

# Study on Temperature Rise of Dry-Type Transformer in Different Cooling Conditions with FEM

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## Abstract

To study the temperature rise of dry-type transformer in different cooling conditions, finite element method is used in this paper to calculate temperature distribution in the transformer. Firstly, thermal-fluid coupled model of a transformer is built up, and the equivalent heat generation of this model is figured out according to the results of delivery test. Then, thermal-fluid coupled model is simulated in both natural cooling condition and forced cooling condition, and temperature distributions in the iron and windings under these two conditions are obtained. Finally, temperature rises in these two conditions are compared to figure out the influence of cooling condition on transformer temperature rise.

**Keywords:** transformer, cooling, thermal-fluid coupled method, temperature rise, finite element

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## 1. Introduction

Power transformers have been widely applied in transmission and distribution system, especially the low-voltage distribution transformer, plays a major part in the daily power supply for residents [1]. Possessing such advantages as fireproofing, explosion-proofing and being environmentally green, dry-type transformers have played an increasingly important role in power systems. Nevertheless, the power loss of transformer in operation will cause the temperature rise. If the temperature rises over the insulation limit, it will speed up the ageing of insulating material and shorten the transformer's working life, or even lead to serious accidents.

An air cooling system can strengthen the internal ventilation of transformer to cool the transformer, but the cooling effect is lacking of quantitative analysis [5]. It's of great value to study the temperature rise of transformer based on two different cooling conditions as natural air cooling and forced air cooling. In this paper the finite element simulation method of thermal-fluid coupled field is used to calculate transformer temperature rise in different cooling conditions, thus quantitatively analyzing the influence of cooling conditions on the transformer's temperature rise.

## 2. Calculation Principle

### 2.1. Mass Conservation Equation

Mass conservation equation is one of the basic equations which must be satisfied by any fluid flowing problems. The mass conservation equation with vector symbol can be written as the following form:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0 \quad (1)$$

Where  $\rho$  is the density (kg/m<sup>3</sup>);  $t$  is the time (s);  $\mathbf{u}$  represents the vector sum of velocity components in the  $x$ ,  $y$ ,  $z$  direction divided by  $u$ ,  $v$ ,  $w$ .

## 2.2. Momentum Conservation Equation

In the solution of fluid flowing in transformer, viscosity coefficient can be considered as a constant, not varying with coordinate position. It can be written in vector form as follows:

$$\frac{\partial(\rho u)}{\partial t} = \rho F + \nabla p + \frac{\mu}{3} \nabla(\nabla \cdot u) + \mu \nabla^2 u \quad (2)$$

Where F is mass force (N); P is pressure(N);  $\mu$  is viscosity coefficient.

## 2.3. Turbulence k- $\epsilon$ Mathematical Model

Applying the most widely used standard k-  $\epsilon$  two equation mode, the general governing equation is given by the following in the case that the fluid is incompressible and in a steady flowing state:

$$\frac{\partial(\rho \phi)}{\partial t} + \text{div}(\rho V \phi) = \text{div}(\Gamma \text{grad} \phi) + S \quad (3)$$

Where  $\phi$  is universal variable,  $\Gamma$  is diffusion coefficient, S is source item.

## 3. Transformer Heat-flow Coupling Model

The dry type transformer is a three-phase planar transformer, with high voltage side using flat copper impregnated winding and low voltage side using the copper foil winding. Its capacity is 4920kVA, the rated voltage of HV side is 6600V, the rated voltage of LV side is 1540V, the insulation temperature rise level is H.

In the case of the three-phase dry type transformer, its high and low voltage coil have rather complex winding as well as large numbers of turns. It will need too much computation that using 3D solid modeling to calculate fluid-thermal coupled field. The coil's power loss and iron loss distribution of each phase is almost the same, as well as the three-phase ventilation circuit. Additionally, thermal radiation between phases can be largely ignored due to small temperature difference. Therefore, just one of the three phases is supposed to be analyzed. Since the structure of one phase is axisymmetric, its fluid-thermal field can be analyzed with a two-dimensional axisymmetric model.

As shown in Figure 1, the transformer model is established on basis of its actual size, of which the upper boundary is 2.25 times the height of the transformer body, and the right boundary is 2.43 times the radius of the transformer body. Therefore the calculation results can reach the requirements of accuracy. The two-dimensional transformer model for calculation is shown in Figure 1. The overall model is shown in Figure 2.

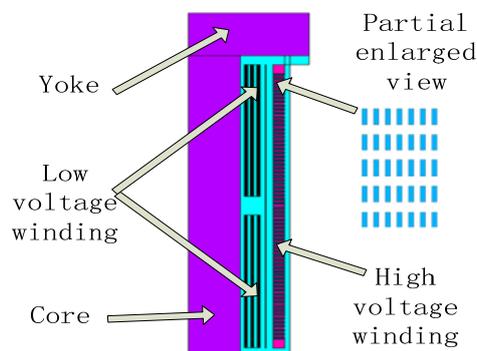


Figure 1. Two-dimensional Fluid-thermal Field Model of Transformer

The transformer model is mainly comprised of iron core, high voltage winding (modeled per turn), low voltage winding (modeled per turn, the upper includes 51 turns, the lower includes

30 turns), an insulating cylinder between high and low voltage winding and end insulation of high-voltage winding. As for the inlet and outlet boundary in Figure 2, the right and upper outlet all load the boundary condition of pressure = 0, the lower end loads the value of the inlet air velocity (When the transformer temperature distribution is calculated under natural cooling condition, the lower inlet air velocity is set to 0).

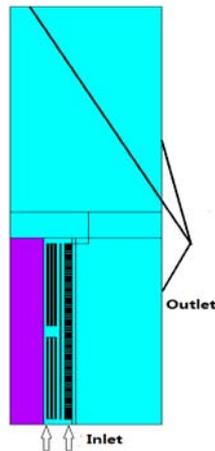


Figure 2. The Model's Loading State of Outer Boundary

Through the product factory report and parameters of the transformer itself, the power loss of the core and coil can be calculated. The results are shown in Table 1.

Table 1. The Power Loss of Transformer Core and coil(75°C)

Loss Classification	P1 ( W )
high-voltage coil	8874.33346
The upper low-voltage coil	4210.53113
The lower low-voltage coil	5154.99467
core	4058.3772

## 4. Simulation under Different Cooling Conditions

### 4.1. Natural Air Cooling

In consideration of the heat productivity and boundary loading conditions mentioned above, the inlet air velocity is set to 0. Then fluid-thermal coupled field in natural cooling conditions can be simulated. Transformer temperature distribution of each part is shown in Figure 3.

Seen from the calculation results, in natural air cooling condition, the hot spot of dry-type transformer is located at the upper part of low-voltage coil, caused by the poor cooling effect of the inner low-voltage windings. The hot-spot temperature is 166.821°C, while the temperature rise is 121.821°C; For transformer cores, the maximum temperature is 117.828°C, located at the upper part of core, and the temperature rise reaches 72.828°C; For the lower part of low-voltage windings, the maximum temperature is 107.827°C, located at the upper part of middle windings; The maximum temperature of high-voltage windings is 142.935°C, located at the top of high-voltage windings.

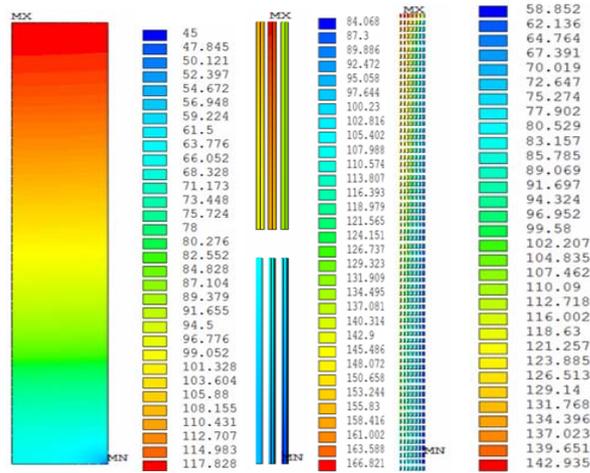


Figure 3. Transformer Temperature Distribution of each Part in Natural Cooling Conditions

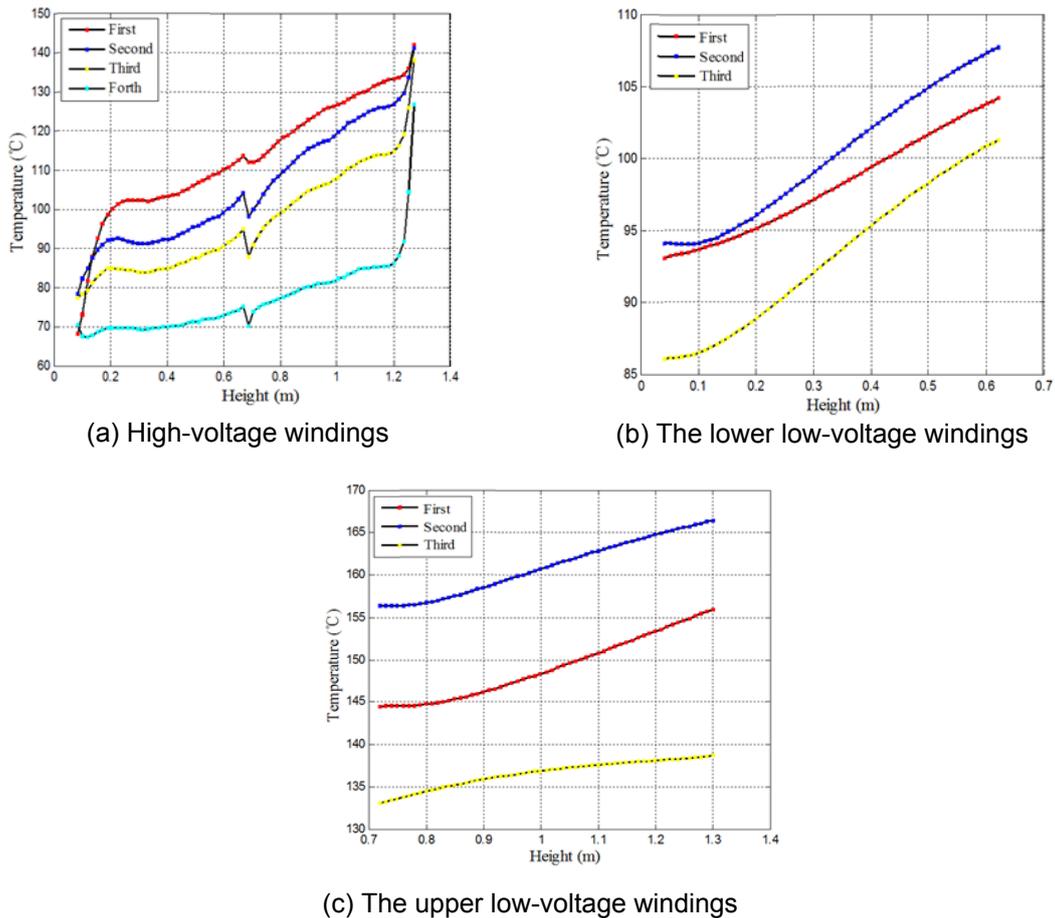


Figure 4. Transformer Temperature of each Part at Various Height in Natural Cooling Conditions

In order to analyze temperature at different height of the winding and core, the observation points are respectively set at different positions. Curves of temperature varying with height of these parts are shown in Figure 4. It appears that temperature in the low-

voltage windings and cores changes more smoothly, contrastly there is a process of temperature drop in the middle of high-voltage windings. This is because at the position where the width of air gap between turns is larger, convective heat transfer effect is better, which leads to the temperature falling.

#### 4.2. Natural Air Cooling

Since the transformer cooling fan gives the ventilation per hour from three-phase fan, which is  $4200m^3$ , it's necessary to be converted into the inlet air velocity.

$$S \cdot v \cdot t = M \quad (4)$$

$$S = \pi(r_2^2 - r_1^2) \quad (5)$$

Where  $S$  stands for the inlet sectional area ( $m^2$ ),  $v$  represents the inlet air velocity ( $m/s$ ),  $t$  is the time ( $s$ ),  $M$  indicates the ventilation per hour ( $m^3$ ),  $r_2$ ,  $r_1$  respectively represent the outer and inner diameter of the inlet air circumferential.

By the above formulas, the inlet air velocity can be obtained as below:

$$v = \frac{M}{\pi(r_2^2 - r_1^2) \cdot t} = 1.224m/s \quad (6)$$

Considering the actual efficiency of the inlet air velocity can't reach 100%, the effective air velocity should be 80%, in this case,  $0.98m/s$ .

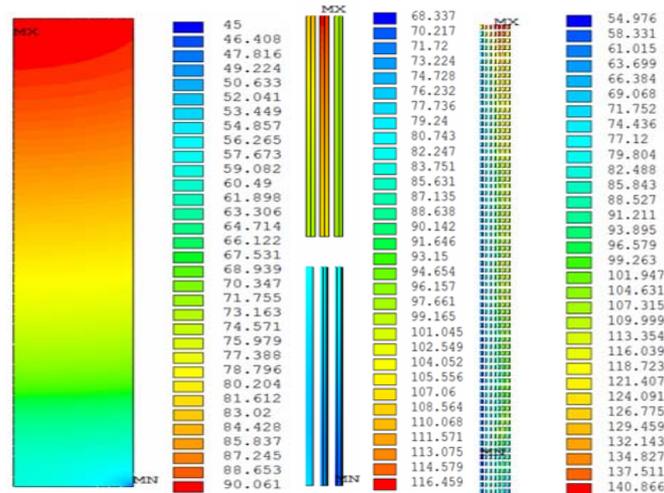


Figure 5. Transformer Temperature Distribution of each Part in Forced Cooling Conditions

Seen from the calculation results, in forced air cooling condition, the cooling effect of the inner low-voltage windings is improved. However, for the reason that the end insulation of high-voltage winding blocks the ventilation at the top of the coil, the hot spot is located at the upper part of high-voltage coil. The hot-spot temperature is  $140.866^{\circ}C$ , while the temperature rise is  $95.866^{\circ}C$ ; For transformer cores, the maximum temperature is  $90.061^{\circ}C$ , located at the upper part of core, and the temperature rise reaches  $45.061^{\circ}C$ ; For the lower part of low-voltage windings, the maximum temperature is  $82.031^{\circ}C$ , located at the upper part of windings; The maximum temperature of the upper part of low-voltage windings is  $116.459^{\circ}C$ , located at the top of windings.

The comparison between transformer hot-spot temperature rise in two cooling conditions is shown in Table 2. Results indicate that adopting the forced air cooling method for transformer parts expect for high-voltage winding can reduce the temperature rise by about 40%

effectively. To further reduce the hot spot temperature rise of high-voltage winding, the structure of end insulation should be improved.

Table 2. Comparison between Transformer Hot-spot Temperature Rise in Two Cooling Conditions

original ventilation structure	Natural cooling temperature rise ( °C)	Forced cooling temperature rise ( °C)	rate of temperature rise change (%)
core	72.828	45.061	38
The upper low-voltage coil	121.821	71.459	41
The lower low-voltage coil	62.847	37.031	41
low-voltage coil	97.935	95.866	2

## 5. Conclusion

This paper mainly focuses on simulation of thermal-fluid coupled field in different cooling conditions and analysis of the temperature rise, by building the model of a dry type transformer. Finally some conclusions can be made as follows:

1. In natural air cooling condition, the overall hot spot of transformer is located at the upper part of low-voltage winding. The maximum temperature rise reaches 121.821°C.
2. In forced air cooling condition, the overall hot spot of transformer is located at the upper part of high-voltage winding close to the end insulation. The maximum temperature rise reaches 95.866°C.
3. Using the forced air cooling method for parts of transformer expect for high-voltage winding, can reduce the temperature rise by about 40%, with an ideal effect.

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