Analysis of Fluid Velocity and Temperature Variation Characteristics in Boundary Layer of Transformer Wall

Shaonan Chen, Qianyi Chen, Kewen Li, Qingfa Chen, and Shifeng Ou

Abstract It is one of the important research contents to understand the fluid velocity and temperature variation characteristics of the boundary layer on the transformer wall in order to analyze the heat dissipation characteristics of the transformer. In this paper, a simplified analysis model of the boundary layer on the transformer wall is established, and the effects of flow velocity, temperature, ambient temperature and ambient convection heat transfer coefficient on the distribution of the fluid temperature boundary layer and velocity boundary layer on the transformer wall are simulated and analyzed. The simulation results show that the main influencing factors of the velocity boundary layer are the inflow temperature and velocity, and the temperature boundary layer is affected by the inflow temperature and velocity as well as the external environment. Given the external ambient temperature and convective heat transfer conditions, as well as the transformer load rate, the temperature and flow velocity of the near wall streamline point can be derived from the transformer shell temperature by combining the results of multiple physical field calculations.

Keywords Oil immersed transformer · Temperature fluid field · Boundary layer · Streamline temperature

1 Introduction

Transformer is one of the important equipment that constitutes the transmission and distribution network of the power system [1]. Transformers play an important role in voltage transformation, energy distribution, and transfer in the system, and their

S. Chen · Q. Chen (✉) · K. Li · Q. Chen · S. Ou
Electric Power Research Institute of Guangxi Power Grid CO., LTD, Nanning 530023, Guangxi, China
e-mail: 345310737@qq.com

S. Chen · K. Li · S. Ou
Guangxi Key Laboratory of Intelligent Control and Maintenance of Power Equipment, Electric Power Research Institute of Guangxi Power Grid CO., LTD, Nanning 530023, Guangxi, China

X. Dong and L. Cai (eds.), *The Proceedings of 2023 4th International Symposium on Insulation and Discharge Computation for Power Equipment (IDCOMPU2023)*, Lecture Notes in Electrical Engineering 1102, https://doi.org/10.1007/978-981-99-7405-4_18

safe and stable operation is of great significance for ensuring the reliability of power supply [2]. In order to accurately obtain the internal temperature field distribution of transformers and provide guidance for the structural optimization of transformers, many scholars and production units have gradually applied numerical calculation methods to the calculation of transformer temperature fluid fields [3–5]. It is one of the important research contents to understand the fluid velocity and temperature variation characteristics of the boundary layer on the transformer wall in order to analyze the heat dissipation characteristics of the transformer. In this paper, a simplified analysis model of the boundary layer on the transformer wall is established, and the effects of flow velocity, temperature, ambient temperature and ambient convection heat transfer coefficient on the distribution of the fluid temperature boundary layer and velocity boundary layer on the transformer wall are simulated and analyzed. The research results of this article can provide a certain reference for the multi physical field inversion detection of transformer winding hot spot temperature.

2 Simplified Analysis Model of Boundary Layer on Transformer Wall

2.1 Simplified Analysis Model

The established boundary layer analysis model for the velocity and temperature of the transformer wall is shown in Fig. 1. The wall flow solid interface is a smooth flat plate, and the fluid inlet velocity is evenly distributed in the vertical inlet direction.

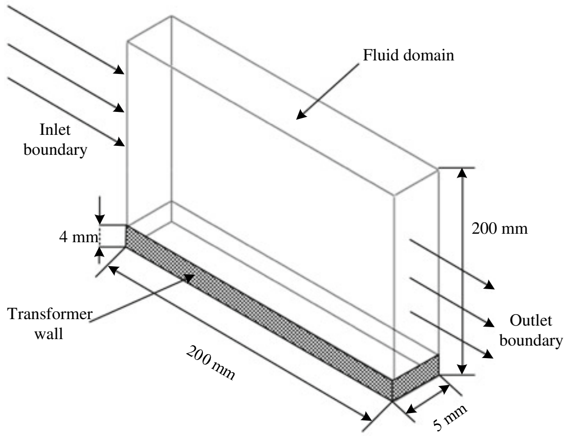

Fig. 1 Analytical model of transformer wall boundary layer of velocity and temperature

2.2 Temperature Fluid Field Control Equation

The mathematical model for the flow and heat transfer of heat dissipating media in a fluid field is established on the basis of the law of conservation of mass, Newton's second law (law of conservation of momentum), and the first law of thermodynamics (law of conservation of energy). The equation expressions for these three laws are as follows [6–8]:

$$\nabla \cdot \boldsymbol{v} = 0 \tag{1}$$

$$\frac{\partial(\rho v)}{\partial t} + \rho \boldsymbol{v} \cdot \nabla \boldsymbol{v} = \rho f - \nabla \boldsymbol{p} + \mu \nabla^2 \boldsymbol{v} \tag{2}$$

$$\frac{\partial(\rho e)}{\partial t} + \nabla \cdot (\rho e \boldsymbol{v}) = \rho \boldsymbol{q} + \nabla(k \nabla T) - \boldsymbol{p} \nabla v + S \tag{3}$$

where, ρ is the fluid density; v is the fluid velocity; f stands for the fluid volume force; p represents the pressure; μ is the dynamic viscosity; k is the thermal conductivity; q indicates the heat source per volume inside the transformer; e is the internal energy of the fluid; T represents the temperature; S represents the part of fluid mechanical energy converted into heat energy under the action of fluid viscous and internal heat source of fluid.

2.3 Boundary Conditions

Inlet boundary conditions: At the inlet of the fluid field, given boundary conditions such as inlet velocity, pressure, and temperature, which are usually set as constants, can be expressed as [9, 10]:

$$\boldsymbol{v}|_{in} = C \quad \text{or} \quad \boldsymbol{P}|_{in} = C \quad \text{or} \quad T|_{in} = C \tag{4}$$

where, C is a known constant.

In this article, the set inlet boundary condition is that the inlet flow velocity and temperature are constants.

Outlet boundary conditions: At the outlet of the fluid field, given boundary conditions such as outlet velocity, pressure, and outlet conditions, usually constant or vector gradient of velocity and temperature is zero, which can be expressed as:

$$\boldsymbol{v}|_{out} = C \quad \text{or} \quad \boldsymbol{P}|_{out} = C \quad \text{or} \quad T|_{out} = C \tag{5}$$

$$\left.\frac{\partial \boldsymbol{v}}{\partial n}\right|_{out} = 0, \qquad \left.\frac{\partial T}{\partial n}\right|_{out} = 0 \tag{6}$$

In this article, the set outlet boundary condition is that the outlet pressure is constant, which is equal to atmospheric pressure.

The boundary condition of the wall flow solid interface: no slip wall, i.e. the fluid velocity at the interface is 0;

Boundary conditions of the external interface of the wall: specify the ambient temperature and external heat transfer convective coefficient;

Boundary conditions outside the fluid domain: free slip wall boundary conditions, with no heat exchange with the outside world.

2.4 Material Parameters

Transformer oil is the main cooling medium inside the transformer. Its thermodynamic parameters include density, specific heat capacity, thermal conductivity, viscosity, etc.

The density and specific heat capacity determine the ability to store heat, and the thermal conductivity represents the ability of transformer oil to transfer heat. The viscosity is generated by the internal friction of transformer oil, so when the fluid flows, the viscosity will produce a certain mechanical energy loss, which will interfere with the shape and flow rate of the fluid, so the viscosity has a great impact on the cooling effect of transformer oil. These thermodynamic parameters are greatly affected by temperature, so in order to more accurately describe the parameters of transformer oil, this paper selects the fitting formula that introduces temperature T as a variable.

The thermodynamic parameters of transformer oil are shown in Table 1. T in the table is the temperature of transformer oil, in °C.

The relationship between viscosity of transformer oil and temperature is as follows [11]:

$$\mu(T) = \exp(B)T^{-A} \tag{7}$$

In the equation, $A = 9.55 \pm 0.23$, $B = 50.24 \pm 1.33$, μ Is the dynamic viscosity of transformer kg/ms, T is the temperature of transformer oil, and the unit is K.

The wall material of transformer oil tank is cold-rolled steel plate, and relevant material parameters are shown in Table 2:

Table 1 Thermodynamic parameters of transformer oil

Parameters	Value
Density ($kg \bullet m^{-3}$)	880
Specific heat capacity ($J \bullet kg^{-1} \bullet K^{-1}$)	$1433 + 5.233\ T$
Thermal conductivity ($W \bullet m^{-1} \bullet K^{-1}$)	0.105

Table 2 Thermodynamic parameters of transformer wall

Thermal conductivity/($W \bullet m^{-1} \bullet K^{-1}$)	Density/($kg \bullet m^{-3}$)	Thermal conductivity/($J \bullet kg^{-1} \bullet K^{-1}$)
60.5	7854	485

3 Distribution of Temperature and Fluid Field in Boundary Layer of Transformer Wall

3.1 Classification of Fluid Boundary Layer

The fluid boundary layer can be further divided into velocity boundary layer and temperature boundary layer. The flow boundary layer is defined as the thin layer of fluid whose velocity changes significantly in the direction perpendicular to the wall. When a fluid flows through a solid wall, due to the non-slip characteristics of fluid molecules in the wall layer, the flow velocity of the near wall fluid will gradually change from zero velocity at the wall to flow velocity in the direction perpendicular to the wall under the action of fluid viscous force. The fluid outside of $u = 0.99u_{\infty}$ can be considered unaffected by fluid viscosity and is called the mainstream region. The region within $u = 0.99u_{\infty}$ has obvious velocity gradient, which is called the boundary layer region.

When the fluid flows through the flat plate and the temperature t_{w} of the flat plate is not equal to the temperature t_{∞} of the inlet fluid, a thin layer with significantly changed temperature can also be formed above the wall, which is often called the thermal boundary layer. When the temperature difference between the wall and the fluid reaches 0.99 times of the temperature difference between the wall and the inlet fluid, that is $(t_w - t)/(t_w - t_{\infty}) = 0.99$, this position is the outer edge of the boundary layer, and the distance from this point to the wall is the thickness of the thermal boundary layer, recorded as $\delta_t(x)$.

3.2 Impact of Inlet Flow Velocity

The ambient temperature is 20 °C, the heat transfer convective coefficient is 20 W/(m^2K), the fluid inlet temperature is 50 °C, and the wall boundary layer thickness and wall temperature difference at different inlet speeds (0.01m/s, 0.02 m/s, 0.04 m/s, 0.1 m/s, 0.2 m/s, 0.5 m/s, 1 m/s) are shown in Fig. 2.

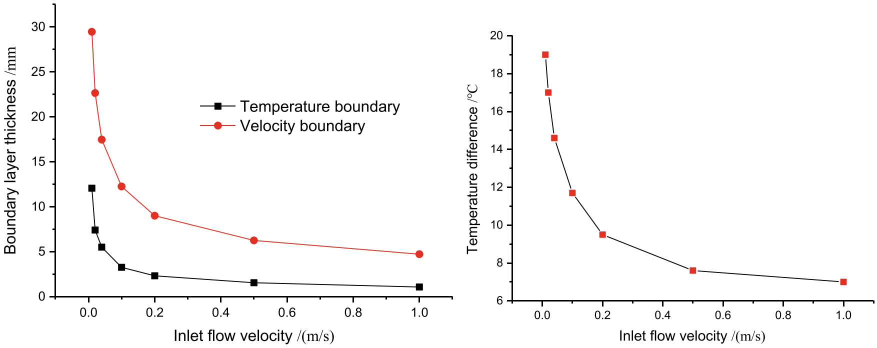

Fig. 2 Impact of inlet flow velocity

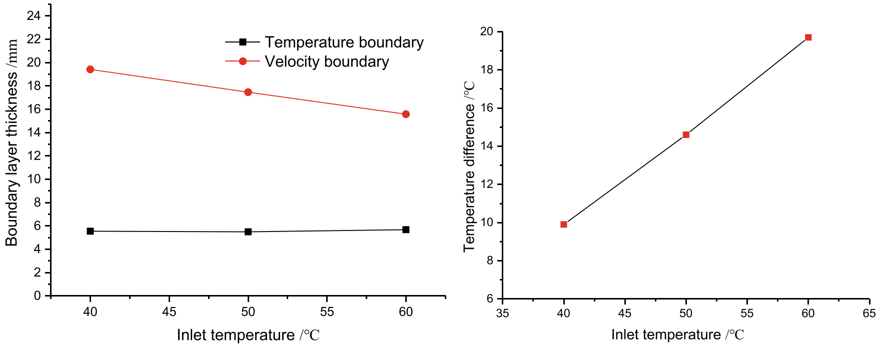

Fig. 3 Impact of inlet flow temperature

3.3 Impact of Inlet Flow Temperature

The ambient temperature is 20 °C, the heat transfer convective coefficient is 20 W/(m^2K), and the inflow velocity is 0.04 m/s. The wall boundary layer thickness and wall temperature difference under different inflow temperatures (40, 50, 60 °C) are shown in the Fig. 3.

3.4 Impact of External Ambient Temperature

The convection heat transfer coefficient of the external environment is 20 W/(m^2K), the inlet temperature is 50 °C, and the inlet speed is 0.04 m/s. The wall boundary layer thickness and wall temperature difference under different ambient temperatures (10, 15, 20, 25, 40 °C) are shown in Fig. 4.

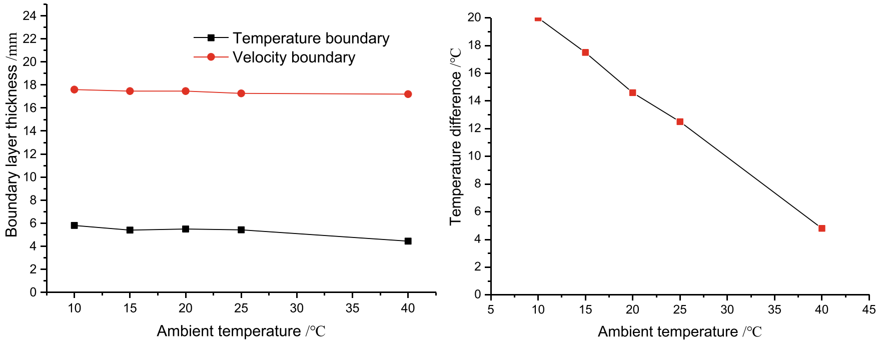

Fig. 4 Impact of external ambient temperature

3.5 *Impact of External Heat Transfer Convective Coefficient*

The ambient temperature is 20 °C, the inlet velocity is 0.04 m/s, the inlet temperature is 50 °C, and the wall boundary layer thickness and wall temperature difference under different heat transfer convective coefficients (10W/(m^2K), 20W/(m^2K), 40W/(m^2K)) are shown in Fig. 5.

The temperature and velocity distribution of the model boundary layer under the conditions of 50 °C fluid temperature, 0.04 m/s fluid velocity, 25 °C ambient temperature, and 20 W/(m^2K) ambient heat transfer convective coefficient are shown in Figs. 6 and 7.

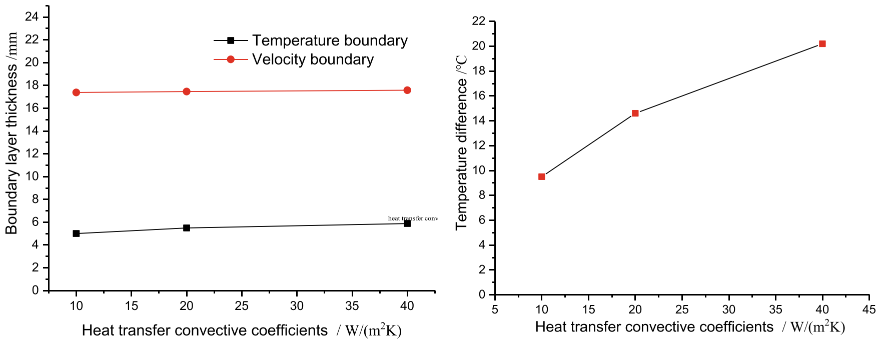

Fig. 5 Impact of external heat transfer convective coefficient

Fig. 6 Cloud chart of wall temperature distribution

Fig. 7 Cloud chart of wall velocity distribution

4 Conclusion

The main conclusions can be drawn as follows:

(1) The thickness of the wall velocity boundary layer is related to the fluid inlet velocity and temperature. The higher the velocity, the thinner the velocity boundary layer, the higher the inlet temperature, and the thinner the velocity boundary layer; The thickness of velocity boundary layer is less affected by ambient temperature and external convection heat transfer coefficient;

(2) The thickness of the wall temperature boundary layer is greatly affected by the inlet flow velocity, and the greater the velocity, the thinner the temperature boundary layer; The thickness of temperature boundary layer is less affected

by the inflow temperature, ambient temperature and external convection heat transfer coefficient;

(3) The higher the inflow velocity, the smaller the temperature difference on the boundary layer wall, the higher the inflow temperature, the larger the temperature difference on the boundary layer wall, the higher the external ambient temperature, the smaller the temperature difference on the boundary layer wall, the higher the external convection heat transfer coefficient, and the larger the temperature difference on the boundary layer wall;

(4) Based on the above analysis, the velocity boundary layer is mainly affected by the inlet temperature and velocity, and the temperature boundary layer is affected by the inlet temperature and velocity as well as the external environment;

(5) Given the external ambient temperature and convective heat transfer conditions, as well as the transformer load rate, the temperature and flow velocity of the near wall streamline point can be derived from the transformer shell temperature by combining the results of multiple physical field calculations.

Acknowledgements This paper is supported by Science and Technology Project of Guangxi Power Grid CO under project number **GXKJXM20220126**.

References

1. Rommel DP, Di Maio D, Tinga T (2021) Transformer hot spot temperature prediction based on basic operator information. Int J Electr Power Energy Syst 124:1–15
2. Thummala P, Schneider H, Zhang Z et al (2016) Investigation of transformer winding architectures for high-voltage (2.5 kV) capacitor charging and discharging applications. IEEE Trans Pow Electron 31(8):5786–5796
3. Torriano F, Campelo H, Quintel AM et al (2018) Numerical and experimental thermofluid investigation of different disc-type power transformer winding arrangements. Int J Heat Fluid FL 69:62–72
4. Mohamed MMS, Diaa-Eldin AM, Muhammad D et al (2020) Thermal performance of transformers filled with environmentally friendly oils under various loading conditions. Int J Electr Power Energy Syst 118:1–10
5. Zhang X, Wang ZD, Liu Q (2017) Prediction of pressure drop and flow distribution in disc-type transformer windings in an OD cooling model. IEEE Trans Power Deliv 32(4):1655–1664
6. Zhang X, Wang ZD, Liu Q et al (2018) Numerical investigation of oil flow and temperature distributions for ON transformer windings. Appl Therm Eng 130:1–9
7. Córdoba PA, Silin N, Dari E (2015) Natural convection in a cubical cavity filled with a fluid showing temperature-dependent viscosity. Int J Therm Sci 98:255–265
8. Córdoba PA, Dari E, Silin N (2019) A 3D numerical model of an ONAN distribution transformer. Appl Therm Eng 148:897–906
9. Habbachi F, Oueslati FS, Bennacer R et al (2013) Simulation of heat transfer and fluid flow in 3D porous media in non-equilibrium. In: 2015 World Symposium on Mechatronics Engineering & Applied Physics (WSMEAP), Sousse, pp 1–12
10. Çengel YA (2008) Introduction to thermodynamics and heat transfer. McGraw-Hill, USA
11. Ruan JJ, Deng YQ, Huang DC et al (2020) HST calculation of a 10 kV oil-immersed transformer with 3D coupled-field method. IET Electr Power App 14(5):921–928