate perpendicular to the cross section in a unit of time. And the cross-sectional area, and the direction of heat transfer is opposite to the direction in which the temperature rises. The thermal conductivity of the solid domain satisfies Fourier's law

$$q = \frac{\Phi}{A} = -\lambda \frac{\partial T}{\partial n} n \tag{7}$$

where $q$ is the heat flux density; $\Phi$ is the conduction heat flow; $A$ is the cross-sectional area perpendicular to the heat transfer direction; $\lambda$ is the thermal conductivity.

In a rectangular space coordinate system, (7) can be expressed as

$$q = -\lambda_x \frac{\partial T}{\partial x} i - \lambda_y \frac{\partial T}{\partial y} j - \lambda_z \frac{\partial T}{\partial z} k \tag{8}$$

where $\lambda_x$, $\lambda_y$, $\lambda_z$ is the thermal conductivity of $x, y, z$ component in the direction.

For solids, the differential equation of heat conduction can also be expressed as

$$\frac{\partial T}{\partial t} = \frac{\lambda}{\rho c}\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}\right) + \frac{\Phi + S_h}{\rho c} \tag{9}$$

where $c$ is the specific heat capacity of the substance; $\rho$ is the density of matter; $S_h$ is the internal heat source in the object.

At the interface between the solid domain and the fluid domain of the transformer, the fluid-solid coupling between the iron core, the winding and the transformer oil is carried out by convection heat transfer. Convection heat transfer is actually a heat exchange process that occurs under the combined action of heat transfer and heat convection on fluid and solid surfaces, the premise of heat exchange is the temperature difference between the fluid and the solid surface. The basic equation describing the convection heat transfer heat q is the Newtonian cooling formula, which can be expressed as

$$q = \alpha \Delta T \tag{10}$$

where $\alpha$ is the surface convection heat transfer coefficient; ΔT is the temperature difference between the fluid and the solid surface.

In the measurement of fluid-solid coupling of the transformer, convection heat transfer occurs on the contact surface of the iron core, high and low voltage windings and transformer oil. Through the software, the convection heat transfer coefficient of the outer part of the tank wall has been calculated. In this context, the air contact part needs to be calculated manually.

The calculation formula of the convection heat transfer coefficient is [19, 20]

$$\alpha = \frac{N_u \lambda}{L} \tag{11}$$

$$N_u = \left\{ 0.825 + \frac{0.387 R_{al}^{1/6}}{[1 + (0.429/\Pr)9/16]^{8/27}} \right\}^2 \tag{12}$$

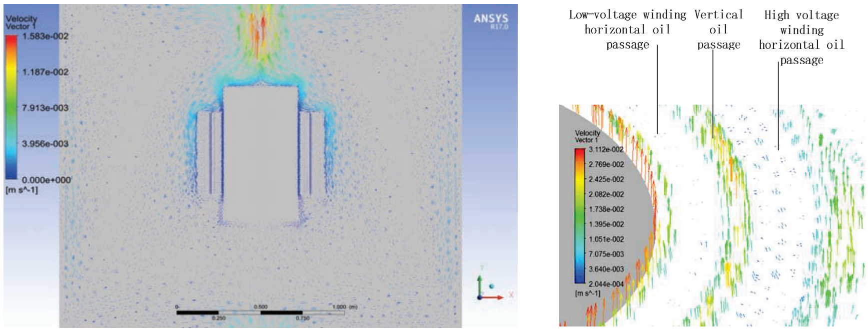
$$R_{al} = \frac{g\beta(T_w - T_\infty)L^3}{kv} \tag{13}$$

where *Nu* is the Nusselt number; *L* is the height of the tank wall, m; $\lambda$ is the thermal conductivity of the fluid. $P_r$ is the Prandtl number; $R_d$ is the Rayleigh number. *g* is the gravity acceleration; $\beta$ is the thermal expansion coefficient of air; $T_w$ is the tank wall temperature; $T_\infty$ is the air temperature; *v* is the dynamic viscosity of air.

## 4 Simulation Calculation and Analysis of Transformer Internal Temperature Field

After creating a two-dimensional interface in the CFX post-processing section CFX-Post, the XY section of the winding horizontal oil channel and the flow velocity diagram of the ZX section can be obtained shown in Figure 4.

It can be seen in Figure 4 that the oil flow rate of the horizontal oil channel is much lower than that of the vertical oil channel, and the oil flow rate of the



(a) XY section oil flow rate diagram (b) XZ section oil flow rate diagram

**Figure 4** Oil flow rate diagram of horizontal oil channel XY section and ZX section.

horizontal oil channel of the low-pressure winding is lower than the oil flow rate of the horizontal oil channel of the high-pressure winding. Due to the small pressure difference between the oil flows on both sides of the winding, the oil velocity in the horizontal oil channel between the two-wire layer is relatively low, which easily causes the oil flow to stagnate, forming a dead oil zone, causing the temperature of the wiring layer to rise to cause the local temperature of the transformer too high.

Through the solution calculation of the fluid-solid coupling heat transfer model of the transformer temperature rise and oil flow, the calculation results of the winding temperature distribution of the transformer single-phase three-dimensional model are obtained. Figure 5 shows the winding temperature distribution.

It can be seen from the three-dimensional distribution of the transformer winding that the temperature distributions of the high and the low voltage winding are approximately equal. Further, the temperature rise of the upper winding is the highest. As the winding height decreases, the winding temperature also decreases, which is mainly due to the convection of transformer oil. The heat dissipation causes the heat to flow upwards. The difference between the oil temperature and the winding temperature decreases in the wake of the height increases, and the heat dissipation effect deteriorates. This causes the temperature at the top of the winding to be higher than the lower part. Simultaneously, since the top of the winding is no more heating, and the oil channel is wide, besides, transformer oil has good heat dissipation conditions. Therefore, the winding hot spot temperature is located above the winding, but not at the top.

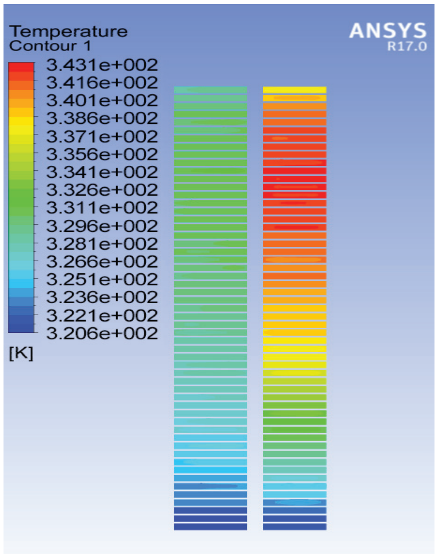


**Figure 5** Winding temperature profile.

## 5 Oil-immersed Transformer Layer Winding Temperature Rise Experiment

To accurately obtain the temperature variation of the transformer winding, besides, to verify the effectiveness of this calculation method for fluid-solid coupling, this paper conducts a temperature rise test for the oil-immersed transformer and uses the fiber Bragg grating temperature sensor to monitor the winding temperature of the transformer.

An FBG is essentially a wavelength-selective filter, which consists of a short segment of single mode optical fiber with a photo-induced periodically modulated index of refraction in the core of the fiber, as shown in Fig. 6. The Bragg wavelength $\lambda_B$ depends both on the physical characteristics of the fiber and geometrical characteristics of the gratin.

In the experiment [21, 22], with the aim to reduce the influence of the sensor on the temperature rise test result and accurately detect the winding temperature rise, the temperature sensor is installed in the block of the winding oil channel, leaving the sensor pigtail and placing the spacers on the winding temperature measuring point. Five temperature sensors are arranged in the winding from top to bottom. The installation method of temperature sensors is shown in Figure 7. The site construction is shown in Figure 8.

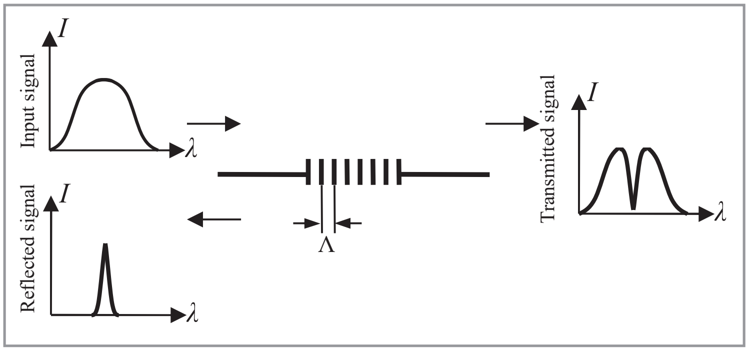


**Figure 6** Spectrum modulation schematic diagram of the optical fiber Bragg grating.

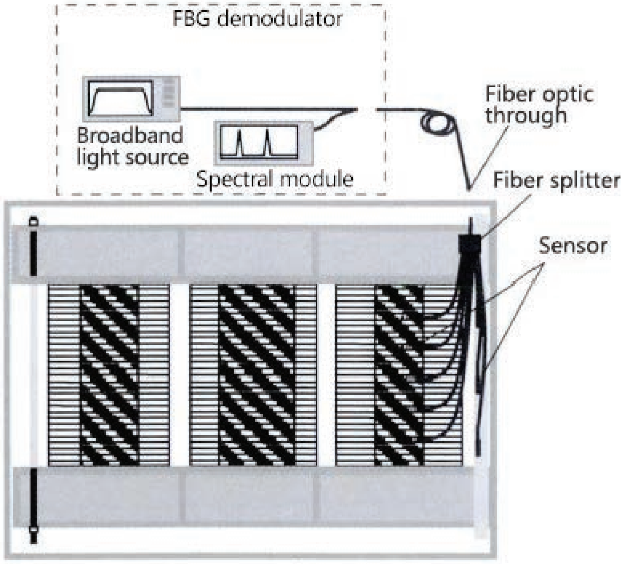


**Figure 7** Sensor installation and layout.

The experiment conducted temperature tests on windings of different heights. The experimental results are shown in Table 4 below.

Figure 9 is the graph of winding temperature as a function of winding position as a function of winding temperature rise simulation.

Since the parameter settings of the simulation calculation are different from the actual parameters and the environment, there are certain errors in the numerical calculation. It can be seen from the experimental data that

**（a）The clamping of the sensor in the winding** **（b）Sensor tail optical fiber**

**Figure 8** Installation photos of FBG temperature sensor.

**Table 4** Winding temperature rise experimental data and numerical calculation values

| Winding Position/cm | Experimental Data/K | Numeral Calculations/K |
|---|---|---|
| 1 | 323.65 | 322.21 |
| 7 | No | 325.88 |
| 13 | 329.35 | 328.59 |
| 25 | 335.35 | 336.11 |
| 37 | 339.75 | 340.59 |
| 45 | No | 342.51 |
| 49 | 340.85 | 341.31 |

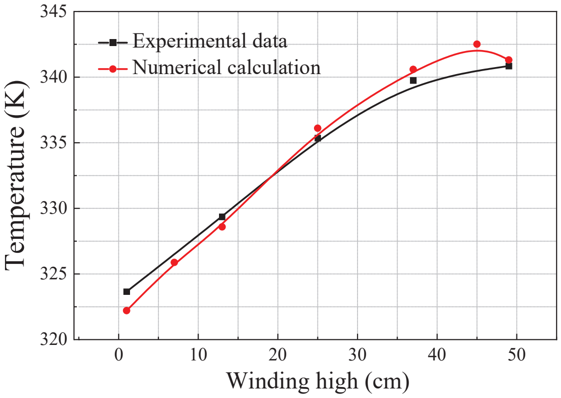


**Figure 9** Winding temperature rise numerical calculation curve.

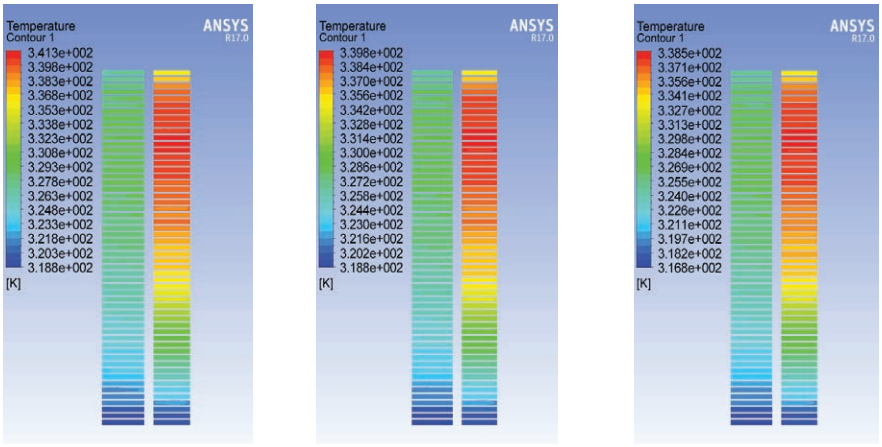
as the winding position increases, the winding temperature also rises. The position of the sensor closest to the hot spot temperature is 37 cm and 49 cm from the bottom. When the hot spot of the simulation curve is at 45 cm from the winding, the simulation is performed. The hot spot temperature obtained is the same as the measured temperature, so the measured temperature is slightly lower than the simulation result.

## 6 Study on the Influence of Horizontal Oil Channel Height on Winding Temperature Rise

In the design and manufacture of the oil-immersed transformer structure, reducing the height of the horizontal oil channel can reduce the winding height, save the winding material and reduce the manufacturing cost, but harms the heat dissipation of the transformer and the temperature rise of the winding. According to the design principle of the transformer winding, the height of the horizontal oil channel can provide more heat dissipation space, which is beneficial to heat dissipation.

In this paper, three-dimensional models of three types of transformers with horizontal oil channel heights of 3 mm, 4 mm, and 5 mm are established. Keeping the other settings unchanged, the fluid-solid coupling model of the transformer is calculated to obtain the winding temperature distribution at different levels of oil channel height. Figure 10 shows the temperature rise diagram of the transformer winding with a horizontal oil channel height of 3 mm to 5 mm. Figure 10 shows that the change in the horizontal oil channel height does not have much influence on the longitudinal oil temperature trend of the winding, and the winding hot spot position does not change, but the overall temperature rise of the winding is reduced, simultaneously, the temperature of the winding hot spot is also lowered. It helps to protect the voltage transformer insulation, thus extending the operating life of the transformer.

Figure 11 is a graph showing the temperature distribution of windings at different oil channel widths. It can be seen that as the height of the horizontal oil channel is widened, the winding temperature is reduced. This is because the heat exchange between the winding and the transformer oil is intensified, which reduces the temperature rise of the hot spot of the winding and rise of the average temperature. It can also be seen that changing the horizontal oil channel height, the high and low voltage winding temperature distribution remains unchanged, besides, the hot spot position of the winding will not



(a) The oil channel is 3 mm wide (b) The oil channel is 4mm wide. (c) The oil channel is 5mm wide.

**Figure 10** Temperature distribution of windings at different oil channel heights.

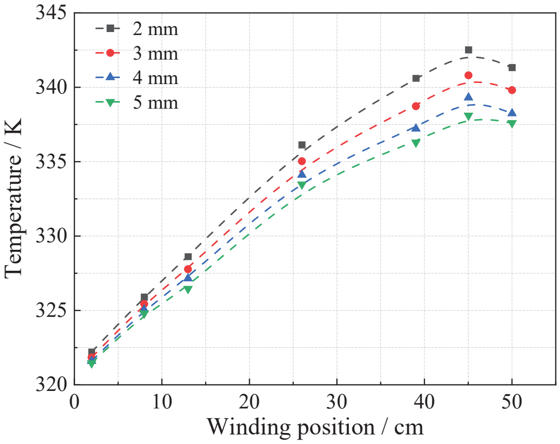


**Figure 11** Winding temperature profile of different oil channel widths.

alter. As the height of the oil channel increases further, the winding hot spot temperature rise trend is also slowing down, indicating that the increase of the oil channel height has a certain limit on the improvement of the oil flow of the oil channel and the effect of the temperature rise of the winding. The oil height channel is 2 mm. The oil flow and winding heat dissipation are greatly improved within the range of 4 mm. When the oil channel height is greater than 4 mm, the influences on the winding temperature rise and the oil flow is gradually reduced.

## 7 Conclusion

In this research work, the experiment pertaining to the rise in temperature for the oil-immersed transformer, using the basic theories of heat transfer and fluid dynamics, combined finite element simulation, a fluid-solid coupling heat transfer calculation model for the natural oil circulation oil-immersed transformer was established.

The simulation calculation and the actual measurement error are in the range of 1K, which proves that the numerical calculation model is feasible. On this basis, the influence of the horizontal oil channel oil flow velocity on the winding temperature distribution is analyzed. The results show that the oil flow rate of the horizontal oil channel of the low-pressure winding of the oil-immersed transformer is lower than the oil flow rate of the horizontal oil channel of the high-voltage winding, which leads to the temperature rise of the low-voltage winding is slightly higher than the high-voltage winding at the same height. Simultaneously, the oil flow velocity of the oil channel is different, resulting in the high and low voltage winding has different temperature distributions. As the width of the oil channel increases, the oil flow resistance between the line layers decreases which increases the oil flow rate. The convection heat transfer of the layers and the oil flow is therefore increased, and the hot spot of the winding is gradually reduced.

## Acknowledgment

This project was jointly supported by the National Natural Science Foundation of China under Grant 51667011, the Applied Basic Research Project of Yunnan province under Grant 2018FB095, and the National Natural Science Foundation of China under Grant 51567013.

## References

[1] Jian Liu, Jianli Ni, Yonghui Deng. Distribution automation system[J]. Power system equipment, 2003(8):14–15.
[2] Heathcote M J, Franklin D P, Peter D. The J & P transformer book: [M]. Butterworths, 1998.

[3] Bengtsson C. Status and trends in transformer monitoring[J]. IEEE Transactions on Power Delivery, 1996, 11(3):1379–1384.

[4] Power transformers part 7: Oil-immersed power transformer load guide[S], GBT 1094.7-2008.

[5] Yucheng Xie. Power Transformer Manual[M]. Beijing: Mechanical Industry Press, 2003.

[6] Chuanyi Liu. Power transformer design calculation method and practice[M]. Shenyang: Liaoning Science and Technology Press, 2002.

[7] Zhenchuan Wang, Xiuchun Wang. Numerical Simulation of Oil Flow Distribution in Oil Channel of Non-steering of layer-type Winding in Vertical Oil Channel of Large Transformer[J]. Transformer, 2013, 50(1):25–29.

[8] Zhenhua Wang. Study on Eddy Current Loss and Hot Spot Temperature of Large Transformer Windings[D]. Hebei University of Technology, 2014.

[9] Jichao Chen. Eddy current loss and temperature field analysis of large oil-immersed transformers[D]. Harbin University of Science and Technology, 2015.

[10] Dursun K. Oil and winding temperature control in power transformers[C]// Fourth International Conference on Power Engineering, Energy and Electrical Drives. IEEE, 2013:1631–1639.

[11] Longnv Li. Study on Oil Flow Distribution and Temperature Field of Natural Oil Circulation Transformer[D]. Shenyang University of Technology, 2016.

[12] Yongming Xu, Fei Xu. Temperature prediction of power transformer winding based on fluid network[J]. High voltage technology, 2017, 43(5):1509–1517.

[13] Xing Zhang. ODFS-334000/500 Numerical Simulation of Winding Temperature Field of Large Oil-immersed Power Transformer[D]. Dalian University of Technology, 2013.

[14] Chuanyi Liu. Power transformer design calculation method and practice[M]. Shenyang: Liaoning Science and Technology Press, 2002.

[15] Kening Yin. Transformer design principle[J]. electric equipment, 2003(5):56–56.

[16] Baoguo Wang. Heat transfer teaching[M]. Mechanical Industry Press, 2009.

[17] Teng Ma. Numerical Simulation of Temperature Field and Velocity Field of Oil-immersed Transformer[J]. Electrical application, 2016(10): 32–35.

## Biographies

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