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3D thermal analysis of a permanent magnet motor with cooling fans

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Abstract: Overheating of permanent magnet (PM) machines has become a major technical challenge as it gives rise to magnet demagnetization, degradation of insulation materials, and loss of motor efficiency. This paper proposes a state-of-the-art cooling system for an axial flux permanent magnet (AFPM) machine with the focus on its structural optimization. A computational fluid dynamics (CFD) simulation with thermal consideration has been shown to be an efficient approach in the literature and is thus employed in this work. Meanwhile, a simplified numerical approach to the AFPM machine with complex configuration in 3D consisting of conduction, forced convection, and conjugate heat transfer is taken as a case study. Different simplification methods (including configuration and working conditions) and two optimized fans for forced convection cooling are designed and installed on the AFPM machine and compared to a natural convection cooling system. The results show that the proposed approach is effective for analyzing the thermal performance of a complex AFPM machine and strikes a balance between reasonable simplification, accuracy, and computational resource.

Key words: Axial flux permanent magnet (AFPM) machine, Computational fluid dynamics (CFD), Cooling fan, Motor drives, Thermal analysis
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1 Introduction

In recent years, permanent magnet (PM) machines have attracted much attention in various industries, such as electric vehicles, wind generators, electric ships, and high-speed trains, due to their high torque density and high efficiency in compact packages. With the ever-growing demand for high torque density and drive power, the thermal problems of PM machines have become increasingly studied and the efficient analysis and design of cooling techniques for PM machines have become very important and necessary.

It is widely known that the performance of PM machines in many applications, including high-speed trains, is affected by overheating, which can easily cause magnet demagnetization, and degradation of the isolation materials and of motor efficiency. Therefore, it is very important to develop an effective heat dissipation technique for PM machines. In this paper, a novel and special cooling system design for an axial flux permanent magnet (AFPM) machine is carried out as a case study. In the literature there has been much research on the electromagnetic

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ORCID: Zheng TAN, http://orcid.org/0000-0002-6957-7006; Wen-ping CAO, http://orcid.org/0000-0002-8133-3020 aspects of AFPM machines, but their thermal performance has not been fully investigated (Mellor *et al.*, 1991; Hendershot and Miller, 1994; Lee *et al.*, 2000; El-Refaie *et al.*, 2004; Boglietti *et al.*, 2005; Mezani *et al.*, 2005; Dorrrell *et al.*, 2006; Trigeol *et al.*, 2006; Yu *et al.*, 2010; Wrobel *et al.*, 2013; Chong *et al.*, 2014; Dong *et al.*, 2014). For other types of electrical machines, there are four methods generally used for thermal analysis. These are the lumped parameter network method, the finite element method (FEM), the computational fluid dynamics (CFD) method, and the experimental method. The lumped parameter network method is widely used due to its fast prediction and reasonable simplification. However, to achieve accurate results, the model parameters such as convective heat transfer coefficients, thermal contact resistances, and the properties of components have to be defined or assumed before the analysis, and some of these properties are difficult or impractical to measure in reality. In comparison, the FEM needs less experimental or empirical values for an accurate analysis and it can provide more details about localized temperature distribution. However, the FEM is usually used for conduction heat transfer problem rather than convection heat transfer and conjugate heat transfer problems, and that restricts its wide application for AFPM machines with air-forced cooling. The experimental method is the most effective method, but the test facilities required can be costly and time-consuming. Therefore, for convection heat transfer analysis of AFPM machines with air-forced cooling devices, the CFD method is chosen here because it can consider both conduction and convection phenomena, even though it usually takes a little more time and effort than the lumped parameter network and FEM.

This paper presents a 3D thermal study of an AFPM machine using CFD analysis. The heat source is obtained and defined based on physical experiments. Two kinds of fans for forced convection cooling are designed and installed on the AFPM machine without adding any cooling equipment. The results show that CFD is very efficient for thermal analysis of the AFPM machine at the design stage. The design of cooling fans is helpful in lowering the temperature and avoiding overheating issues in the machine.

2 AFPM machine

The AFPM used in this study for thermal analysis is shown in Fig. 1. It is used for traction drive applications. There are three main components of the machine, of which the first is the rotor disc with 30 embedded permanent magnets, the second is the stator with copper wires wound around a steel core, and the third is the casting supporting the rotor disc and the stator. The copper windings are bundles of individual wires of 0.5 mm diameter coated with a layer of insulation. Fig. 2 shows a simplified model in 3D,

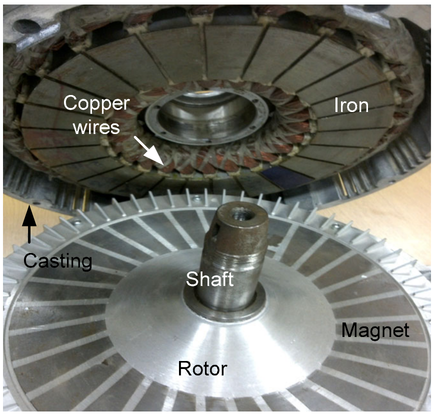

Fig. 1 Photo of the AFPM

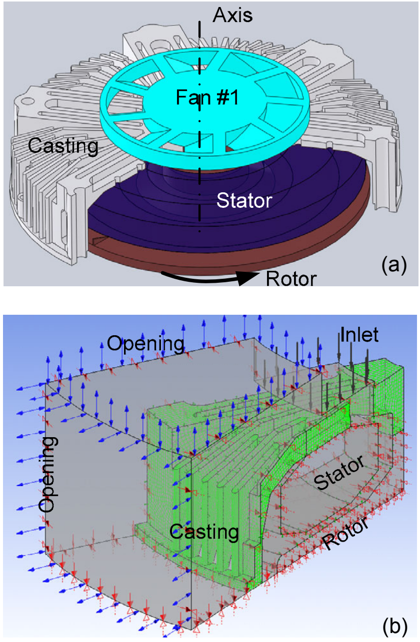

Fig. 2 Numerical model of the AFPM
(a) CAD model; (b) CFD model

which considers the bundles as one non-individual body. The air enters through the cut-out on the casing around the shaft, and flows out from the cut-out on the casing in the axial direction.

3 CFD modelling

The approach used for thermal analysis in this study is based on steady CFD analysis. As mentioned above, it involves both heat conduction and convection transfer. To solve such a conjugate heat transfer problem with a high accuracy, 3D steady Reynolds-averaged Navier-Stokes equations and the energy equation are developed and numerically solved.

Some assumptions are required for solving the heat transfer problem. These are: (1) the flow is turbulent and incompressible, (2) the flow is steady-state, (3) buoyancy and radiation heat transfer are neglected, and (4) the thermo-physical properties of the fluid are temperature independent. Based on these assumptions, the governing equations (continuity, momentum, and energy equations) are established as follows:

$$\frac{\partial(\rho u_i)}{\partial x_i}=0, \tag{1}$$

$$\begin{aligned}\frac{\partial(\rho u_i u_j)}{\partial x_j}=&-\frac{\partial p}{\partial x_i}+\frac{\partial}{\partial x_j}\left[\mu\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}-\frac{2}{3}\frac{\partial u_k}{\partial x_k}\delta_{ij}\right)\right]\\&+\frac{\partial}{\partial x_j}\left(-\overline{\rho u_i' u_j'}\right),\end{aligned} \tag{2}$$

$$\frac{\partial[u_i(\rho E+p)]}{\partial x_j}=\frac{\partial}{\partial x_j}\left[\lambda_{\text{eff}}\frac{\partial T}{\partial x_j}+u_i(\tau_{ij})_{\text{eff}}\right]+S_E, \tag{3}$$

where ρ is the fluid density, u_i and u_j are the velocity vectors in two perpendicular directions i and j, respectively, p is the static pressure, μ is the molecular viscosity, also referred to as the dynamic viscosity, δ_{ij} is the Kronecker delta function, E is the total energy per unit mass, S_E is the energy generation rate per unit volume, T is the temperature, u'_i and u'_j represent the velocity fluctuations, $\overline{\rho u_i' u_j'}$ is the Reynolds stress, λ_{eff} is the effective thermal conductivity, and $(\tau_{ij})_{\text{eff}}$ is the deviatoric stress tensor. Since this is also a conjugate heat transfer problem, which involves heat conduction, the governing equation of the solid is also required:

$$\frac{\partial}{\partial x_j}\left(\lambda_{\text{s}}\frac{\partial T}{\partial x_j}\right)+S_E=0, \tag{4}$$

where λ_{s} is the thermal conductivity of the solid.

A 3D model is built to contain all the rig components and the cooling fan. Fig. 2a shows the sectional structure model with reasonable simplification and with addition of the cooling fan which does not exist in the original model shown in Fig. 1. Fig. 2b depicts the CFD model used for the thermal analysis of the AFPM based on the simplified structural model in ANSYS CFX 14.0. The CFD model is verified in terms of grid size, turbulence model selection, and discretization schemes, and it encloses all components in an air cabinet by using solid-solid interfaces and fluid-solid interfaces. A total of four parts including the flow field (outside and inside) and structure model are built and connected together. Taking advantage of symmetrical geometry, it is only necessary to develop a 1/24 model (30° in the symmetrical model) to reduce the computational burden, in which symmetrical boundary conditions instead of periodic boundary conditions are used in the cut planes, since the planar smooth surfaces of the rotor have less effect on heat transfer even during high speed rotation. The effect of small fins installed along the diameter edge is ignored, because the air gap between the rotor and stator is very small and its precise implementation in the calculation is difficult. From a basic electromagnetic simulation, the total heat generated in the full model is 780 W at 2600 r/min (including winding copper loss and iron loss), so an approximate estimation of heat generated at the stator and rotor can be made as shown in Table 1.

Table 1 Heat generated in the 1/24 model

Component	Volume (m^3)	Heat (W)	Source (W/m^3)
Stator	3.74×10^{-5}	16.25	4.34×10^{5}
Rotor	1.29×10^{-4}	16.25	1.26×10^{5}

To optimize the cooling design, a comparative study is conducted for the AFPM machine under three conditions: no fan, fan #1, and fan #2. Fan #1 is an empirical design based on engineering experience, which is shown at the upper left corner of Fig. 3. Fan #2 with curved surfaces is optimized by aerodynamic study and is shown at the lower right corner of Fig. 3. The two have identical outer diameters and numbers of blades. For the model without a cooling fan, the inlet region in Fig. 2b is set as an opening boundary. In the case of the models with cooling fans, the opening boundary condition at the inlet region is replaced by a constant inlet air mass flow, which is calculated in terms of CFD simulation as shown in Fig. 3 and Table 2. This gives a straightforward way of estimating the mass flow condition for the thermal performance of the AFPM machine, and it can be easily used for other similar CFD analyses without prior knowledge of the mass flow condition.

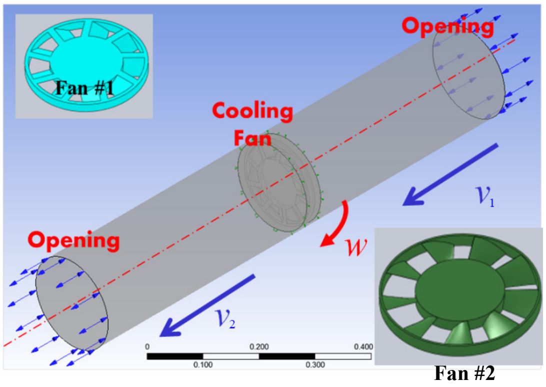

Fig. 3 Simple cooling fan model for mass flow calculations

Table 2 Mass flow rate at three cooling conditions

Fan type	Mass flow rate (kg/s)		
	2600 r/min	4600 r/min	6600 r/min
No fan	No forced ventilation		
#1	0.060	0.106	0.152
#2	0.128	0.227	0.327

Grid quality and independence have been examined to minimize their influence, where the grid of flow field has 462117 nodes, the casting model has 55574 nodes, and the rotor and stator models have 8577 and 1593 nodes, respectively. In addition, the standard k-ε turbulence model is used, and a scalable wall function is implemented over the solid walls. Thermal energy instead of total energy is used to model the transport of enthalpy through the fluid domain due to the low speed flows through and around the machine. Automatic time step control is used and the convergence criteria are assumed to be satisfied if the root mean square (RMS) residual is lower than 1×10^{-5}.

4 Analysis of CFD results

The thermal analysis is carried out on a 64-bit workstation, and each analysis takes about 3 h to converge. Fig. 4a plots the streamline through and around the AFPM with the cooling fan #1. It is found that 74.8% of the total mass flow pumped by the cooling fan flows outside the machine and the remaining 25.2% of the total mass flow ventilates the inside space through the cut-out on the casting. It is evident that both the external air flow and the internal flow play a significant role in heat dissipation. However, the wall heat transfer coefficient plot in Fig. 4b indicates that the external air flow provides the majority of the total heat dissipation as the external flow is much greater than the inside one on the disc surface. To enhance the total cooling performance, it is desired to design a better cut-out on the casing, which would have less pressure loss and thus allow more air flow through it to directly cool the inside surfaces.

Fig. 5 plots the temperature distribution on the three main components of the machine and the middle plane between the stator and rotor discs, where the maximum temperature can be found at the stator at the side approaching the rotor. The contact surfaces between the casting and stator play a significant part in the heat conduction, which leads to a temperature reduction in the stator. The temperature distribution on the middle plane illustrates the flow temperature and shows that, as expected, much heat is taken away by means of the cut-out on the casting.

Table 3 lists the minimum and maximum temperatures in each component with and without cooling fans. Fans #1 and #2 are efficient in decreasing the temperature. In particular, the temperatures of the stator, rotor, and casting with fan #1 decrease by approximately 150, 110, and 150 °C, respectively,

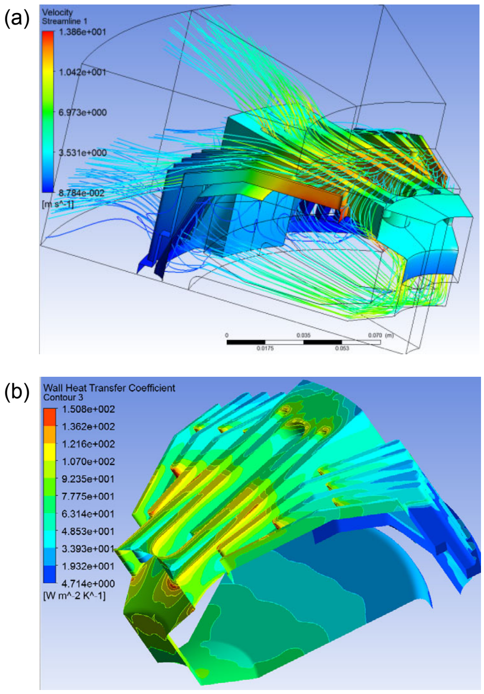

Fig. 4 Air streamline (a) and wall heat transfer coefficient (b) around the AFPM with fan #1

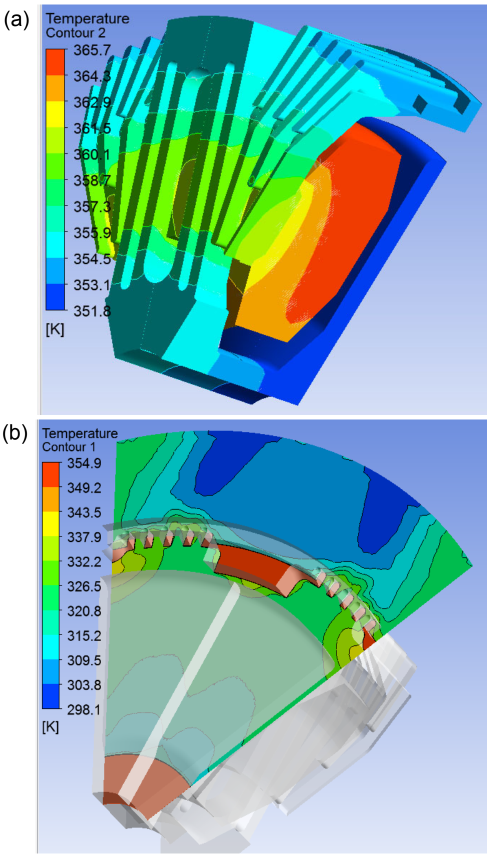

Fig. 5 Temperature distribution of the machine (a) and the middle plane at the air gap (b)

Table 3 Component temperature at three ventilation conditions

Fan type	Temperature (°C)					
	Stator		Rotor		Casting	
	Min	Max	Min	Max	Min	Max
No fan	237.5	247.2	192.1	215.4	213.6	242.5
#1	86.8	92.5	78.6	80.5	80.5	87.6
#2	72.1	77.7	65.4	66.7	66.0	72.9

as compared to the machine without a cooling fan. The design with fan #2 has an even better cooling performance, resulting in a further 15 °C reduction compared to fan #1.

5 Conclusions

In this study, the CFD method has been used to investigate heat transfer in an axial flux permanent magnet machine and to optimize a cooling fan design. Some simplifications and assumptions are made to facilitate a numerical analysis, based on the steady CFD method, to predict the coolant air mass flow, velocity, and pressures outside and inside of the machine and the temperature distribution of the machine. The comparison results of the AFPM machine without a cooling fan and with two designs of cooling fans reveal that cooling fans are helpful in enhancing heat transfer and reducing the temperature of the machine, and a good design of cooling fans based on aerodynamics is efficient and essential to avoid overheating problems. Further work will be set out to conduct extensive experimental tests on these prototypes.

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中文概要

题　目： 配有冷却风扇的永磁电机三维热分析

目　的： 提出一种适合永磁电机的冷却系统设计方案，降低电机本体温度。

创新点： 提出一种适合永磁电机热分析的CFD仿真模型。

方　法： 采用计算流体动力学方法对包含冷却风扇的永磁电机进行空间三维热力学分析和优化设计。

结　论： 本文提出并优化后的冷却风扇可有效降低永磁电机的最高和平均温度。

关键词： 轴向磁通永磁电机；计算流体动力学；冷却风扇；电机驱动；热分析