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Thermomagnetic Cooling for High Power/Torque Density Electrical Machines

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I. Introduction

Thermal management has long been regarded as one of the main limiting factors for the achievable power/torque density of electrical machines. A common technique for improving the cooling efficiency of high-power density applications is to use forced liquid cooling involving channels, ducts, or water jackets. Such methods provide excellent cooling within the active part of the windings (in stator slots). However, due to the lack of a good thermally conductive path between end-winding and cooling systems, often located in the stator housing, they do not have the same effectiveness around end-windings, resulting in a single hottest spot being localized in this area. Methods such as spray cooling, flooded, or semi-flooded stators are proposed for end-winding cooling. Both methods are very effective because the cooling fluid is in direct contact with the end-winding. However, due to corrosion and erosion of spray nozzles, spray cooling suffers from reliability and robustness issues. Moreover, both spray cooling and flooded stator often require a closed-circuit liquid (oil or deionized water) supply equipped with mechanical pumps, filters, etc., which adds to capital and operating costs while also leading to a reduction in effective machine power density [1].

In order to overcome the challenges facing traditional spray cooling or flooded stator cooling, we have proposed a novel thermomagnetic liquid cooling, as shown in Fig. 1, where a carbon sleeve is used to prevent liquid leakage to the rotor. This research was supported by the UK Engineering and Physical Science Research Council (EPSRC) under Grant No. EP/T017988/1. The thermomagnetic cooling medium is based on ferrofluid, which is an electrically nonconductive, temperature sensitive fluid mainly consisting of ferrimagnetic nanoparticles (usually magnetite – Fe_3O_4 with a particle diameter of 5-15nm) suspended in a liquid carrier (synthetic oils, hydrocarbons, or water). When such a liquid experiences a temperature variation under an external magnetic field, the fluid behaves as a smart fluid, i.e. it will have higher magnetisation in lower temperature region (further away from the heat source) than in higher temperature region [2]. As a result, a net magnetic driving force is produced to self-drive the fluid to flow towards the heated area (heat source with higher temperature). Due to this special feature, the thermomagnetic liquid cooling will be self-regulating, pumpless and maintenance free and hence very cost effective. Such thermomagnetic convection principles have already been investigated for electronic systems cooling [3], and could have promising potentials for electrical machine cooling as well [1].

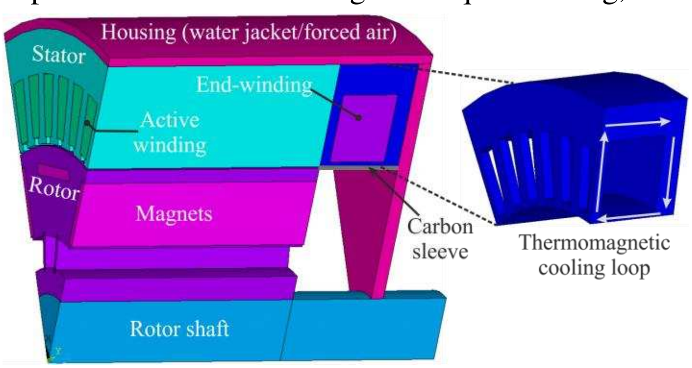


Fig. 1. Interior permanent magnet machine with thermomagnetic cooling loop (1/16 model). End-winding is immersed in the ferrofluid. Arrows in cooling loop represent fluid circulation.

II. Theoretical Background and Multiphysics Modelling

A. Theory about Ferrofluid

As mentioned earlier, ferrofluids can be utilized in machine cooling due to their response to an external magnetic field (often generated by the end-windings). When exposed to this external magnetic field, the nanoparticles within the ferrofluid experience a magnetic body force, as described by equation (1) [4]. This force propels the coolant, inducing thermomagnetic convection, which aids in cooling the end-windings. It is generally understood that increasing this magnetic body force can improve the cooling efficiency of the ferrofluid. The magnitude of the magnetic body force primarily relies on the intensity of the applied external magnetic field (***H***) and the temperature-dependent magnetization (***M***) of the ferrofluids.

$$\boldsymbol{F_m} = \mu_0(M \cdot \boldsymbol{\nabla})\boldsymbol{H} \quad (1)$$

B. Assumptions and Boundary Conditions for Multiphysics Modelling

Given the unique properties of ferrofluids, it is important to highlight that multiphysics modelling must account for the significant coupling between electromagnetics, thermal dynamics, and fluid dynamics. To streamline simulation time and ensure solvability of the multiphysics model, several assumptions and simplifications should be introduced, as outlined 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 [5]. 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 considered as the same as the direction of 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 direct current (DC) to represent the AC has been deemed acceptable.

b. Electric Current and Lorentz Force in Ferrofluid: Based on the findings in [6], the electrical resistivity of the ferrofluid is larger than 10^9 Ω·cm. Therefore, the electric current and Lorentz force in the ferrofluid can be neglected.

c. 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, which is placed horizontally. The thermal expansion of ferrofluid is 6.62×10^{-4} K^{-1}, which is relatively small, and hence has been neglected in the modelling.

d. Boundary Conditions: For the investigated machines, a water jacket is introduced 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.

III. Results and Discussions

A. Machine Specifications and Ferrofluid Properties

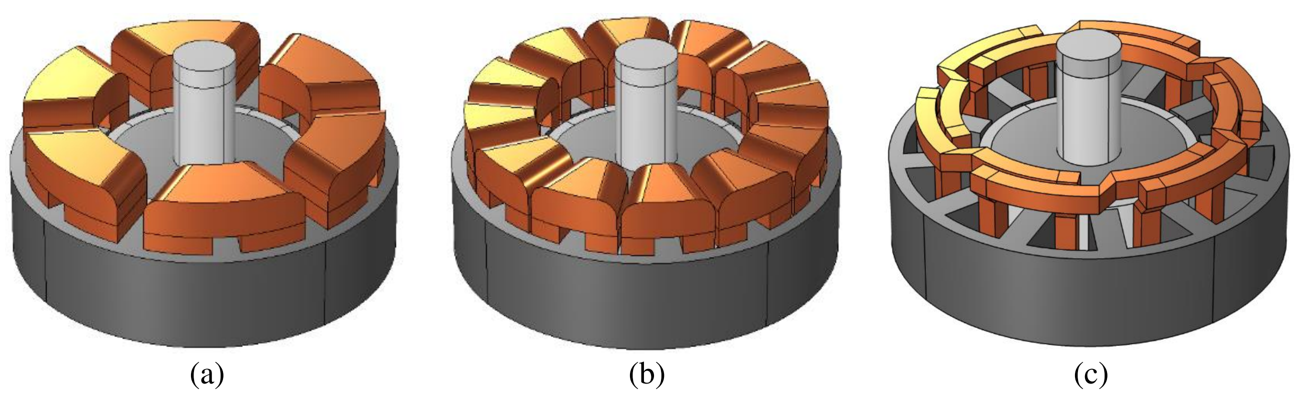


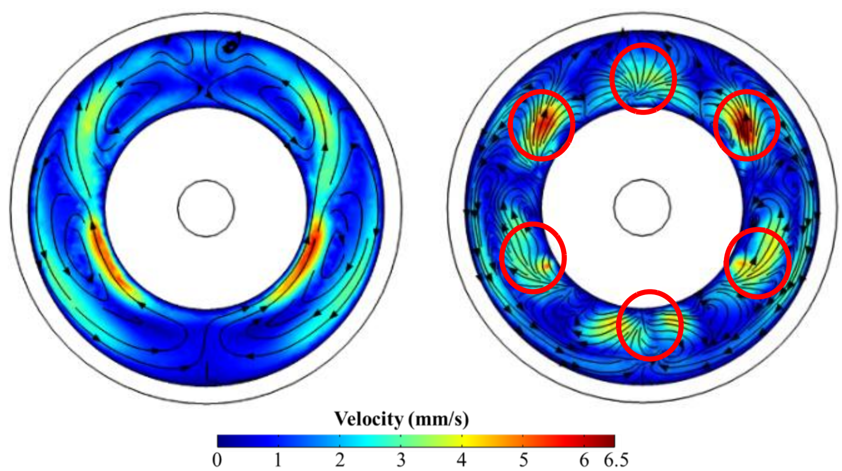
Fig. 2 Machine topologies investigated with (a) and (b) single- and double-layer concentrated windings [7], and (c) distributed windings [8].

Some typical permanent magnet (PM) machines with different winding structures have been investigated. These machines are shown in Fig. 2, and they cover a wide range of industry applications, ranging from electrical vehicles, through renewables to aerospace. For comparison purposes, these machines all have the same specifications. For example, they all have 12 slots and 14 poles, the stack length is 50mm, the outer diameter is 100mm, the airgap length is 1mm, the number of turns per phase is 132, the current density is $18.4 \mathrm{A/mm^2}$, and the rated speed is 400rpm. The magnet has a thickness of 3mm and a remanence of 1.2T.

The ferrofluid used in the simulations is the same as that used in [9]. The liquid base for the ferrofluid is vegetable oil. The parameters of the ferrofluid are: particle volume fraction is 5.4%, particle average diameter is 16nm, magnetization is 3.87×10^5 A/m, Curie temperature is 793K, density is $1115 \mathrm{kg/m^3}$, thermal conductivity is $0.186 \mathrm{W/m \cdot K}$, dynamic viscosity is $0.0787\ \mathrm{Pa \cdot s}$ and specific heat capacity is $1.685\times 10^3\ \mathrm{J/kg \cdot K}$.

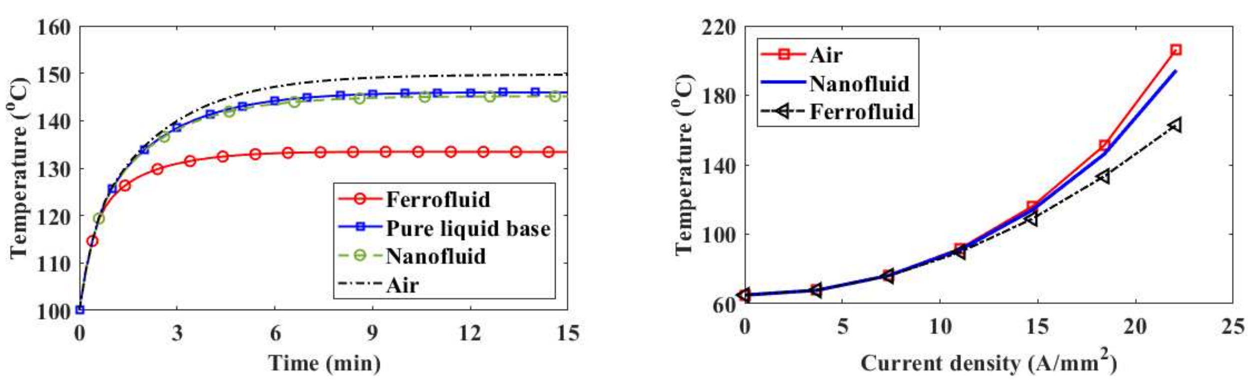
B. Numeric Results

For comparison purposes, other coolants have also been investigated and compared against ferrofluid. These materials include air, pure liquid base (without nanoparticles), and nanofluid. The latter is a virtual material that has the same property as ferrofluid but has no magnetic body force. As a result, it does not have thermomagnetic convection effect. Using the single layer machine shown in Fig. 2 (a) as example, the coolant velocity within the end-winding space has been calculated, as show in Fig. 3. If the coolant is nanofluid within the end-winding region, it will be circulating from the bottom to the top. This circulation is mainly driven by buoyancy, where hotter coolant (lighter) moves upwards, while cooler (heavier) coolant moves downwards. This phenomenon is also observed with air and pure liquid base. However, due to the magnetic body force generated by ferrofluid, its circulation is more localized, around 6



(a) (b)

Fig. 3 Coolant velocity within end-winding space (cross-sectional view). (a) Nanofluid, and (b) ferrofluid.



(a) (b)

Fig. 4 Peak temperature at end-windings. (a) Temperature *vs* time at rated condition, and (b) temperature *vs* current density.

individual end-windings. This provides a more uniform coolant flow, thereby enhancing cooling efficiency.

This has been validated by calculating the peak temperature at the end-windings, as depicted in Fig. 4. In Fig. 4 (a), it can be observed that the temperature decreases by approximately 4°C when transitioning from air to pure liquid base. This reduction is primarily attributed to the higher thermal conductivity of liquids compared to gases. Similarly, there is a slight temperature decrease when nanofluid is used compared to pure liquid base. This is mainly because nanoparticles (essentially metals) added to nanofluid slightly increase its thermal conductivity. When ferrofluid is employed, there is a further 10°C temperature reduction, attributable to thermomagnetic convection. Moreover, as the load current increases, this thermomagnetic convection becomes more pronounced, resulting in a larger temperature reduction, as illustrated in Fig. 4 (b).

Ferrofluid cooling has been found effective in reducing end-winding temperatures for other machines featuring double-layer concentrated windings and distributed windings. When operating all machines with ferrofluid cooling at a current density of 11A/mm², compared to nanofluid cooling, ferrofluid cooling can reduce the end-winding temperature by 1.3°C for single-layer windings, 0.8°C for double-layer windings, and a significantly larger value of 4.2°C for distributed windings. This finding is particularly noteworthy, as the longer end-windings in machines with distributed windings are often considered a drawback. These large end-windings increase the overall axial length of the machines, making them bulkier compared to machines with concentrated windings. Additionally, extended end-windings result in more end-winding leakage fluxes and higher copper losses. However, in the context of ferrofluid cooling, the increased leakage fluxes become a desirable feature as they enhance the magnetic body force, facilitating ferrofluid circulation and consequently increasing cooling efficiency for machines with distributed windings.

IV. Conclusion

In this paper, machines with ferrofluid cooling have been investigated, revealing superior cooling efficiency compared to air, pure liquid, and nanofluid. Ferrofluid, in contrast to air, boasts higher thermal conductivity and density, resulting in a more pronounced gravitational effect. Furthermore, ferrofluid experiences a magnetic body force generated by the end-winding leakage flux, facilitating coolant circulation between the housing and the end-winding. This thermomagnetic effect significantly contributes to temperature reduction.

Overall, compared to conventional spray cooling and flooded stator cooling, ferrofluid cooling offers distinct advantages. For instance, ferrofluid is self-driving and pumpless, thereby avoiding additional mechanical losses. Moreover, it circumvents issues associated with spray cooling, such as corrosion and erosion of spray nozzles and winding insulation. Consequently, ferrofluid cooling requires minimal maintenance. However, it's important to note that ferrofluid is presently more expensive than other coolants. This higher cost primarily stems from ferrofluid cooling being a niche area. As ferrofluid cooling scales up, its cost is expected to decrease in the future.

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