Research on Different Cooling methods for High Speed Permanent Magnet Machine

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Abstract. The temperature of electrical machine is determined by the cooling effect and the temperature rise can affect the service life and the power rating of machines. Therefore, improving the method of cooling the machine has an important practical significance. In this paper, a 12-slot high speed PM machine is investigated. The three-dimensional fluid field modes with oil cooling and mixture cooling of air and water are established based on the fluid dynamics theory and the corresponding boundary conditions are given. The calculated value based on the coupled analysis of fluid field with temperature field shows the validity and feasibility of the cooling structure.

Introduction

The high speed permanent magnet machine has been widely investigated since it has high speed, small size, high efficiency and power density [1]. They can be used in various application fields, such as high speed grinder, flywheel energy storage system, centrifugal compressor and so forth. However, the heat dissipation of high speed PM machine becomes a serious problem [2]. Although the high speed machines have many advantages, some new problems appear in high speed condition. The kinds of losses produced by the machines may make the temperature increase and excessive temperature would lead to the insulation failure and even make the machine damaged. In order to ensure the temperature in allowable range, on one hand the loss should be reduced, on the other hand the cooling capacity should be increased.

So, how to ensure the safe and stable operation of machine is always the focus problem during mechanical and electrical fields.

In this paper, according to three-dimensional fluid field theory, the temperature field is studied for a 12-slot high speed PM machine with oil cooling. At the same time the fluid field mode with water and air cooling is established. The calculated value shows the validity of the cooling structure.

The Oil Cooling Mode of High Speed PM Machine

The Oil Cooling Structure of High Speed Machine

Fig.1 represents the oil cooling structure of high speed machine. In this figure, the non-magnetic and nonmetal sheath is used between the stator and the rotor in order to reduce the high frequency eddy loss produced by the high speed. But on the other hand, the disadvantage is that the air gap length and rotor thermal resistance increase.

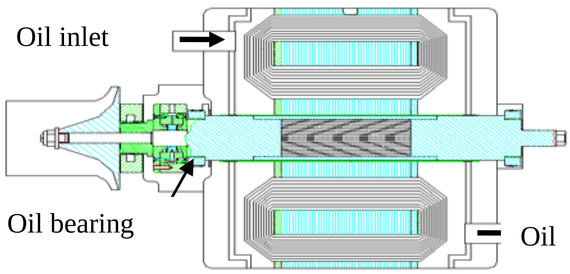


Figure.1 The oil cooling structure of high speed PM machine

Under Cartesian coordinate the fluid motion equation can be represented as the following equations.

Continuous equation

$$\frac{\partial \rho}{\partial t}+\frac{\partial}{\partial x_{\mathrm{i}}}(\rho u_{\mathrm{i}})=0 \tag{1}$$

Momentum equation

$$\frac{\partial u_{\mathrm{i}}}{\partial t}+u_{\mathrm{j}}\frac{\partial u_{\mathrm{i}}}{\partial x_{\mathrm{j}}}$$

$$=-\frac{1}{\rho}\frac{\partial p}{\partial x_{\mathrm{i}}}+\frac{1}{\rho}\frac{\partial}{\partial x_{\mathrm{j}}}\left[\mu\left(\frac{\partial u_{\mathrm{i}}}{\partial x_{\mathrm{j}}}+\frac{\partial u_{\mathrm{j}}}{\partial x_{\mathrm{i}}}\right)\right]+\frac{1}{\rho}\frac{\partial}{\partial x_{\mathrm{i}}}\left(\lambda\frac{\partial u_{\mathrm{i}}}{\partial x_{\mathrm{j}}}\right)+f_{\mathrm{i}} \tag{2}$$

Energy equation

$$\rho c_{\mathrm{V}}\left(\frac{\partial T}{\partial t}+u_{\mathrm{j}}\frac{\partial T}{\partial x_{\mathrm{j}}}\right)=-p\frac{\partial u_{\mathrm{j}}}{\partial x_{\mathrm{j}}}+\phi+\frac{\partial}{\partial x_{\mathrm{j}}}\left(\kappa\frac{\partial T}{\partial x_{\mathrm{j}}}\right) \tag{3}$$

On the basis of viscosity fluid mechanics and the mean method, the fluid general continuous equation and instantaneous N-S control equation are established [3].

$$\frac{\partial \overline{u}_i}{\partial x_i}=0 \tag{4}$$

$$\frac{\partial u_i'}{\partial x_i}=0 \tag{5}$$

$$\rho\frac{\partial \overline{u}_i}{\partial t}+\rho\overline{u}_j\frac{\partial \overline{u}_i}{\partial x_j}=\rho\overline{F}_i-\frac{\partial \overline{p}}{\partial x_i}+ \frac{\partial}{\partial x_j}(\mu\frac{\partial \overline{u}_i}{\partial x_j}-\rho\overline{u_i'u_j'}) \tag{6}$$

Where $\bar{u}_i$ is mean velocity, u_i' is fluctuating velocity, F_i is mass force, p is mean pressure, $i=j=x,y,z$ and $i\neq j$, μ is fluid viscosity coefficient and ρ is fluid density.

The Determination of Computational Area and Basic Area

By the symmetry, the 12th part model of the machine for fluid-solid coupled analysis is as shown in Fig. 2.

In order to facilitate the analysis, the boundary conditions of the model for thermal field analysis are defined as follows:

1) When the machine is steady operation, cooling oil is in a continuous and stable circulation flow state .The physical parameters in oil cooling system are constant and don't vary with time.

2) The stator is soaked in the oil and considering the symmetry of the cooling passages, it can assume that the cooling oil flows into the every oil cooling passage equally by pressure.

3) The fluid is isotropic and incompressible.

In Fig.2, the PM, sheath, stator, inner winding and outer winding are heat source. The interface referred by the black arrow is periodic boundary. The model of fluid-solid coupled boundary condition is as shown in Fig.3.

The boundary conditions of the model for fluid field analysis are defined as follows:

1) A-side is the fluid inlet assumed velocity-inlet and the fluid outlet is set to pressure-outlet.

2) B-side is defined as the interface.

3) C-side and the other side are the fluid-solid coupled interfaces.

4) D-side is defined as the tin shell and simulated as oil jacket.
5) Air gap part is defined as moving Reference Frame.

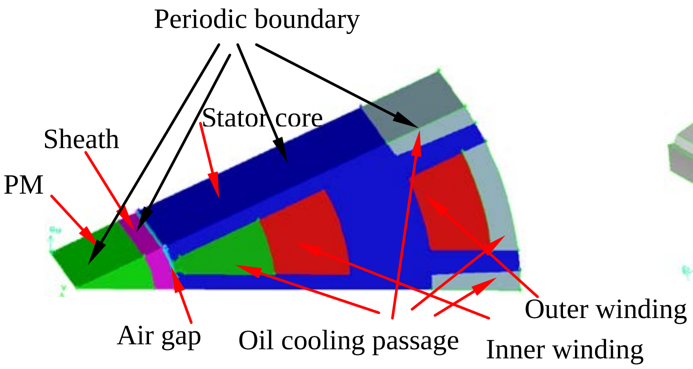
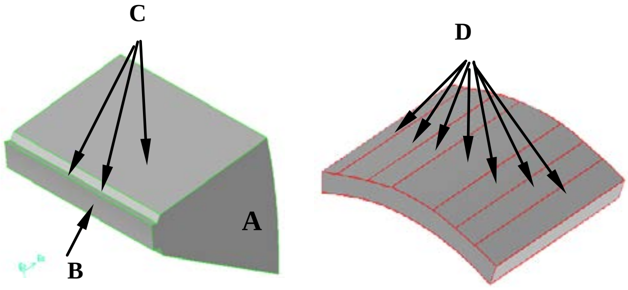


Fig.2.The fluid-solid coupled model for 12-slot PM machine



a) Inner-cooled passage b) Air gap

Fig.3. 3D model of fluid field analysis for PM machine

The Thermal Calculation of High Speed PM Machine with Oil Cooling

The Loss Calculation of High Speed Machine

Accurate calculation of loss is the basis for temperature rise calculation and cooling system design. Through the analysis of core loss and high-frequency additional copper loss, it can be found that the loss has a non-linear relationship with the frequency and the current. Thus, in order to analyze the loss of high speed PM machine, the coupled analysis model and the external circuit are established, as shown in Fig.4 and Fig.5. Fig.6 is the loss curve of core, sheath and winding by finite element analysis.

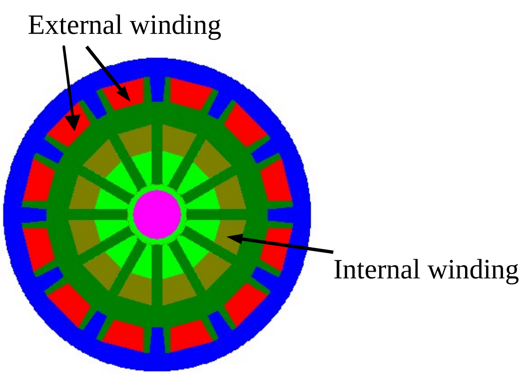


Fig.4 The finite element model for 12-slot PM machine

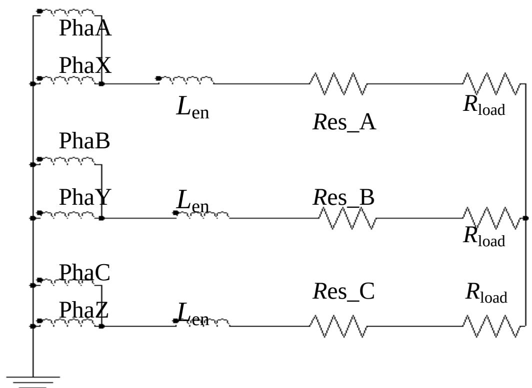


Fig.5 The external circuit for 12-slot PM machine

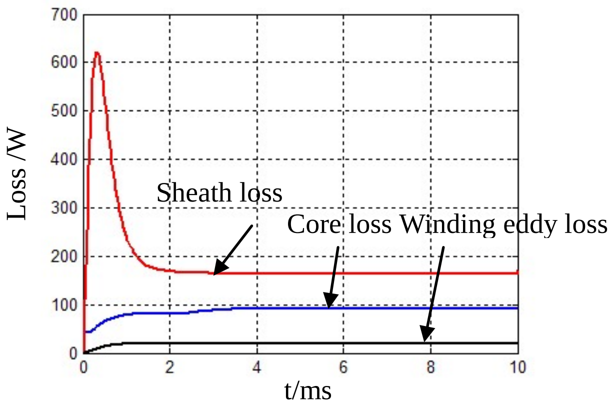


Fig.6 The loss curve for 12-slot PM machine

The Thermal Analysis and Calculation of High Speed PM Machine

The loss results are taken into the fluid field calculation model and windage loss of rotor surface can be obtained by defining speed of rotor surface and surface roughness of rotor [4]. Fig.7 is the temperature distributed diagram of 12-slot oil cooling machine with rated speed of 15000rpm. From Fig.7, it appears that the temperature of stator winding is basically the same as the cooling medium when the machine is operating with rated speed of 15000rpm. So with the increase of the cooling oil temperature, the temperature of the electric machine rises.

The Study of Mix Cooling Methods for High Speed PM Machine

According to the above analysis, the oil cooling method has a good effort on the high efficiency and power density machine. But the disadvantage is that the oil suspension bearing system and the oil cooling system share and it is difficult to ensure oil cooling ability. If oil supply system is divided into two parts, it will make the design complicated and there is also oil spilling question.

Air cooling system has the advantage of simple structure, reliable function and convenient maintenance, but it is hard to meet the ventilation and cooling problem of high loss power density machine. Figure.8 is the temperature distribution of air cooling for12-slot PM machine with rated speed.

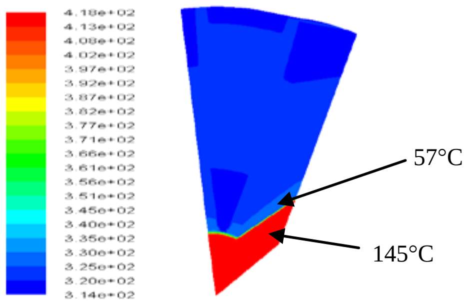


Fig.7 .The temperature distributed diagram with rated speed of 15000rpm for oil cooling

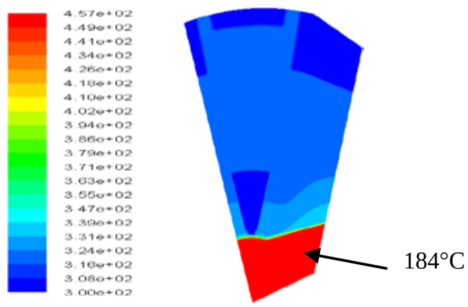


Fig.8 .The temperature distributed diagram for air cooling

From Figure.8, it can be found that PM temperature is beyond the limiting temperature requirement and the magnetism of the permanent magnet may vanish at high temperature. So, design the simple and long running system is concerned with stability operation of high speed PM machine.

When the air cooling can't meet cooling requirement of high speed machine, the air-water mixture cooling method is proposed in this paper. After taking into account the features of air cooling and water cooling, this paper employs a mixture cooling method which means that the air cooling is used in inner ventilation and the water cooling is used in stator shell.

Figure.9 is the fluid-solid coupled model of mixture cooling based on the fluid field and thermal field. Figure.10 is the temperature distribution of air- water mixture cooling for12-slot PM machine with rated speed. The limiting temperature of PM is 180℃. From the figure, it can be shown that air-water mixture cooling method can satisfy the ventilation cooling requirement.

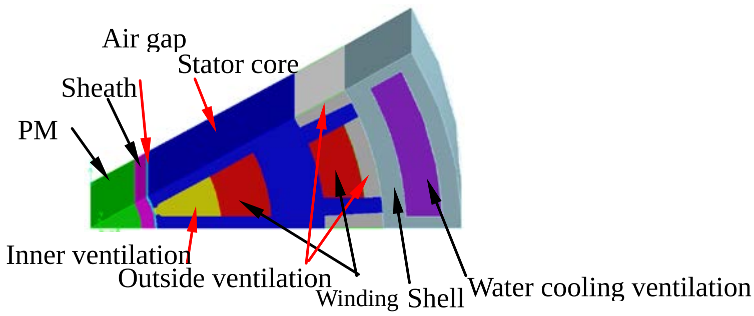


Fig.9 The coupled model for 12-slot PM machine with mixture cooling

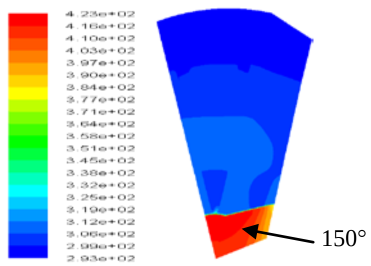


Fig.10 The temperature distributed diagram with air-water mixture cooling

Conclusion

1) According to the features of ventilation system, the oiling cooling analysis model is established by fluid dynamics. The temperature calculation based on fluid-solid coupled model shows the validity of analysis method and the feasibility of cooling structure.

2) By comparing analysis of different cooling methods, it is proposed that the water cooling for stator core and air cooling for inner ventilation are effective and the permanent magnet can't vanish at high temperature.

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