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Multiphase Flow and Thermal Analysis of Hollow-Shaft Cooling System for Motors of Electric Drive Units

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Abstract

Automotive electric drive unit designs are often limited by installation space and the related environmental conditions. Electrical losses in various components of the motor such as stator, rotor and coils can be significant and as a result, the thermal design can become a bottle neck to improve power and torque density. In order to mitigate the thermal issue, an effective liquid cooling system is often employed that ensures sufficient heat dissipation from the motor and helps to reduce packaging size.

Although both stator and rotor are cooled in a typical motor, this paper discusses a multiphase oil-air mixture analysis on a spinning hollow rotor and rotor shaft subjected to forced oil cooling. Three-dimensional computational fluid dynamics (CFD) conjugate heat transfer (CHT) simulations were carried out to investigate flow and heat transfer. The effect of centrifugal force, shaft RPM, density gradients and secondary flows were investigated.

Initially, the computational model was validated with bench test data in terms of pressure loss and temperature data for a specific flowrate of oil. Later, the model was simulated using a range of shaft RPM, oil flow rates and rotor heat loss maps. Overall, the centrifugal force in the spinning shaft did not influence density gradients and secondary flow, hence had minimal effect on heat transfer. However, it has significant effect on hydraulic loss and phase distribution. Phase distribution of oil and air in certain regions within the shaft does affect overall heat transfer.

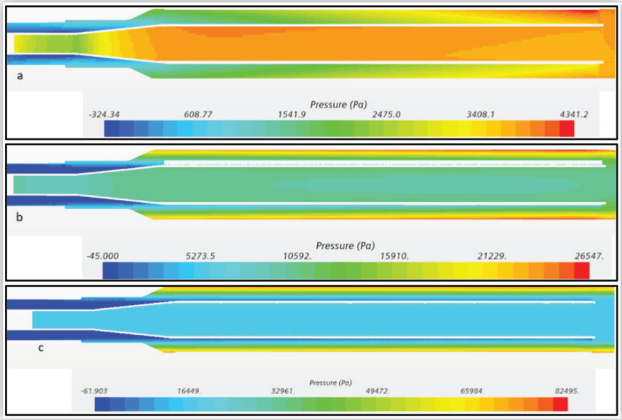
Introduction

The shift towards sustainable mobility is driving the development of new electric vehicle motor drives, also known as electric drive units or EDUs. For a competitive design, motors must meet many of the criteria such as minimal required packaging space, high torque capacity and high power density. With increasing power density in electric motors, efficient cooling systems are needed for thermal management. Thermal issues mainly arise due to losses in the windings and laminations causing both the demagnetization of magnets and insulation aging.

A typical electric drive unit consists of a motor, a gearbox and an inverter as shown in Figure 1. In a motor, both stator and rotor require thermal design consideration. However, the rotor is usually associated with poor heat transfer due to the fact that the major boundary around the rotor is the rotor-stator airgap which is a relatively weak heat transfer boundary. As discussed earlier, poor heat transfer leads to a loss of electromagnetic performance. Several methods of cooling are used for traction motors. Forced air systems with a shaft mounted fan or an extra blower have been investigated by several authors for totally enclosed fan cooled motors [1, 2]. In this type of design, sufficient air flow is created to remove heat from the interior parts of the motor. Alternatively, the motor could be totally flooded, and the rotor and stator surfaces directly flushed by a coolant such as water or oil [3]. However, such an immersion cooling method is not economical and practical due to the risks of short circuit faults, corrosion, and viscous drag. Another effective cooling method may be accomplished by direct circulation of coolant through a hollow-shaft system where, coolant flows through a passage inside a rotating shaft. Rotation could be attained in two ways, one scenario is when the shaft is rotated about its own axis and another, when it is rotated about a parallel axis. The fluid in such a case will be subjected to both centrifugal and axial forces. The body force in a centrifugal field caused by a high-speed revolution may affect both flow resistance/hydraulic loss and heat-transfer rate. The problem discussed in the present paper is related to hydraulic loss and convective heat transfer influenced by secondary flow caused by the body force in a straight pipe rotating about a parallel axis.

A brief qualitative description of the effect of rotation on the flow and heat transfer is provided initially. The basic flow geometry consists of a shaft with a concentric inner tube that rotates about its own axis and a plurality of outer tubes that rotate about the shaft axis - an axis parallel to, but displaced

FIGURE 11 Static pressure distribution at RPMs a) 0, b) 5000, c) 10000.



oil-air distribution. Higher static pressure pushes oil towards the outer diameter of both inner and outer tubes.

The coverage of oil along the cross-section is also shown in Figure 11. As observed at low and mid RPMs oil fully occupies the inner and outer tube. At higher RPMs, air begins to occupy the outer tube ID.

Design Iteration to Improve Effect of Multiphase Flow on Heat Transfer

As discussed in section 4, with an increase in shaft RPM, the air phase tends to occupy the shaft end. In motors, the rotor shaft is typically in contact with components such as rotor, bearings and housing. Bearings that support the rotor shaft could be either ball/cylindrical in nature. Regardless of the construction, depending on the load conditions, bearings may generate heat in the range of 100-200 Watts. The oil flow within the rotor shaft is usually designed to extract heat mainly from rotors and bearings. Considering the oil-air distribution as shown in Figure 12, at higher RPM oil extracts heat only from the rotor however this could overheat the bearings located on the shaft end as shown in Figure 12. In order to improve the heat dissipation from the bearings, oil flow at the shaft end was rerouted as shown in Figure 13. The model was simulated with this new change. As observed from Figure 14, oil has further travelled downstream reaching the

FIGURE 12 Schematic illustrating location of bearings.

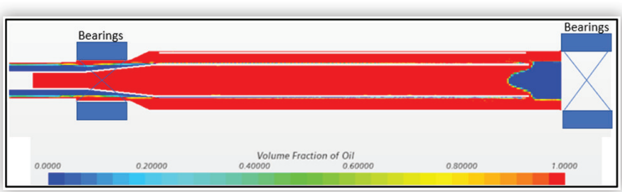


FIGURE 13 Design change to improve bearing heat transfer.

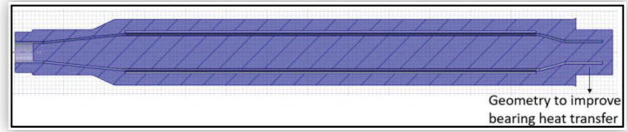
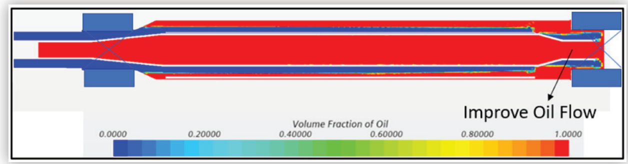


FIGURE 14 Improved oil flow to extract heat from the bearings.



other end of the shaft. Also, from the figure it appeared that the new design significantly reduced the air bubble region thus enhancing bearing heat transfer. Thus, in the latest design the rotor shaft effectively extracted heat from both the rotor and the bearings that support it.

Summary/Conclusion

Effective cooling of the rotor may be accomplished by direct circulation of coolant through centrally located channels inside the rotor shaft. A computational investigation on shaft rotation about a parallel axis carrying high Prandtl number fluids was conducted. Initially this model was validated with bench test data by comparing pressure loss and temperature data. Later, the model was simulated at various shaft RPM for one and two-phase flow. In single-phase flow, the shaft rotation had no significant impact on heat transfer as a result of low density and temperature gradients. However, shaft rotation had significant impact of the hydraulic work required to pump oil through the shaft. In the case of two-phase flow, shaft RPM affected the oil-air phase distribution. At certain locations in the shaft, a large air bubble was found at higher RPM. This relative distribution of oil and air phase influenced by shaft rotation indirectly affected the heat transfer.

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