Three-dimensional Simulation of Forced Convective Flow and Heat Transfer in Air-Cooled Motor Stator

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Abstract. The reliable prediction of cooling medium velocity and stator temperature distribution is very important for a running motor to ensure the temperature rise of stator below the limit. In this paper, taking the stator ventilation duct of an air-cooled motor as the research object, a 3D physical model including the iron core, the windings, the stator ventilation duct and the main insulation was established. In order to fully reveal the characteristics of forced convective flow and heat transfer in air-cooled motor stator, the fluid field and temperature field were calculated by using finite volume method. The radial and axial distribution characteristics of the fluid field were analyzed deeply. It’s shown that the velocity decreases in the axial direction on the half of the axial plane and varies greatly in the radial direction. The temperature distribution in the main insulation layer of the stator was elaborated emphatically. The temperature of the insulation material along the length of the slot and the temperature difference between inner and outer insulation were discussed in detail. Based on the experimental results, the reliability of the calculation method was evaluated and the relative error is within 15%.

1. Introduction
Air-cooled motor has been widely used in many fields with the advantages of low price, simple cooling system, convenient operation and maintenance. The research on the fluid field and temperature field of the ventilation system in the motor stator is of great significance to ensure the reliable operation of the air-cooled motor. Most studies have been conducted to calculate the temperature field which of 2-5 measuring points [1-3] with two-dimensional fluid field model [4-5], finite element method [6-7] and finite volume method [8-9] in the stator ventilation slot. However, the two-dimensional fluid field cannot exactly reflect the temperature distribution of the motor in the axial direction. In addition, a few measurement points are not conducive to the verification of the reliability of the simulation analysis. Therefore, it is very necessary to study the temperature distribution with more measuring points by using the 3D calculation model.

In this paper, the three-dimensional model of the radial ventilation duct of a real generator was established. Fluid field and temperature field were calculated with the purpose of making the cooling method more reliable. Combining with the experimental results, the distribution characteristics of the fluid field and temperature field in the stator ventilation duct was shown.

2. 3D physical model and mathematical model
2.1. 3D physical model and basic assumptions
In this paper, the stator radial ventilation duct of a 1250kW air-cooled motor is illustrated for calculation and analysis. The three-dimensional stator radial ventilation structure diagram is shown in figure 1. The solution domain can be determined as the range of a core section in the axial direction and circumferential direction. It is assumed that the air velocity does not change along the axis and the cooling air flows into the radial vent vertically.

![Figure 1. The structure of the stator radial ventilation duct](image)

Experiment was carried out with the actual model. In the experiment, the temperature of the stator was measured by T type thermocouple. Figure 2 depicts the distribution of thermocouples in the stator windings. Measuring points “1”, “2”, “5” and “6” are located outside the insulation of the top and bottom windings. Measuring points “3” and “4” are located between the insulation layers, and measuring points “7”, “8”, “9” and “10” are located between the windings and the insulation.

![Figure 2. The distribution of thermocouples in the stator winding](image)
2.2. Mathematical model
Because of the large Reynolds number of the fluid in the motor, the mathematical model of turbulence under steady flow was adopted. The Reynolds Averaged Navier Stokes equations have been used for the steady state simulations. The obtained equation group is described in detail[10].

\[
\frac{\partial}{\partial t} (\rho \phi) + \frac{\partial}{\partial x} (\rho u \phi) + \frac{\partial}{\partial y} (\rho v \phi) + \frac{\partial}{\partial z} (\rho w \phi) = \frac{\partial}{\partial x} (\Gamma \frac{\partial \phi}{\partial x}) + \frac{\partial}{\partial y} (\Gamma \frac{\partial \phi}{\partial y}) + \frac{\partial}{\partial z} (\Gamma \frac{\partial \phi}{\partial z}) + S
\]  

where \( \phi \) is the universal variable, \( \Gamma \) is the diffusion coefficient of general meaning, \( S \) is the generalized source term corresponding with \( \phi \).

As for temperature field, the steady-state heat conduction equation in the Cartesian coordinate system is described as follows:

\[
\lambda \frac{\partial^2 T}{\partial x^2} + \lambda \frac{\partial^2 T}{\partial y^2} + \lambda \frac{\partial^2 T}{\partial z^2} = -q
\]

where \( \lambda_x, \lambda_y, \lambda_z \) (W/m·K) is the thermal conductivity in the x, y, z direction respectively, \( q \) (W/m³) is the heat flux.

2.3. Boundary conditions
According to the flow characteristics of the cooling air in the radial ventilation duct of the motor, the boundary conditions are shown as follows:

(1) The pressure outlet is adopted at the outlet, and the pressure value is set to 1 atm.
(2) The inlet is set as the velocity inlet, and the velocity is set to 7.88 m/s according to the air volume.
(3) The surface of the slot wedge in the stator ventilation ditch, the two walls of the ventilation duct, the top and bottom surfaces of the stator iron and the outer surface of the insulation layer are set as non-slip boundary conditions.
(4) The average loss is applied for stator core and windings respectively.
(5) The adiabatic surface and heat dissipation surface are arranged according to the structure of the stator ventilation ditch[11].

3. Results and Discussion

3.1. The fluid field of the stator ventilation duct
The finite volume method was used to simulate the three-dimensional fluid field. Figure 3(a) shows the velocity distribution of the three-dimensional fluid field along the radial vent at the half in the axial direction.
In Figure 3(a), the velocity distribution is nonuniform in the radial direction. The cooling air velocity varies dramatically at the inlet due to the reduction of the cross area in the radial ventilation duct. The flow velocity reaches a maximum value rapidly on both sides of the ventilation duct. With the increase of the cross section, the flow velocity decreases gradually. In the yoke, wind velocity approaches to a flat gradually and reaches to a minimum at the outlet of the stator ventilation duct. Two strands cooling air meets at the bottom of the rod and forms eddy currents which flows from both walls of the stator ventilation duct.

The field distribution on both sides of the stator ventilation duct (x=-16mm, x=16mm), on the surface of the windings (x=-5mm, x=5mm) and on the centre plane of the iron core tooth (x=0mm) in the axial direction are shown in figure 3(b). The fluid field is symmetrical along the length of the ventilation duct, while is not uniformly distributed in the axial direction. As approaching the surface of the core, the flow velocity decreases. The air forms some small gaseous circulations in the yoke. The closer to the centre plane of the tooth, the greater the influence of the eddy current on velocity distribution. From centre plane to ventilation duct walls, the number of the gaseous circulations declines. When the air reaches the outlet of the stator duct, the velocity is minimally affected by the eddy and almost evenly distributed.

3.2. The temperature field of the stator

The temperature distribution of the stator is affected by the calculation results of the fluid field. The heat dissipation coefficients of different boundaries with the stator are calculated by corresponding empirical formulas [12]. Figure 4 shows the three-dimensional temperature distribution of the stator. The lowest temperature of the stator appears on the slot wedge at the inlet of the cooling air for the reason that the lower air temperature here and there is no heat source for the slot wedge. While the highest temperature appears on the bottom winding. The temperature distribution of the main insulation layer is analyzed with the purpose of reducing the temperature rise of the windings, which makes the temperature of the windings close to the stator temperature. Figure 5 shows the temperature distribution of the main insulation of the stator windings.
The temperature of the main insulation is distributed symmetrically along the length of the slot, and the temperature inside the layer is higher than that outside. For example, the temperature of measuring points “7”, “8”, “9” and “10” is higher than that of measuring points “1”, “2”, “5” and “6” which located outside the insulation layer. This is because the small thermal conductivity of the insulation material which is not conducive to the cooling of the windings. The temperature of the insulation layer of the top winding is lower than that of the bottom winding, which is shown that the temperature of measuring points “5” and “6” are higher than that of measuring points “1” and “2”. As for measuring points “3” and “4”, located between the top and bottom winding insulation layers, the similar temperature is obtained. In addition, the temperature distribution is different in the circumferential direction of the stator. The insulation temperature of the top winding is lower at the inlet where the cooling air flows into.

**Table 1.** Temperature calculation result comparing to experimental result

| measurement points | 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   | 9   | 10  |
|--------------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Simulation value/°C| 79.18 | 79.18 | 79.94 | 79.75 | 78.22 | 78.52 | 80.43 | 80.45 | 80.79 | 80.58 |
| Experiment value/°C| 69.14 | 68.97 | 76.65 | 77.06 | 70.48 | 70.63 | 77.90 | 78.42 | 77.84 | 77.01 |
| relative error/%   | 14.52 | 14.80 | 4.29 | 3.49 | 9.56 | 9.76 | 3.25 | 2.59 | 3.79 | 4.64 |

**Figure 4.** 3D temperature distribution of the stator core and windings

**Figure 5.** The temperature distribution of the main insulation layer of the stator windings
Comparison of the simulation results and the experimental results is shown in table 1. In figure 6, it shows that the simulation value is viable comparing with the measurement value curve. The maximum error is less than 15%, which meets the needs of basic engineering. The points with the greatest error are located at points “1” and “2”. The factor may be that the air flows through the small gap to cool the stator which between the slot wedge and the top insulation in the experiment. While the small gap is not established in the simulation model, which leads to the higher temperature at measuring points “1” and “2”. The error of other measuring points is kept within 10%, verifying that the solution method is of validity.

4. Conclusion
In this paper, the study was conducted to simulate the three-dimensional fluid field and temperature field of air-cooled motor stator. The following conclusions are obtained:

(1) Through the calculation of the fluid field, the velocity distribution characteristics in the axial and radial direction were analyzed in detail. The air velocity varies greatly along the radial direction in the stator ventilation duct. On the axial plane, the field distributes symmetrically and the velocity decreases along the axial direction.

(2) In the results of the stator temperature field, it was found that the lowest temperature value appears on the slot wedge at the inlet of the stator ventilation duct, and the highest temperature appears on the bottom winding of the stator. As for the temperature of the main insulation, the temperature is distributed symmetrically along the length of the slot. The temperature of the inner insulation is higher than the outer insulation, and the temperature of the bottom winding insulation is higher than that of the top.

(3) Compared with the experimental results, the calculation results verify the reliability of the calculation method with the relative error less than 15%, which contributed to the study of the fluid field and temperature field of the air-cooled motor.

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