Comparison of Full-Area Simulation Method and Separated Simulation Method of Motor Temperature Field

Wenjie Wang\(^1\), Shuangfu Suo\(^2*\), Jinshun Hao\(^3\) and Yang Wang\(^3\)

\(^1\)Department of Mechanical Engineering, Tsinghua University, Beijing, 100084, China
\(^2\)State Key Laboratory of Tribology, Tsinghua University, Beijing, 100084, China
\(^3\)School of Engineering and Technology, China University of Geosciences, Beijing, 100083, China

\(^*\)Corresponding author’s e-mail: sfsuo@mail.tsinghua.edu.cn

Abstract. Permanent magnet motor has become the main research direction of high power density motor, and the heat dissipation capability of the motor has become an important factor restricting the increase of motor power density. High-power density motor generates higher temperature when it works, and high temperature may cause motor insulation burnout, even irreversible demagnetization of permanent magnets. Therefore, thermal analysis and optimal design of cooling structure are very important for high power density motors. In this paper, a 3-D model of thermal simulation of permanent magnet motor is established, and the temperature field is calculated by two methods. 1. The fluid-solid coupling method is used to calculate the global temperature field of the motor and the cooling structure. 2. The fluid-solid coupling method is used to calculate the convective heat transfer coefficient of the cooling structure, then the heat transfer model is used to calculate the temperature field of the motor body. These two methods are introduced and compared in this paper, and the second method is considered to be well suited for optimal design of motor cooling structures.

1. Introduction
As an energy conversion device, motor has been applied in all fields of economy and people’s daily life. With the continuous development of motor technology and the increasing demand for the comprehensive performance of motors in the application of various industries, the requirement of improving the power density of motors has become a hot topic. With the continuous improvement and improvement of the performance of permanent magnet materials and the development of power electronic devices, permanent magnet motors have been vigorously studied and applied, and become the main research direction of high power density motors. Early research on high power density motors mainly focused on electromagnetic analysis. With the deepening of research, people find that the heat dissipation ability of motors is one of the main factors that restrict the improvement of power density of motors. Therefore, thermal analysis of motor is of great significance to motor design and motor control.

At present, there are many methods for calculating temperature field of motor, such as simplified formula method, thermal network method, and finite element method. The formula method for calculating the temperature rise of motor depends on various parameters and heat transfer coefficient, and ignores the nonlinearity of material, which results in low accuracy and can only get the average temperature rise. This method cannot meet the requirement of higher and higher accuracy of motor
design and thermal calculation. The thermal network method describes the relationship among temperature rise, heat flow and thermal resistance of an object according to Fourier’s law of heat conduction. Thermal network method is still widely used by many designers, but it requires more experience and is difficult to further improve the accuracy. Finite element method (FEM) is the most widely used method to solve the temperature field of motor at present [1]. It is still applicable in the case of irregular region and boundary, and has high accuracy.

In this paper, the FEM and CFD method is used for calculation. If the whole-area model of motor is modelled, the modelling process of this method is complex, which is not conducive to optimal design. Therefore, in this paper, the motor model is established, two calculation methods are provided and compared, and the method which can be used conveniently for optimum design of cooling structure is pointed out.

2. Calculation of heat loss

The loss of the motor will turn into heat, which will raise the temperature of the motor. These losses include copper loss, iron loss, permanent magnet eddy current loss and mechanical loss[2]. For high power density motors, mechanical losses account for a small proportion, so mechanical losses are ignored in this paper. In this paper, a 10-pole 12-slot motor model is analysed.

The copper loss of the heat source of motor[3] can be calculated based on formula (1).

\[ P_{Cu} = \sum I_x^2 R_x \]  

(1)

Where \( I_x \) is the current of the winding, \( R_x \) is the resistance of winding \( x \) at the working condition.

According to Bertotti iron loss separation calculation model introduced in Reference[4][5], core loss can be expressed as formula (2).

\[
\begin{align*}
P_{Fe} &= P_n + P_c + P_{ex} \\
P_n &= K_n B_m^b \\
P_c &= K_c f^2 \int_0^{2\pi} \left( \frac{dB(\theta)}{d\theta} \right)^2 d\theta \\
P_{ex} &= K_{ex} f^{1.5} \int_0^{2\pi} \frac{d|B(\theta)|}{d\theta}^{1.5} d\theta
\end{align*}
\]  

(2)

If the magnetic density waveform is assumed to be an ideal sinusoidal wave and the air gap magnetic density is decomposed by Fourier transform, then the formula for calculating iron loss is as formula (3).

\[ P_{Fe} = \sum_{i=1}^{n} \left( K_i B_m^b + K_c f^2 B_m^{2.5} + K_{ex} (fB_m)^{1.5} \right) \]  

(3)

In this paper, the electromagnetic model of the motor is established by using the motor design software, and the loss of the motor is calculated. The copper loss of the motor is 108W, the iron loss of the motor is 359W, and the permanent magnet eddy current loss is 5W.

3. Establishment of the motor model

Before calculating the temperature field, the calculation model of the motor should be established first. The structure of the permanent magnet motor is complex, and it is important to accurately and reasonably establish the calculation model of the motor temperature field.

Because the stator winding is composed of conductors and insulating materials, and its structure is complex, it is necessary to simplify the model. The simplified method[6] for winding is shown in Figure 1. The winding is equivalent to a whole copper conductor placed in the centre of the slot, and all insulating materials are equivalent to an insulating material with uniform thickness parallel to the stator slot wall.
According to the basic law of heat transfer, the formula for calculating the thermal conductivity of equivalent insulation layer is as formula (4).

\[
\lambda_{eq} = \frac{\sum_{i=1}^{n} \delta_i \lambda_i}{\sum_{i=1}^{n} \left(\delta_i \lambda_i\right)}
\]

(4)

Where \(\lambda_i\) is the thermal conductivity of each layer of the insulation material. \(\delta_i\) is the thickness of each insulation material.

The stator and rotor cores of motors are made of silicon steel sheets laminated. Therefore, in the axial direction of the motor, the thermal conductivity can be equivalent to the series structure of silicon steel sheet and thin dielectric layer, while in the radial and circumferential direction, it can be equivalent to the parallel connection of silicon steel sheet and dielectric thin layer. According to the basic law of heat transfer, the formula for calculating the equivalent thermal conductivity of stator and rotor silicon steel laminates is as formula (5).

\[
\begin{align*}
\lambda_x &= \frac{\delta_{Fe} \lambda_{Fe} + \delta_0 \lambda_0}{\delta_{Fe} + \delta_0} = K_{Fe} \lambda_{Fe} + \left(1 - K_{Fe}\right) \lambda_0 \\
\lambda_y &= \frac{\delta_{Fe} \lambda_{Fe} + \delta_0 \lambda_0}{\delta_{Fe} + \delta_0} = \frac{1}{\lambda_{Fe} + \frac{K_{Fe}}{\lambda_{Fe} + \frac{1-K_{Fe}}{\lambda_0}}} \\
\lambda_z &= \frac{\delta_{Fe} \lambda_{Fe} + \delta_0 \lambda_0}{\delta_{Fe} + \delta_0} = \frac{K_{Fe}}{\lambda_{Fe} + \frac{1-K_{Fe}}{\lambda_0}}
\end{align*}
\]

(5)

Where \(\delta_{Fe}\) is the thickness of silicon steel sheet for stator and rotor. \(\lambda_{Fe}\) is the thermal conductivity of stator and rotor silicon steel sheets. \(\delta_0\) is the thickness of insulation material. \(\lambda_0\) is the thermal conductivity of laminated core insulation material. \(K_{Fe}\) is the lamination coefficient of stator and rotor silicon steel sheets. \(\lambda_x, \lambda_y, \lambda_z\) are the equivalent thermal conductivity of the stator and rotor silicon steel sheets along the radial, circumferential and axial directions respectively.

The thermal conductivity of materials varies with temperature, and it can be approximately considered that the thermal conductivity varies linearly with temperature. Formula for calculating thermal conductivity of materials is as formula (6).

\[
\lambda = \lambda_0 (1 + bt)
\]

(6)

Where \(\lambda_0\) is the thermal conductivity of materials at 0 °C. \(b\) is a material constant determined by experiments. \(T\) is the actual temperature.

When calculating the temperature field of the motor, the complex heat exchange of air in the air gap is caused by the rotation of the rotor. In order to simplify the calculation, the equivalent thermal conductivity is introduced according to reference [7]. That is to say, the thermal conductivity of stationary fluid is used to describe the heat exchange capacity of the air flowing in the air gap. When the air flow in the air gap is laminar, the equivalent thermal conductivity is equal to the thermal conductivity of air. When the air flow in the air gap is turbulent, the equivalent thermal conductivity is calculated by formula (7) according to reference [7][8].

\[
\lambda_e = 0.069 \rho \eta^{2.9084} \cdot [K_{Fe}^{0.4614} \rho^{3.3364} \mu_{\gamma}]
\]

(7)

In this paper, the motor body model and the axial structure waterway model are established.
4. Calculation of motor temperature field by using method 1

The fluid-solid coupling method is used to calculate the global temperature field of the motor and the cooling structure. In this method, the water circuit and motor are integrated into a whole model, and the whole temperature field is calculated by CFD software. In the calculation, the loss is applied in the form of body heat source [9], then the initial cooling water speed is set to 0.1 m/s, and the initial cooling water temperature is set to 300K.

The temperature field of cooling water and winding is calculated as shown in Figure 2 and Figure 3.

![Figure 2](image1.png)

**Figure 2.** The temperature field of cooling water calculated by method 1.

![Figure 3](image2.png)

**Figure 3.** The temperature field of winding calculated by method 1

From the calculation results, it can be seen that the water temperature increases gradually. The maximum temperature of cooling water is 335K and the average temperature of outlet is 327.1K. It is found that the highest temperature of the motor is at the end of the winding. As can be seen from
Figure 3, the temperature of different windings is different, and the winding end near the outlet has the highest temperature of 382K. The winding temperature near the inlet is lower.

From the calculation results, it can be seen that the temperature distribution of windings is similar to that of cooling water. With the flow of cooling water and heat exchange with motor, the temperature of cooling water increases gradually. Then, the heat transfer capacity between cooling water and motor will gradually decrease. This shows that method 1 can well reflect the change of convective heat transfer coefficient.

The axial temperature distribution of the highest temperature winding is shown in Figure 4.

![Figure 4](image-url)

Figure 4. The axial temperature of the highest temperature winding calculated by method 1.

The basic formula for calculating convective heat transfer is Newton's law of cooling [10]. When the fluid is heated, there is formula (8).

\[ q = h(t_w - t_i) \]  

(8)

Where \( q \) is the heat flux, \( h \) is the convective heat transfer coefficient, \( t_i \) is the temperature of fluid. \( t_w \) is the temperature of the solid wall.

The average convective heat transfer coefficient between cooling water and the motor shell calculated by method 1 is 349.3 W/(m^2*K).

5. Calculation of motor temperature field by using method 2

The fluid-solid coupling method is used to calculate the convective heat transfer coefficient of the cooling structure by CFD software, then the heat transfer model is used to calculate the temperature field of the motor body by FEM software. When calculating the convective heat transfer coefficient, the parameter setting of cooling water is the same as that of method 1. The heat source is applied to the contact surface of the cooling structure and the motor in the form of heat flux.

The temperature field of cooling water is calculated as shown in Figure 5. From the calculation results, it can be seen that the maximum temperature of cooling water is 337K and the average temperature of outlet is 327.3K. This result is almost the same as that calculated by method 1. The average convective heat transfer coefficient calculated by method 2 is 337.1 W/(m^2*K), which is 3.5% error with the calculation result of Method 1.
When calculating the temperature field of the motor body, it is necessary to calculate the equivalent convective heat transfer coefficient. Equivalent coefficient of convective heat transfer is calculated by formula (9)

$$h_{eq} = \sum_{i=1}^{N} \frac{h_i s_i}{S}$$  

(9)

Where $s_i$ is the inner wall area of cooling structure. $h_i$ is the heat transfer coefficient of the inner wall. $S$ is the outer circle area of the stator.

Then, the heat transfer coefficient and the heat transfer model are used to calculate the temperature field of the motor body. The outer circular surface of the stator is used as a convective heat transfer surface, and the convective heat transfer coefficient is applied to this surface. When calculating, the setting of heat source is the same as that of the first method.

Because the heat transfer coefficient is uniformly applied to the stator outer circle, the calculated temperature distribution of each winding is basically the same. The temperature field of winding is calculated as shown in Figure 6.

As can be seen from Figure 6 that the winding end has the highest temperature of 378.7K and the central temperature is lower. If the unit is converted to Celsius, the maximum winding temperature calculated by Method 2 is 3% lower than that calculated by Method 1. The axial temperature distribution of the winding is shown in Figure 7.
Figure 7. The axial temperature of the highest temperature winding calculated by Method 2.

The radial temperature distribution of stator teeth is shown in Figure 8. As can be seen from Figure 8, method 1 can reflect the different temperatures between different stator teeth, and method 2 can calculate the maximum temperature of stator teeth very well.

Figure 8. The radial temperature of stator teeth calculated by Method 1 and Method 2.

The variation of maximum temperature of winding with different inlet velocity is shown in Figure 9. As can be seen from the figure, the two methods have a good coincidence.

Figure 9. The highest temperature of windings calculated by Method 1 and Method 2.
For the temperature of high power density motors, we are most concerned about the maximum temperature of their windings. From this point of view, the two calculation methods of motor temperature field have good consistency. The second calculation method can separate the cooling structure of the motor for modelling and calculation, so it is very conducive to the optimal design of the cooling structure, and does not need to repeat the modelling of the motor body. Therefore, when optimizing the cooling structure of the motor, if the method 2 is used, there is no need to repeat the modelling of the motor body, which can greatly improve the design efficiency.

6. Conclusions
Through the analysis of this paper, the following conclusions can be drawn for the two calculation methods.

1. The maximum temperature of the motor is at the end of the winding. The two methods have a good consistency in the calculation of the temperature at the ends of the winding and at the permanent magnets.
2. The first method can better reflect the temperature distribution of the winding while the second method only reflects the highest temperature of the winding.
3. The second method is to separately model and calculate the cooling structure and has very accurate calculation results, therefore, this method can be well used for the optimal design of the cooling structure without repeatedly establish the motor body model, which can greatly improve the design efficiency.

References
[1] Liu, J.H., Li, D.N., Cai, W. (2018) Temperature Rise Analysis of Permanent Magnet Synchronous Motors for EVs in Different Working Conditions. Small & Special Electrical Machines. 46: 5–14.
[2] Li, D. H. (2016) Temperature Field Calculation of Permanent Magnet Synchronous Motor for Pure Electric Vehicles. Small & Special Electrical Machines. 44: 12–16.
[3] Liu, L., Liu, G.F., Liu, M.L. (2015) Analysis on Three-dimensional Temperature Field of Permanent Magnet Synchronous Motor in Vehicles. China Mechanical Engineering, 26: 1438–1444.
[4] Hao, J.S., Suo, S.F. (2018) Investigation on the relationship between winding wire size and total loss of BLDC. In: International Symposium on Power Electronics and Control Engineering. Xi’an.
[5] Zhang, W., Wan, Y.H., Wang, Q. (2016) Analysis on Core Loss Calculation of Permanent Magnet Brushless DC Motor With High Power Density. Micromotors. 49:17-22.
[6] Li, W.L., Li, S.F., Xie, Y. (2007) Stator-rotor Coupled Thermal Field Numerical Calculation of Induction Motors and Correlated Factors Sensitivity Analysis. Proceedings of the CSEE.27:85-91
[7] Jin, T.C., Li, W.L., Li, S.F. (2006) Numerical calculation and analysis of stator thermal field in an induction machine. Electric Machines and Control, 10:492-497.
[8] Tai, Y., Liu, Z.S. (2010) Analysis on Three-dimensional Transient Temperature Field of Induction Motor. Proceedings of the CSEE, 30: 114–120.
[9] Xiong, W.L., Xu, G.S., Lv, L. (2014) Optimizing Heat Dissipation Efficiency for Air-cooling Holes of Rotor of High-speed and Large-power Motor. Mechanical Science and Technology for Aerospace Engineering, 33:735-740.
[10] Li, C.P., Chai, F. (2014) Optimization Design and Analysis of Cooling System Used for Mini Electric Vehicle Motor. In: 17th International Conference on Electrical Machines and Systems. Hangzhou.2413-2417.