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Investigation of Ferrofluid Cooling in Modular Permanent Magnet Machines

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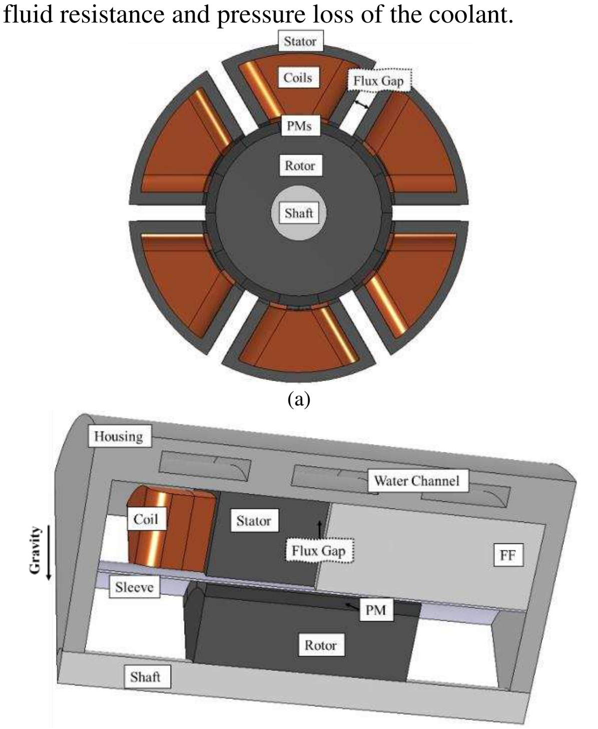
***Abstract*— Compared with conventional non-modular machines, the flux gaps in alternate stator teeth of the modular machines can increase the winding factor and provide flux focusing effect, and hence can increase the torque/power density. In addition, the flux gaps can also be used as cooling channels to improve the thermal performance. This paper investigates an advanced cooling approach using ferrofluid as coolant to fill in the cavity around end-windings and flux gaps. The multiphysics modelling in this paper has shown that the influence of the flux gaps on machine thermal performances comes from two aspects: (1) the gravitational effect, the flux gaps allow more self-circulating coolant to transfer heat to the housing. This helps to reduce machine temperature by around 5℃ for a flux gap width of 2mm; (2) the magnetic body force, i.e., the thermomagnetic effect. This is very effective in non-modular machine cooling. But its efficiency slightly deteriorates in the modular machines. This is because the self-circulation of ferrofluid in the flux gaps due to the gravitational effect has been negatively affected by the thermomagnetic effect.**

***Index Terms*— Ferrofluid cooling, magnetic body force, permanent magnet machine, thermomagnetic effect.**

I. Introduction

Permanent magnet (PM) machines are widely used in various applications, including aerospace, electrical and hybrid electrical vehicles, and wind power due to their high torque/power density and high efficiency. By inserting flux gaps into alternate stator teeth of a conventional PM machine [see Fig. 1 (a)], a modular PM machine with stator modularity has been obtained [1]. Such modular machine can achieve even higher torque/power density than the conventional PM machine. This is because the introduced flux gaps can maximize the winding factor and introduce a flux focusing effect. In addition, the introduced flux gaps can also mitigate the magnet demagnetization of the modular PM machines [2]. However, for all the PM machines, elevated temperature will reduce the remanence of PMs, which will affect and limit the electromagnetic performance of the PM machines. In addition, overheating PMs can even lead to irreversible demagnetization that permanently reduces the magnetization of PMs. Temperature rise is also harmful to winding insulation. As a rule of thumb, a 10℃ temperature rise over the rated temperature would halve the insulation life. Therefore, advanced cooling methods become increasingly important for PM machines as they can improve machine power density and efficiency, and protect them from overheating.

The literature review has shown that many different cooling methods have already been adopted for PM machines used in various applications. Some of them are passive cooling methods, e.g., back-iron lamination extension [3]. The passive cooling methods do not employ extra pump or fan to drive the coolant. However, it is less efficient than forced air/liquid cooling methods. Water jacket is a typical forced cooling method that can remove heat very efficiently within the machines [4]. The forced air cooling [5] and semi-flooded/wet stator [6] are other efficient forced cooling methods. Different from water jacket, the coolant of these types of cooling methods is in direct contact with the end-windings and other machine internal components, e.g., stator and rotor iron cores as well as PMs. Therefore, they can achieve virtually the best heat transfer rate [7]. Such cooling methods have also been adopted for the modular PM machines as flux gaps in the stator can be used as extra cooling channels that allow the fluid to pass through. One study in [8] has shown that, compared to a standard water jacket, extending the water jacket to the flux gaps can reduce the temperature in slot area by 10%. Other studies employed the flux gaps as a cooling channel for forced air cooling and semi-flooded cooling [9]. The results have shown an approximately 10% temperature reduction after introducing the flux gaps. This is mainly because the flux gaps not only can increase the contact area between the coolant and the machines, it also can increase the cross-sectional area of the coolant path, which will reduce the fluid resistance and pressure loss of the coolant.



(b)

Fig. 1. Topology of the modular machine. (a) Internal components and (b) whole machine with water jacket and ferrofluid cooling.

Ferrofluid (FF) cooling is a novel semi-flooded cooling method that the coolant is also in direct contact with the end-windings, but it does not require extra pumps to drive the coolant. Therefore, it becomes an attractive alternative for machine cooling. The ferrofluid can be driven by external magnetic field due to the magnetic body force, which results in a self-circulation of the coolant and improve the overall heat transfer rate. This phenomenon is called thermomagnetic effect [10]. This paper investigates the possibility of adopting ferrofluid for cooling the modular machine. In this study, ferrofluid will be used to fill in the cavity in both the end-space and flux gaps, as shown in Fig. 1 (b). In order to investigate the ferrofluid cooling, multiphysics modeling is essential. To this end, 3D COMSOL Multiphysics software has been selected for the investigations as it can consider the strong coupling between electromagnetics and fluid dynamics. This means that during each iteration of simulations, interaction between electromagnetic (EM), fluid dynamics and thermal will be considered. For the computational fluid dynamics (CFD) modelling, the mesh near the wall should be cuboid mesh, and the aspect ratio of which is large. However, this will be computationally expensive. To ensure the models are computable and to achieve an accurate prediction of machine temperature, high y^+ wall treatment [11] is introduced in the coolant that around the machine end-windings. According to the mesh sensitive test in [14], the predicted machine temperatures are accurate enough. For the modular machine, the thickness of the first mesh layer is 0.1mm for the machines with different flux gap widths and the total number of layers is 8 in the flux gaps.

II. Theoretical Background

Ferrofluid is one type of suspension that the nano-sized ferro- or ferrimagnetic particles dissolve in a liquid base. It can subject to magnetic body force because each magnetic dipole of the ferrofluid subjects to different polarization force in the presence of magnetic field gradients or discontinuities [10]. Similar to ferromagnets, the magnetization of ferrofluid increases with increased magnetic field strength, while the increase rate gradually reduces to near 0 when it reaches the saturation magnetization. However, the ferrofluid in the presence of relatively weak magnetic field (whose Langevin argument is much smaller than 1) can be considered as a superparamagnetic material. In other words, the magnetization (M) linearly increases with the magnetic field strength (H) as

$$M = \chi H \tag{1}$$

where χ is the susceptibility of ferrofluid and given by an approximation of Langevin's law [12]

$$\chi = \frac{\phi \mu_0 \pi d^3 M_{s,p}(T)^2}{18 k_B T} \tag{2}$$

where ϕ and d are the volume fraction and average diameter of ferromagnetic particles, respectively. μ_0 is the vacuum permeability, $k_B = 1.38 \times 10^{-23}$ J/K is the Boltzmann constant, and T is the absolute temperature. $M_{s,p}(T)$ is the saturation magnetization, which can be derived by Bloch's law

$$M_{s,p}(T) = \begin{cases} M_0\left(1 - \left(\frac{T}{T_c}\right)^{1.5}\right), (if\ T \leq T_c) \\ 0, \quad (if\ T > T_c) \end{cases} \tag{3}$$

where M_0 and T_c are the saturation magnetization at absolute zero kelvins and the Curie temperature of the ferromagnetic particles in the ferrofluid.

Since the ferrofluid is considered as a superparamagnetic fluid, the magnetic body force (F_m) it is subjected to can be derived by Kelvin body force formula as [10]

$$\boldsymbol{F_m} = \mu_0(\boldsymbol{M} \cdot \boldsymbol{\nabla})\boldsymbol{H} \tag{4}$$

III. Multiphysics Modelling of Ferrofluid Cooling

A. Machine Specifications

The specifications of the modular machine investigated in this paper are given in Table I and the cross-section is shown in Fig. 1 (a). To reveal the impact of flux gaps on the ferrofluid cooling of the PM machines, a comparative study of the conventional PM machine, i.e., the non-modular machine without flux gaps, will also be investigated for comparison. The ferrofluid has filled in the cavity around the end-windings for both investigated machines, as well as in the flux gaps for the modular machines, as shown in Fig. 1 (b). The properties of the ferrofluid used in this study are the same as in [12], as listed in Table II.

TABLE I Parameters of the Modular SPM Machine

Slot number	12	Magnet remanence (T)	1.2
Pole number	14	Stack length (mm)	50
Stator outer radius (mm)	50	End-winding overhang (mm)	20
Stator yoke height (mm)	3.7	Housing radius (mm)	65
Tooth width (mm)	7.1	Housing length (mm)	120
Flux gap width (mm)	2	Housing thickness (mm)	10
Airgap length (mm)	1	Number of coils per phase	132
Rotor outer radius (mm)	27.5	Wire diameter (mm)	1.32
Rotor yoke thickness (mm)	15.5	Current density (A/mm^2)	18.4
Magnet thickness (mm)	3	Rated speed (rpm)	400

TABLE II Parameters of the Ferrofluid [12]

Particle volume fraction (%)	5.4
Particle average diameter (nm)	16
Magnetization (A/m)	3.87×10^5
Curie temperature (K)	793
Density (kg/m^3)	1115
Thermal conductivity ($W/m \cdot K$)	0.186
Dynamic viscosity ($Pa \cdot s$)	0.0787
Specific heat capacity ($J/kg/K$)	1.685×10^3

B. Assumptions and Initial Conditions

In order to reduce the simulation time and make the multiphysics model solvable, several assumptions and simplifications should be introduced as below:

a. Load Current

The relaxation time of magnetization (τ_m) is of the order of 10^{-5}s that specified by Brownian and Neel mechanisms [13]. The onload current is an alternating current (AC) with a period (τ_e) of $3/140$s. Since $\tau_m \ll \tau_e$, the direction of the magnetic body force can be assumed to change instantly with the magnetic field. In addition, the hydrodynamics and thermodynamics time constant (τ_f), ranging from minutes to hours, is much larger than τ_e. As a result, using a DC to represent the AC has been deemed acceptable. This assumption has been wildly employed in the literature [10, 12, 13].

b. Losses and Heat Sources

For the investigated machine with a load current density of 18.4 A/mm^2 and a rotational speed of 400rpm, the copper losses is the major loss component (>99.5%) and heat source. Therefore, the iron losses and the PM eddy current losses have been neglected in the modelling. In addition, since this paper focuses on the comparison of ferrofluid cooling performance for the modular and non-modular machines, both machines will be assumed to have the same copper losses.

c. Electric Current and Lorentz Force in Ferrofluid

Based on the findings in [10], the electrical resistivity of the ferrofluid is larger than 10^9 $\Omega\cdot$cm. Therefore, the electric current and Lorentz force in the ferrofluid can be neglected.

d. Gravitational Effect and Thermal Expansion

Based on the simulations, it is found that the gravitational effect (gravity) is significant and can also lead to the circulation of the ferrofluid. Therefore, the gravity has been considered in the simulations and its direction is vertical to the shaft, as shown in Fig. 1 (b). The thermal expansion of ferrofluid is 6.62×10^{-4} K^{-1}. This means that the density variation due to thermal expansion is relatively small, and hence the thermal expansion has been neglected in the modelling. To consider the gravitational effect without density variation, the Boussinesq approximation is employed in the models.

e. Boundary Conditions

For the investigated PM machines, a water jacket is introduced, as shown in Fig. 1 (b), to maximize the cooling efficiency of the ferrofluid. The inlet flow rate and temperature of the water jacket are 1.37L/min and 65℃, respectively. This inlet flow rate can be achieved by assuming a 1200Pa pressure drop. The water jacket is represented by an effective convection coefficient (h_e) in the multiphysics models to reduce the computation time. It can be derived by

$$h_e = \frac{Q}{T_{wall} - T_{ref}} \tag{5}$$

where Q is the average heat transfer rate per surface area from the machine inner regions to its housing. T_{wall} is the temperature of the housing surface and T_{ref} is the reference temperature. Based on the CFD simulations, the convection coefficient is 3718 $W/m^2/K$ while the reference temperature is 65℃. On the surface of endcaps that is not wrapped by water jacket, natural cooling is used, and the convection coefficient is assumed to be 8 $W/m^2/K$ and the reference temperature is 20℃.

C. Results and Discussion

Two planes that are vertical (plane 1) and horizontal (plane 2) to the machine rotation axis (along the shaft) are chosen to show the temperature distribution and fluid flow, as shown in Fig. 2. The plane 1 is located at end-space of the investigated machines and its distance to the endcaps is 5mm. It is worth noting that the models built in this paper are similar to those that have been validated by experiments in [14] and [12]. This provides sufficient confidence in the results obtained in this paper.

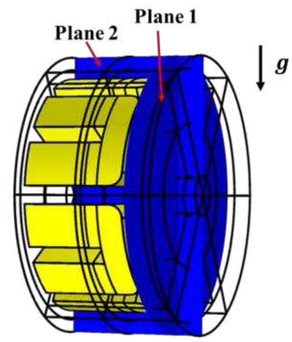


Fig. 2. Planes chosen to show the temperature distribution and fluid flow.

a. Different Machine Topologies

In this section, the cooling performance of ferrofluid for modular and non-modular SPM machines has been compared. To fully assess the impact of thermomagnetic effect, air and nanofluid are introduced as new coolant materials to be compared against the ferrofluid. It is worth noting that the properties of nanofluid is the same as the ferrofluid, except it is not subject to magnetic body force from an external magnetic field. Therefore, there is no thermomagnetic effect for the nanofluid. Typically, the coolant circulations established by air and nanofluid follows the same principle. When coolant is heated by the coils, the warmer coolant, due to buoyancy, will move towards the opposite direction of gravity. In the cases investigated in this paper, the warmer coolant moves from end-winding region to the housing. The ferrofluid is also influenced by this phenomenon. However, it is also subject to magnetic body force, which is affected by the gradient of magnetic field, the gradient of temperature and the magnetic field strength. For the cases investigated in this paper, both coolant circulations established by gravity and magnetic body force of the ferrofluid occur between the housing and the end-windings. Therefore, the ferrofluid is expected to exhibit good cooling efficiency.

For all the investigated machines with different coolants (air, nanofluid and ferrofluid), the initial temperature is the inlet temperature (65℃) of the water jacket. The temperature gradually increases to the steady state temperature, as shown in Fig. 3. The results show that, the maximum winding temperatures of the modular (127.8℃) and non-modular (128.1℃) machines are very close when air is used as coolant. This indicates that, although the modular machine with 2mm flux gaps rearranges the losses distribution and improve the contact surface area between the stator iron core and coolant (air), the temperature reduction is insignificant due to the poor thermal conductivity of air.

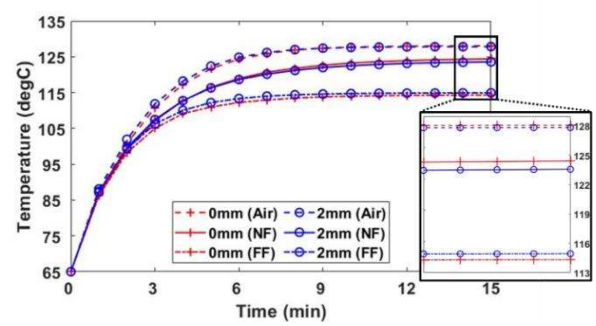
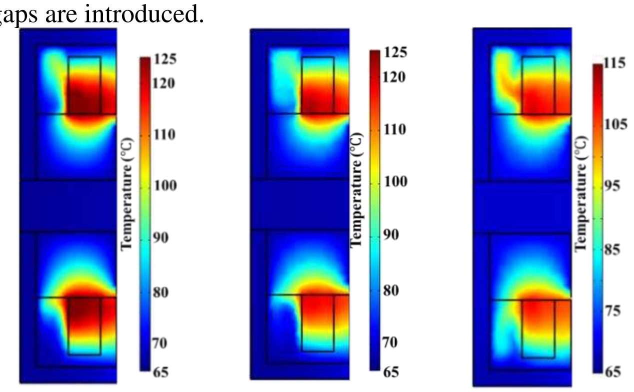


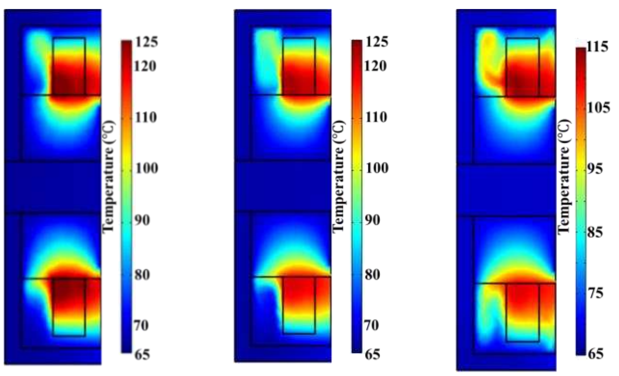
Fig. 3. Maximum winding temperature for the modular (FG=2mm) and non-modular machines (FG=0mm) with different coolants such Air, NF (nanofluid) and FF (ferrofluid).

However, when nanofluid is used, a noticeable temperature reduction can be achieved as the self-circulation of the nanofluid is much more efficient than air, as shown in Fig. 4 and Fig. 5. This is because thermal conductivity is increased from 0.025W/m/K (air) to 0.19W/m/K (nanofluid). Faster heat transfer rate allows the coolant to move more heat from end-windings to the housing and end-caps. Therefore, compared with air cooling, nanofluid cooling reduces the winding temperature by 3.7℃ for the non-modular machine and the temperature reduction (4.3℃) is more pronounced when flux gaps are introduced.



(a) (b) (c)

Fig. 4. Temperature distributions at plane 2 for the non-modular machine with (a) air, (b) nanofluid and (c) ferrofluid.



(a) (b) (c)

Fig. 5. Temperature distributions at plane 2 for the modular machine with (a) air, (b) nanofluid and (c) ferrofluid.

When nanofluid is replaced by ferrofluid, the machine temperature can be further reduced for both the investigated machines. According to Fig. 4 (c) and Fig. 5 (c), the cooler coolant is attracted by end-windings and moves towards their centers. This is because the direction of the magnetic body force that the ferrofluid is subjected to points towards the end-windings, which are the sources of magnetic field and heat. Therefore, the cooler coolant can be driven to the center of the end-windings (hotspot), as shown in Fig. 6. It can enhance the self-circulation rate of the coolant. As a result, it is found that for the non-modular machine, using the ferrofluid to replace the nanofluid can further reduce the maximum temperature by 10.1℃, while it is 8.6℃ for the modular machine. It is revealed that, unfortunately, the introduced flux gaps reduce the cooling efficiency of the ferrofluid. This is because different from the magnetic field produced by the end-windings that can generate a coolant circulation between the housing and the end-windings, the magnetic body force of the ferrofluid in the flux gaps drives the cooler coolant, not the warmer coolant, to the housing, as shown in Fig. 7. As a result, it slightly deteriorates the cooling efficiency of the ferrofluid in the flux gaps.

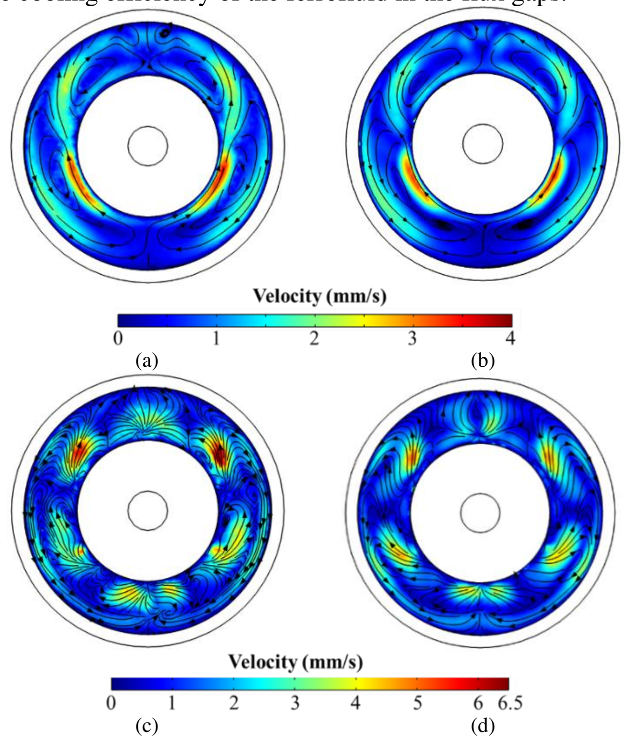


Fig. 6. Coolant velocity distributions at plane 1 of (a, c) non-modular and (b, d) modular PMSM with (a, b) nanofluid and (c, d) ferrofluid fluid cooling.

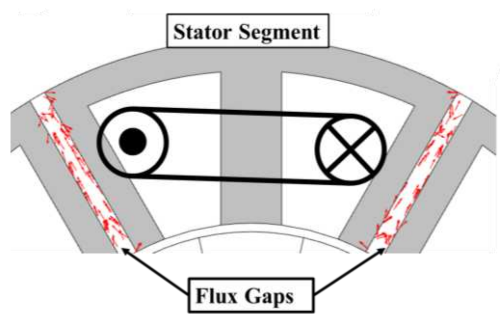


Fig. 7. Magnetic body force vectors in the flux gaps.

b. Different Flux Gap Widths

In the section above, the investigations based on modular machines with a 2mm flux gap width has shown improved cooling performance with ferrofluid cooling. In this section, the influence of different flux gap widths on the cooling performance will be investigated. When the flux gap width increases from 0mm (non-modular machine) to 5mm (modular machine), the maximum winding temperatures for air cooling and nanofluid cooling will gradually reduce as shown in Fig. 8, meaning that the cooling efficiency improves. The main reason is that, with the increase in flux gap width, the fluid resistance reduces. The gravitational effect is more significant due to wider flux gaps. Therefore, a faster self-circulation of coolant in the flux gaps can be achieved. For example, the maximum nanofluid velocity in the flux gaps is 0.17mm/s when the flux gap width is 2mm. This value increases to 0.8mm/s when the flux gap width increases to 5mm.

However, when the ferrofluid is used, the trend is not obvious, as some flux gap widths will increase the temperature. This is because although the wider flux gaps will increase gravitational effect of the coolant, same as air and nanofluid cooling, the wider flux gaps can also enhance the influence of magnetic body force. The improved magnetic body force deteriorates the self-circulation of coolant. The temperature difference ($\Delta_{NF\text{-}FF}$) between nanofluid and ferrofluid, as shown in Fig. 8, shows that wider flux gaps will lead to more significant deterioration of the ferrofluid self-circulation.

In conclusion, the simulation results have demonstrated that, the flux gap width has significant influence on machine cooling performances. And wider flux gaps have positive influence on the gravitational effect but negative influence on the thermomagnetic effect.

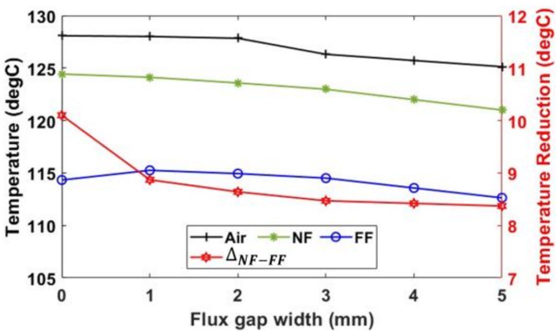


Fig. 8. Maximum winding temperatures *vs* flux gap width for different coolants such as Air, NF and FF, and temperature difference ($\Delta_{NF\text{-}FF}$) between NF cooling and FF cooling *vs* flux gap width.

IV. Conclusion

An advanced cooling technology that uses ferrofluid to fill in the cavity around end-windings and flux gaps of the modular machines has been investigated. 3D multiphysics models have been developed to predict the behavior of coolant and the thermal performances of investigated machines. The simulation results have shown that the ferrofluid can significantly reduce machine temperatures, especially the end-winding temperatures. Its cooling performance comes from two aspects: (1) compared with air, the ferrofluid has higher thermal conductivity and density. Hence, its gravitational effect is more significant; (2) the ferrofluid subjects to magnetic body force in the presence of non-uniform magnetic field, leading to a coolant circulation between the housing and the end-windings. The simulation results show that, when ferrofluid is employed to replace air for a conventional non-modular machine, the maximum temperature is reduced by 13.8℃, in which 10.1 ℃ is attributed to the magnetic body force and 3.7 ℃ results from the gravitational effect.

The results have also revealed the impacts of flux gaps on the cooling efficiency. They provide extra cooling path for coolant circulation and more contact surface between the coolant and the machine active parts. Therefore, if only the gravity for ferrofluid cooling is considered, the machine temperature reduces further by 0.9℃ when 2mm flux gaps are introduced. This temperature reduction is enlarged to 3.4℃ when flux gap width increases to 5mm. However, when magnetic body force for ferrofluid cooling is also considered, the presence of flux gaps deteriorates the cooling performance due to the magnetic body force. Although ferrofluid has been effective in reducing the temperature, for example, 10.1℃ reduction due to magnetic body force for a 0mm flux gap width, i.e., non-modular machine, this reduces to 8.4℃ for the modular machine with a flux gap width of 5mm.

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