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NUMERICAL STUDY OF OIL JET COOLING FOR HAIRPIN WINDING MOTORS IN ELECTRIC VEHICLES

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1. ABSTRACT

Oil jet cooling and hairpin winding have become increasingly popular in electric machine design. Combining the two technologies resulted in improved motor designs with high power density and efficiency. This study examines the effect of jet configuration, nozzle diameter, and flow rate on heat extraction performance using high-fidelity numerical simulations. Results show that the axial jet, although superior in heat extraction, performs poorly at low inlet velocities. Therefore, a minimum velocity threshold is necessary.

2. INTRODUCTION

Electric motors with hairpin windings have been used in traction motors of the latest electric vehicles due to their advantages such as increased slot fill factor up to 0.75 (compared to 0.4-0.5 achievable with typical winding), greater current density, superior thermal performance, and reduced DC electrical resistance. With the continuous demand to improve the power density and efficiency of hairpin traction motors, its heat dissipation has also attracted increasing attention. Notably, direct oil cooling of the end winding via jet impingement has proven effective in heat extraction from hairpin winding motors [1]. The thermal performance of the impinging jet is contingent upon the oil layer formed on the end winding. Studies [2] and [3] underscore the variability in heat extraction capability and oil layer formation across different applications due to system parameter variations. Consequently, further exploration is required to understand the impact of system parameters on impinging jet performance. The present study aims to investigate the impact of nozzle configurations using computational fluid dynamics (CFD) simulations. High-fidelity numerical simulations are employed to study the system parameters, i.e. oil flow rate and nozzle diameter with two nozzle configurations considering a single jet.

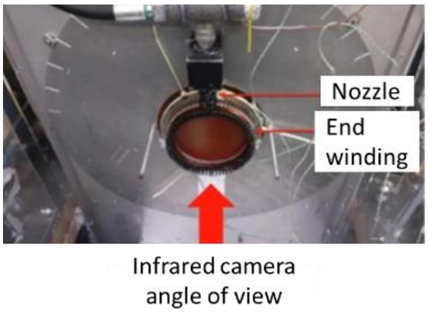

Fig 1. Experimental setup

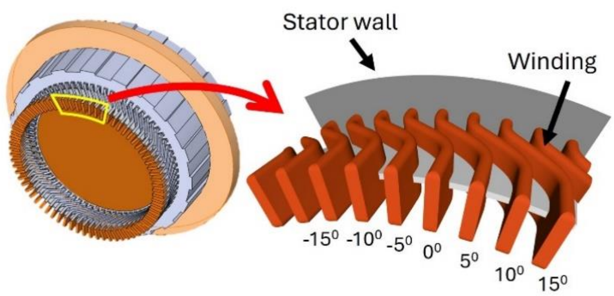

Fig 2. Computational domain of the study

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3. METHODOLOGY

A two-layer hairpin winding stator is used for the investigation with a silicon-based oil, i.e. SilOil M40.165/200.10. The numerical model developed is derived from the experimental setup depicted in figure 1. ANSYS Fluent commercial CFD software is used for the simulation experiments. For the purposes of this study, a computational domain of 45^0 is selected, as illustrated in figure 2. Simulation experiments are conducted in two stages. First, heat extraction by natural convection is solved with the steady state solver. Secondly, fluid flow and heat extraction by forced convection are solved with the transient solver. The two phases, air and oil are modelled as a multi-phase flow using the volume of fluid (VOF) method. The turbulence model k-ω SST and Compressive interface scheme are also employed.

The accuracy of the simulation results is evaluated by comparing Heat Transfer Coefficient (HTC) values with Chen at al. [1]. Figure 3 shows the comparison of HTC values of the complete end windings inside the computational domain. Each winding is defined by the angular position of the front most surface. An average HTC of each winding is calculated. The reference temperature value is taken as the inlet oil temperature.

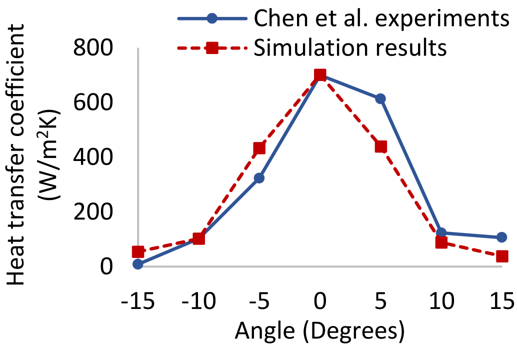

Fig 3. Comparison of simulation results with Chen et al. [1] experimental HTC results

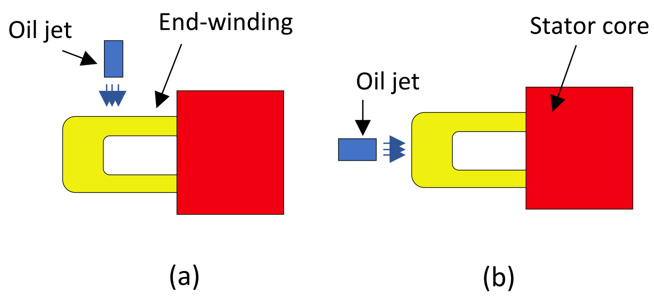

Fig 4. Nozzle configurations: (a) radial jet; (b) axial jet

The prototype stator in the experimental setup contains an insulation ring between the two winding layers, which facilitate fluid spread through the end winding. However, commercially mass-produced hairpin windings typically lack this insulation layer. To ensure the study's findings are applicable to a wider array of applications, the geometry is modified by removing the insulation layer. As depicted in figure 4, this modified geometry is employed in subsequent simulations to analyse fluid flow and heat transfer under two nozzle configurations: radial and axial jets.

4. RESULTS

The HTC of two nozzle configurations is examined, considering variations in both nozzle diameter and fluid flow rate. Simulations are conducted for axial and radial jets using nozzle diameters of 2mm and 4mm. Furthermore, these jets are examined at different flow rates, specifically 75 kg/min and 35 kg/min. Figure 4 and 5 shows the variation of average HTC of the windings. Each winding in the computational domain is defined considering its angular position. The nozzle is positioned at 0^0 winding.

Radial jet showed a maximum per winding HTC of 530 W/m^2K with the 2mm nozzle and 75 kg/min flow rate. Minimum HTC on the 0^0 winding was recorded with 4mm nozzle at 35 kg/min. The difference of oil layer coverage between the two configurations was 10%. On the other hand, highest HTC per winding reported with axial jet was 940 W/m^2K with the 2mm nozzle and 75 kg/min flow rate. Lowest HTC on the 0^0 winding was the 4mm nozzle with 35 kg/min. The difference of the oil layer coverage between the two configurations was 41%.

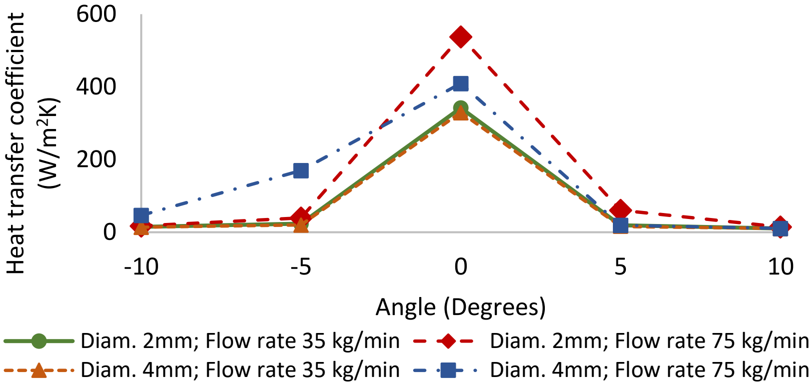

Fig 4. Radial nozzle HTC with varied nozzle diameter and flow rate

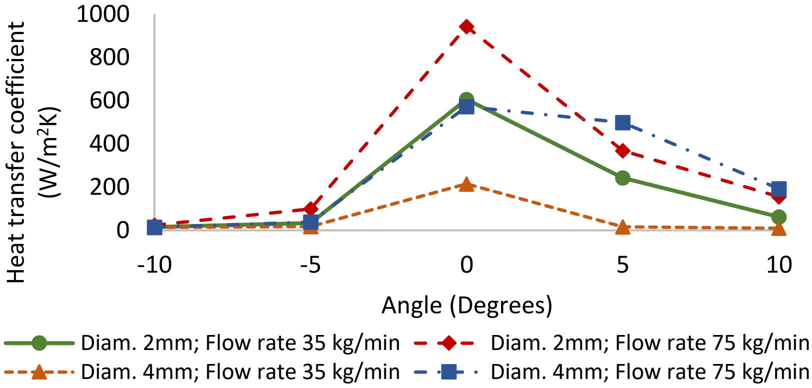

Fig 5. Axial nozzle HTC with varied nozzle diameter and flow rate

Variation of nozzle diameter inversely effected the inlet fluid velocity. Increased velocity facilitated spread of the oil layer and increased flow speed in the oil layer resulting a higher HTC. In comparison to the radial jet, the axial jet results in a greater spread of the oil layer on the winding. Specifically, the axial jet with a 2mm nozzle results in 47% oil coverage on the winding, which is significantly higher than the 19% coverage achieved with the radial jet. When comparing the average HTC for each configuration, the 2mm axial jet outperforms the radial jet by 137% and 134% at flow rates of 75 kg/min and 35 kg/min, respectively. However, it's important to note that a low inlet velocity has a significant impact on the performance of the axial jet. For instance, the performance of the axial jet with a 4mm nozzle and a flow rate of 35 kg/min is 30% lower than that of the radial jet.

5. CONCLUSIONS

The axial jet proves to be more effective in heat extraction compared to the radial jet, demonstrating its potential for enhanced cooling. However, it's important to note that the performance of the axial jet significantly diminishes at low inlet velocities. This observation suggests the need to define a minimum velocity threshold during the design process to ensure sufficient performance. While higher inlet velocities can enhance overall heat extraction, the potential negative impact of splash effects at high velocities must also be taken into consideration.

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