# Two-Dimensional Numerical Simulation of Temperature Field Distribution in Transformer Windings

**Jianwen Zhu, Jianhua Zhang, Guoliang Li, Sen Li, Yuqing Lin, Zuhui Liang, and Chengzhen Li**

**Abstract** With the rapid development of economy, modern power industry demands more and more transformer capacity. The increase of transformer capacity leads to the increase of heat production during operation and the corresponding increase of operating temperature. It is very important to analyze and calculate winding temperature rise for transformer product development and operation maintenance. In this paper, based on the heat generation and heat dissipation conditions of transformer windings, the finite element equations of temperature field and flow field are established by applying the principles of heat transfer and fluid mechanics, and the distribution of temperature field of windings is further obtained.

**Keywords** Temperature field · Transformer · Winding losses

## 1 Introduction

With the rapid development of economy, the demand for electric energy in the whole society is increasing, and the capacity requirements of transformer in the modern power industry are increasing. The increase of transformer capacity increases the loss generated in the operation process of the transformer, and also further improves the operation temperature of the transformer [1–3]. The temperature rise of the transformer winding is too high from time to time, which easily leads to the damage of the transformer and affects the normal working condition of the transformer.

The hot spot temperature of winding is one of the biggest factors limiting the load capacity of transformer, and it is also one of the main reasons leading to the aging of transformer insulation materials. Therefore, the relevant standards for transformers at home and abroad stipulate that the average temperature rise of the winding and the hot spot temperature of the transformer during operation must be controlled below

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the specified value [4]. However, it is very difficult to accurately obtain the hot spot temperature of the transformer winding in operation, and the generation, conduction and loss process of heat inside the transformer is very complicated, so it is difficult to obtain the accurate winding hot spot temperature by analytical method. At present, there are three methods to obtain winding hot spot temperature [5]: The first is direct measurement method, which can be measured by optical fiber temperature sensor or thermocouple. However, it is difficult to ensure the accuracy because the location of winding hot spot mainly depends on experience. In addition, fiber optic sensors are expensive, so they are not widely used. The second is the prediction model based on thermoelectric analogy. The hot spot temperature is obtained by numerical calculation. However, because there are many nonlinear parameters in it, and it is difficult to determine these parameters reasonably, this method is not widely used. The third method is IEC354 and GB1094.2 standard recommended hot spot temperature analytical formula calculation method, which is more used in transformer design hot spot temperature approximate estimation method, but can't determine the distribution of temperature field.

For product development and operation, it is very important to analyze and calculate the temperature rise of transformer winding [6]. The traditional concept of average temperature rise neglects the influence of hot spot temperature on transformer and can't fully and accurately reflect the real condition of winding [7]. Therefore, based on the principles of heat transfer and fluid mechanics, the finite element equations of temperature field and insulating oil flow field of winding model are established in this paper. Through numerical calculation, the temperature of each point of the winding can be obtained, and the temperature field distribution of the whole transformer winding can be further obtained.

## 2 Heat Generation and Heat Dissipation Analysis

### *2.1 Heat Generation Analysis of Transformer Windings*

In order to further explore the temperature distribution characteristics of transformer winding, we adopt a solid model of small transformer winding without iron core, in which the box is a rectangular epoxy box. The resistance loss of the winding and the eddy current loss inside the winding are the main sources of temperature rise of the transformer winding. The expression is shown as follows:

$$P = P_R + P_{WL} = I^2 R + P_{WL} \tag{1}$$

where $I$, $R$ and $P_{WL}$ are the current, resistance and eddy current loss of transformer windings respectively. The formula for calculating unit heat source used in subsequent calculation is: $q = P/V$, $P$ is the measured active power loss; $V$ is the volume of the winding.

## *2.2 Heat Dissipation Analysis of Transformer Winding*

Heat dissipation of transformer windings is mainly realized through convection heat transfer, including natural convection heat transfer (for heat exchange between the outside of the transformer housing and the outside air) and forced convection heat transfer (for heat exchange between the transformer oil flow and the inside of the housing and the winding).

Natural convection heat dissipation mainly depends on the temperature difference between the two transfer, convection heat transfer coefficient and heat transfer area. Because of the regular geometry of the box, the mean value of the natural convection heat transfer coefficient $\alpha_1$ has little influence on the calculation results. The formula for calculating $\alpha_1$ is as follows:

$$\alpha_1 = C(\lambda/H)(Gr_m P_r)^n \tag{2}$$

where, $\lambda$ is the thermal conductivity of air; $H$ is the height of the box; $G_{rm}$ is Grashof number; $P$ is Prandtl number; $C$ and $n$ are constants.

The forced convection heat dissipation of oil flow and winding is more complicated than that of natural convection heat dissipation. This is due to the influence of many factors, such as the physical characteristics and flow mode of oil, heat generation rate and geometry of winding, as well as the spatial position of each winding, etc. Therefore, the $\alpha_1$ between each winding and oil is very different and cannot be approximated by average value. In addition, the oil flow mode can be divided into laminar flow and turbulent flow, which will seriously affect the heat transfer effect. The state and effect of laminar flow and turbulent flow are quite different, which can be judged by Reynolds number:

$$R_e = \rho V L_c/\mu \tag{3}$$

where, $\rho$ is fluid density; $V$ is the fluid velocity; $L_c$ is the characteristic size; $\mu$ is the absolute viscosity of the fluid. When $R_e < 2300$, the oil flow mode in the transformer is laminar flow; Otherwise, it is turbulence.

It can be clearly seen that the temperature distribution of transformer winding is greatly affected by the flow field. Therefore, it is necessary to combine the temperature field of transformer winding and the flow field of insulating oil to obtain a more ideal winding temperature distribution.

# 3 Differential Equations and Boundary Conditions

In order to better calculate the temperature field in transformer windings, the following four assumptions are made:

1. When heating and heat dissipation reach the equilibrium state, the temperature and velocity distribution of winding and oil no longer change with time;
2. The physical characteristics of transformer oil (such as density, dynamic viscosity, specific heat, etc.) are constant and incompressible;
3. The only heat source of the transformer model is the heating of the winding, and the calorific value per unit time per unit volume is fixed, and the heat transfer coefficient is uniform;
4. Constant ambient temperature.

The temperature and velocity fields of oil flow and heat dissipation are affected by mass, momentum and energy transfer, equations are shown as follows:

Continuity equation,

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \tag{4}$$

Momentum differential equation in the $x$ direction,

$$\rho\left(u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y}\right) = F_x - \frac{\partial P}{\partial x} + \mu\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2}\right) \tag{5}$$

Momentum differential equation in the $y$ direction,

$$\rho\left(u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y}\right) = F_y - \frac{\partial P}{\partial y} + \mu\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2}\right) \tag{6}$$

Energy differential equation,

$$\rho c_p\left(u\frac{\partial t}{\partial x} + v\frac{\partial t}{\partial y}\right) = \lambda_1\left(\frac{\partial^2 t}{\partial x^2} + \frac{\partial^2 t}{\partial y^2}\right) \tag{7}$$

where, $u$ and $v$ are velocity components of oil per unit volume in $x$ and $y$ directions respectively; $P$ is the pressure of unit volume oil; $\mu$ is the absolute viscosity of the fluid; $t$ is the temperature of unit volume oil; $F_x$ and $F_y$ are the components of the force in $x$ and $y$ directions on the unit volume oil; $c_p$ is the specific heat of transformer oil; $\lambda_1$ is the thermal conductivity of the winding.

Since the temperature field and the flow field need to be solved simultaneously iteratively, the boundary conditions are determined by the boundary conditions of the temperature field:

$$\begin{cases} -\lambda_1\left(\frac{\partial t}{\partial x} + \frac{\partial t}{\partial y}\right) = q \\ -\lambda_2\left(\frac{\partial t}{\partial x} + \frac{\partial t}{\partial y}\right) = \alpha_1(t - t_a) \end{cases} \tag{8}$$

and boundary conditions of flow field:

$$v = v_0, \quad P = P_0, \quad u = 0, \quad v = 0,$$

Among them, $q$ is the heat generation rate of winding; $\lambda_2$ is the thermal conductivity of the box; $\alpha_1$ is the natural convection heat transfer coefficient between the air and the outside of the box; $t_a$ is the temperature of the outside air; $v_0$ is the initial speed of oil at the transformer inlet; $P_0$ is the pressure at the outlet of transformer oil flow; $u$ and $v$ are the velocity components of the unit volume oil in the $x$ and $y$ directions on the surface of the stationary wall (including the inner side of the box and the winding in contact with the oil).

The temperature field and flow field are discretized into degrees of freedom of several nodes, and then the four differential equations listed above are converted into the corresponding variational problems. Under the boundary conditions of temperature field and flow field, cross iteration method is used to solve the problem. First, determine the speed, temperature and winding temperature of the transformer oil. Calculate natural convection heat (heat exchange between the outside of the box and the outside air) and forced convection heat (heat exchange between the inside of the box and the windings and the transformer oil) and compare them with the total heat production. If the two are not equal, the initial value is updated and the total heat lost is recalculated until the condition is met that it is equal to the total heat produced. The temperature sequence at this point is the desired temperature field.

## 4 Simulation Example of Temperature Field of Transformer Winding

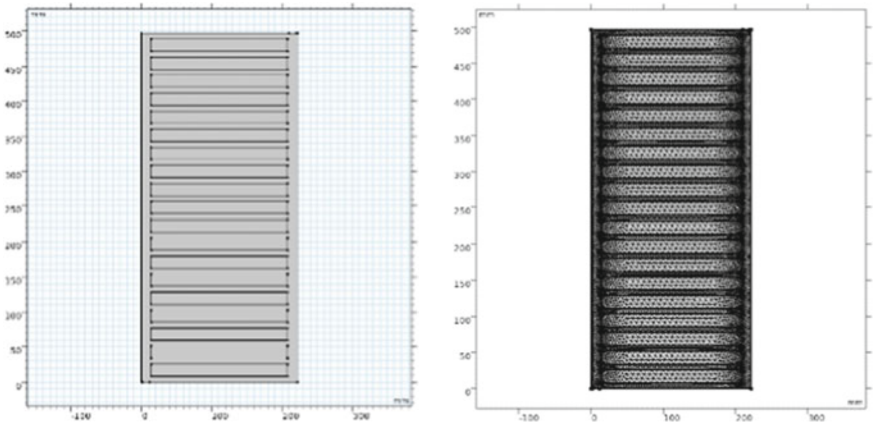
### *4.1 Two-Dimensional Finite Element Model of Transformer Winding*

The solid model of small transformer adopted in this paper has no iron core in its winding, and the specific data are shown in Table 1.

Since the length of the winding is much larger than the width of the vertical oil passage, the temperature field of the transformer winding and the insulating oil flow field nearby can be regarded as uniform in length direction, thus reducing the three-dimensional problem to a two-dimensional problem for processing. Figure 1a shows

**Table 1** Transformer model specific data

| Component | Quantity (pcs) | Length (mm) | Width (mm) | Height (mm) |
|---|---|---|---|---|
| Box | 1 | 1200 | 222 | 497 |
| Winding | 19 | 400 | 194 | 17.4 |
| Horizontal oil passage | 20 | – | – | 7.9 |
| Vertical oil passage | 2 | – | 10 | – |



(a) 2D finite element model of transformer.

(b) Grid profile of transformer.

**Fig. 1** In-plane displacement–time curves under single excitation

the two-dimensional finite element model of the transformer used to calculate the temperature and flow fields. The upper right corner is the oil outlet, and the lower left corner is the oil inlet.

## *4.2 Mesh Subdivision*

The grid division of the model will affect the accuracy and efficiency of the calculation. In general, the more grids are divided, the higher the accuracy of the calculation will be, but the efficiency will be reduced [8–11]. Considering that the model used in this paper is not complicated, two meshing methods, quadrilateral and triangle, are adopted. In addition, considering the influence of the flow boundary layer, higher density of the winding and the oil flow channel near the box wall and the oil flow outlet and entrance is divided. The subdivision of this example is shown in Fig. 1b. There are 10,860 grid vertices, 14,270 triangular grids and 2552 quadrilateral grids.

## *4.3 Parameter Setting*

For smooth simulation, parameters are set as follows: oil density is 821 kg/m$^3$; dynamic viscosity coefficient is 5.32829 mPa s; thermal conductivity of oil is 0.107 W/(m K); specific heat of oil is 2163 J/(kg K); The average thermal conductivity of winding is 0.78 W/(m K); the heat transfer coefficient between box wall and air is 1.2 W/(m$^2$ K).

The boundary conditions [12] to be introduced are:

1. The temperature of the outside air is constant at 293 K;
2. $v_0$ has only a $y$ component, and $v_y = 0.297$ m/s;
3. The inlet temperature of oil is 334.25 K;
4. The relative pressure at the outlet is 0;
5. $u$ and $v$ at static wall surface are 0;
6. According to the loss of the transformer winding, the heat source density of the winding is $1.457 \times 10^5$ W/m$^3$.

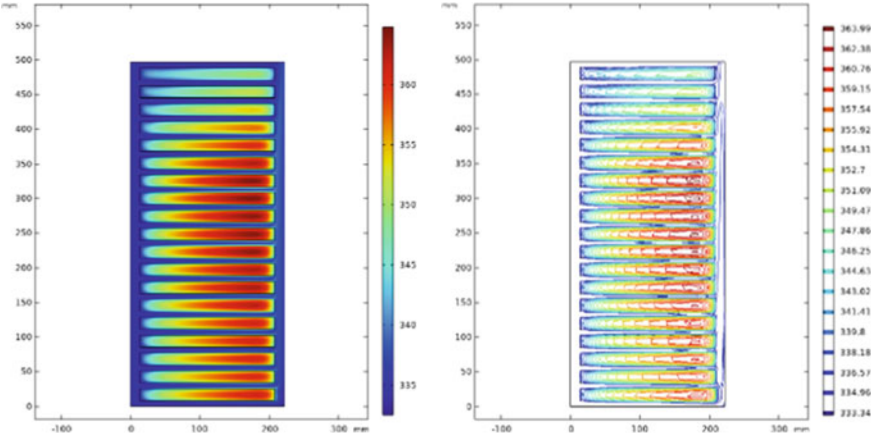
## 4.4 Calculation Results and Analysis

After the above material parameters and boundary conditions are set, the calculated winding temperature distribution nephogram and isotherm distribution nephogram of the small transformer are shown in Fig. 2.

It can be clearly seen from Fig. 3 that the temperature of different windings is different, and the temperature of each part in the same winding is also different. The highest temperature is measured in the middle of several windings, and its position is biased to the oil outlet.

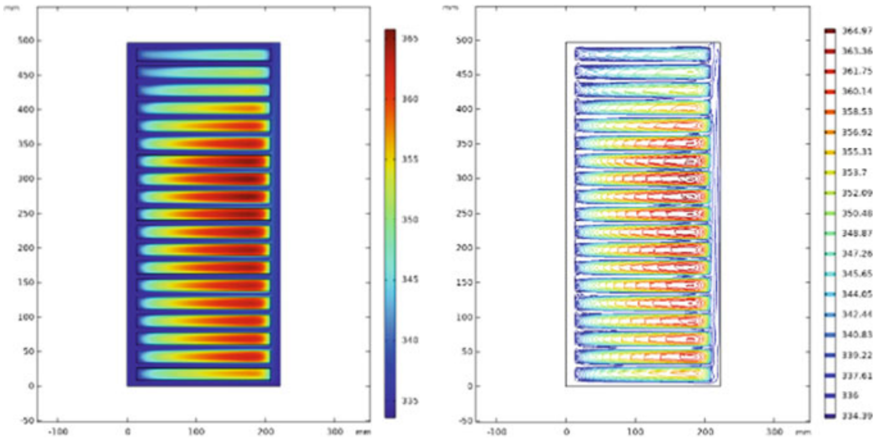
Change the positions of the oil inlet and outlet, explore the influence of the winding temperature distribution, change the positions of the oil inlet and outlet in the transformer model, move 2 mm inward, keep the material parameters and boundary conditions unchanged, and re-establish the simulation model. In this case, the winding temperature distribution cloud diagram and isotherm distribution cloud diagram are shown in Fig. 3.

By comparing the winding temperature cloud map before and after the oil inlet and outlet position changes, it can be clearly seen that the oil inlet and outlet position can



(a) Temperature distribution cloud map. (b) Isotherm distribution diagram.

**Fig. 2** Distribution diagram of winding temperature field of small transformer



(a) Temperature distribution cloud map. (b) Isotherm distribution diagram.

**Fig. 3** The winding temperature field distribution after changing the oil passage

affect the heat dissipation of the winding. Moreover, it can be seen from the analysis that the oil flow velocity of the winding in the middle of the right side is slow, the heat dissipation is poor, and the temperature is higher than other positions. Therefore, increasing the oil flow velocity of transformer oil is also an effective method to reduce the winding temperature. In addition, the temperature of the transformer winding can be reduced by reducing the oil temperature of the oil inlet and broadening the width of the oil passage.

## 5 Conclusion

In this paper, the temperature field distribution of a small transformer winding model is analyzed based on the numerical method. The model comprehensively considers the influence of the internal oil channel distribution on the winding temperature field, and adopts the method of solving the temperature field and the flow field simultaneously to obtain the temperature field distribution cloud diagram of the small transformer winding. At the same time, the influence of vertical oil passage inlet and outlet position on winding temperature field distribution is also studied, and the validity of transformer two-dimensional simulation model based on finite element analysis is verified in transformer temperature field simulation. This research result can provide important basis for insulation design and life evaluation of transformer.

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