2022-01-0663 Published 29 Mar 2022

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

Bangalore Lingaraj Yashwanth, Jeffrey J. Ronning, Alexy Kolesnikov, and Yogesh Mehta
American Axle & Manufacturing Inc.

Citation: Yashwanth, B.L., Ronning, J.J., Kolesnikov, A., and Mehta, Y., "Multiphase Flow and Thermal Analysis of Hollow-Shaft Cooling System for Motors of Electric Drive Units," SAE Technical Paper 2022-01-0663, 2022, doi:10.4271/2022-01-0663.

Received: 24 Jan 2022 Revised: 24 Jan 2022 Accepted: 10 Jan 2022

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 1 Typical electric drive unit (EDU).

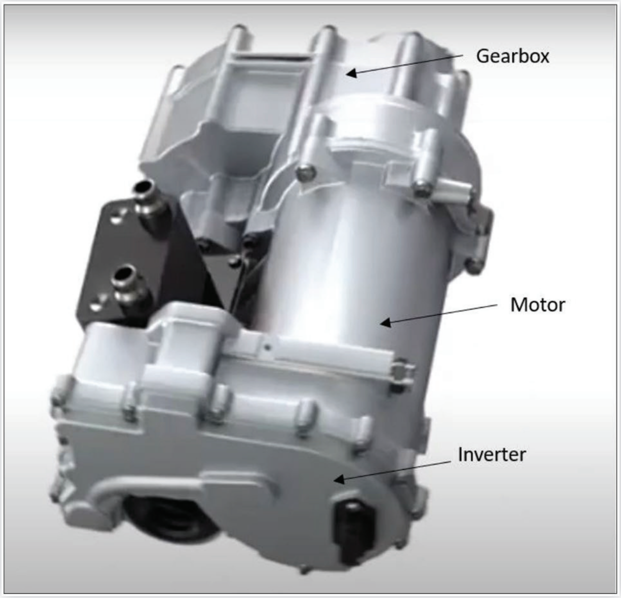
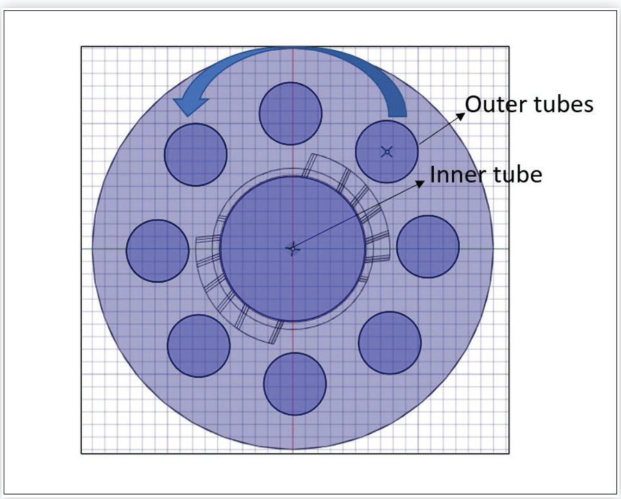


FIGURE 2 Rotor shaft with inner and outer cooling loops.



from, the outer tube axes (Fig. 2). Cooling fluid is pumped along the inner tube while it rotates. The fluid loops around at the end of the inner tube, flows back through the outer tubes in the opposite direction. Due to thermal loss, the rotor around the rotor shaft transfers heat to the coolant. As the coolant picks up heat and rotates within the tube, density gradients resulting from heat transfer interact with centripetal and coriolis components of acceleration to give rise to a secondary movement of fluid. Cooler and relatively denser fluid in the central core region moves outwards while simultaneously the warmer fluid near the walls moves inwards towards the axis of rotation [4]. This buoyancy-impelled secondary flow interacts with the axial flow resulting in a spiraling motion.

For shaft rotation about a parallel axis, Morris [5] analyzed aspects for laminar flow conditions. Morris investigated the influence of rotation on fluid flow through a tube about a parallel axis with uniform angular velocity. Morris indicated that rotation induced a secondary free convection flow in the plane perpendicular to the axis of rotation. The Prandtl number of fluids analyzed were of ~1, hence the Morris findings were mostly applicable to gases. Also, [5] used a series expansion technique to solve the controlling equations and the resulting solution was valid only for low rotational speeds and heating rates. In Mori et al. [6] assumed a secondary-flow distribution, which they claimed to be valid for high rotational speeds and used an integral-type analysis to predict flow details and, subsequently, heat transfer.

The present flow geometry has also been investigated experimentally by [7-9]. Le Feuvre [8] investigated air passing through axially cooled ducts of rotors. Their results show an increase in heat transfer due to rotation. All three investigations predicted improvement in heat transfer with increase in rotational speed. Although reliable quantitative predictions were not possible, qualitative agreement with previous analytical studies have been confirmed. Humphreys et al. [9] considered a short, revolving pipe through which air was introduced via a radial rotating pipe and a bend. Significant increase in mean heat transfer coefficient were detected and these were attributed mainly to entry swirl.

For shaft rotation about its own axis, Reich et al. [10] examined experimentally the effect of tube rotation on the velocity distribution and heat transfer on fluid flowing through a tube for fully developed turbulent flow conditions. They observed a remarkable decrease in heat transfer with increasing rotation rate. This contradicts the effects of shaft rotation about a parallel axis discussed earlier. Weigand et al. [11] investigated the effects of external insulation and tube rotation on heat transfer to fluid. The turbulent flow was assumed to be hydrodynamically fully developed. The heat transfer was found to be strongly suppressed by tube rotation. It was shown that the significance of external insulation on the Nusselt number increases with growing rotation rate of the pipe.

Borisenko et al. [12] studied the effect of rotation on the turbulent velocity fluctuations using hot-wire probes and showed that they were suppressed by rotation. Murakami, et al. [13] measured the time-mean velocity components and hydraulic losses in an axially rotating pipe when a fully developed turbulent flow was introduced into the pipe. Like the conclusions of [12], the pipe rotation suppressed the turbulence in the flow and reduced the hydraulic loss.

The literature discussed so far investigated flows involving low Prandtl number fluids, however most motors used in the automotive applications use fluids with higher Prandtl number as coolant. Also, most coolant flows involve flow of oil or oil-air mixture, as the rotor shaft system is subjected to rotation. The shaft rotation in these applications could either be about its own axis or a parallel axis. All these factors can significantly influence the overall heat transfer characteristics of rotating systems and has not been investigated by previous literature.

As complexity increases, model-based approaches have become standard in the systems engineering community, Zhu et al. [15] and Kumar et al. [16]. This paper investigates the effect of rotation and multiphase flow on heat transfer when the rotor shaft was subjected to forced oil cooling. The rotor shaft had various cooling tubes and exhibited both kinds of rotation. 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, hydraulic loss and secondary flows were investigated on heat transfer of fluids with higher Prandtl number.

Various sections in this paper have been organized as follows. Initially in section 2, the computational model consisting of rotor and rotor shaft with oil flow subjected to rotation was validated with bench test data in terms of temperature and pressure loss for various oil flowrates. Later in section 3, the rotor shaft geometry was simplified to investigate the effect of shaft rotation on heat transfer at various shaft RPM considering one phase flow. Later in section 4, the effect of multiphase flow is investigated where the effect of oil-air distribution on heat transfer is discussed.

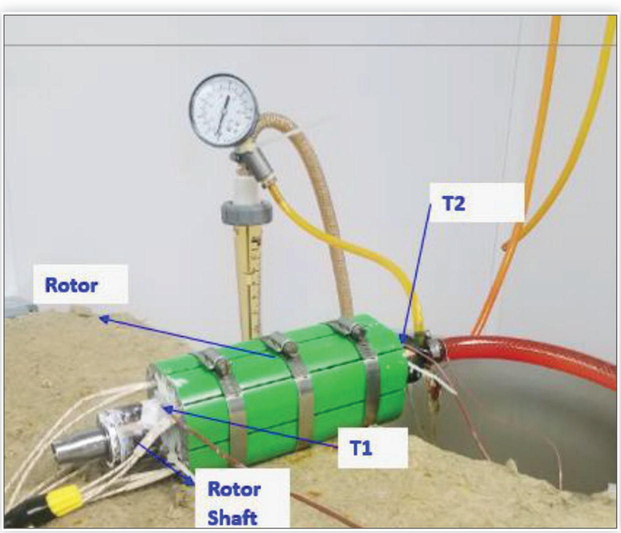
Rotor Shaft Cooling

As discussed earlier, effective cooling of EDU rotors may be accomplished by direct circulation of coolant through centrally located channels inside the rotor shaft. The test setup consists of a rotor shaft with inner tube and an array of outer channels that aid in heat dissipation. The inner tube rotates about its own axis whereas the outer channels, rotate about a parallel inner tube axis with an eccentricity parameter similar to literature [4, 5]. Hydraulic fluid is pumped at a fixed flowrate though the inner tube at one end. At the other end of the shaft, oil turns around and later flows down in the opposite direction via the outer channels. The computational model was initially validated with bench testing with respect to temperature and pressure loss data and is discussed in the next section.

2a. Test Section

The details of the test section used for the experimental investigation is shown in Figure 3. The section consists of both the rotor and the rotor shaft. The rotor was equipped with a heater to behave as a heat source with 718 Watts. The rotor and the rotor shaft system were insulated to ensure heat was dissipated only to oil. Oil flow through the rotor shaft was provided by a variable speed DC positive displacement oil pump. Oil temperature was measured at the inlet and outlet of the rotor shaft using T-type thermocouples. Oil flows into the system at 80C. Similar thermocouples were used to measure the rotor shaft temperature near the oil inlet (T2) and at the hot end of the shaft (T1). The flowrate and inlet temperature of oil was varied as shown in table 2. Flow rate was indicated by a variable area flow measuring device and confirmed with stopwatch and beaker for each oil temperature condition. To achieve this flow measurement, oil was collected in the beaker for a fixed period, usually 20 seconds. The net mass of oil collected for each measurement is then converted to volume based on density for a given oil temperature.

FIGURE 3 Test apparatus consisting of rotor, rotor shaft and connections to measure pressure drop.



As the static pressure drop for the rotor heat exchanger for warm oil tended to be relatively low, a 15 psi pressure gauge was disconnected from the inlet pressure tap and exchanged for a simple vertical tube manometer of oil. This allows high resolution measurement of pressures and can accurately measure resistance pressures as low as 200 Pa. In this way, the very oil that flows through the rotor in the thermal and fluid testing apparatus serves as the pressure indication media. A column of oil stands vertically in a Tygon hose (3/16 inch diameter) and the height of this oil column above the perpendicular flow tube surface corresponds to the static gauge pressure at the specific location. For reference, one inch of oil column corresponds to approximately 204 Pa, given the type of oil used in this research.

The rotor inlet tube static pressure sensor is located relatively close to the shaft end where the tube goes into the rotor, approximately 1 inch from shaft end. The rotor shaft outlet flow exits freely to atmosphere. For this reason, static gauge pressure at the inlet represents total pressure drop of the rotor shaft system, including dynamic pressure of the oil exiting the shaft.

2b. Computational Setup

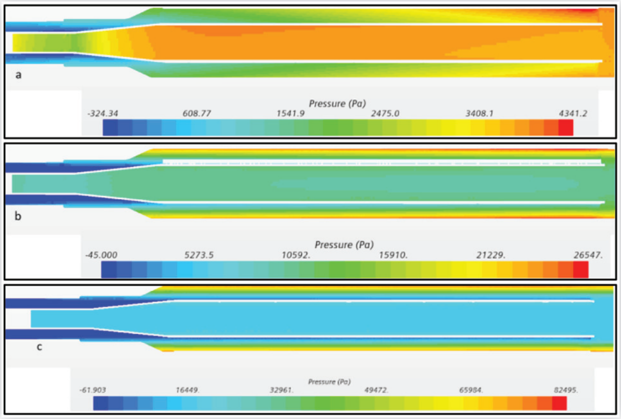
The computational model was set up as shown in Figure 4. The model mimics the test apparatus and has been simulated at various oil flowrates.

The shaft was modeled to be stationary following the test conditions. The goal in this section was to build a conjugate heat transfer (CHT) model that would mimic both the pressure drop and heat transfer load from the rotor to oil. The mesh resolution and timesteps used here have been benchmarked in a priori study and a k-epsilon turbulence model is used to model turbulence. The heating conditions in the rotor were mimicked by adding a volumetric heat source of 718 Watts in the model. Also, the rotor and rotor shaft external boundaries were made adiabatic to eliminate any heat loss to surrounding air, whereas their internal boundaries shared a common interface. The material properties of the oil, rotor and rotor shaft are shown in Table 1.

TABLE 1

	Density-Kg/m3	Thermal Cond-W/mK	Specific heat-J/KgK
Steel Shaft	7800	51	430
Steel Rotor	7800	51	430
Oil	800	0.13	2100

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.

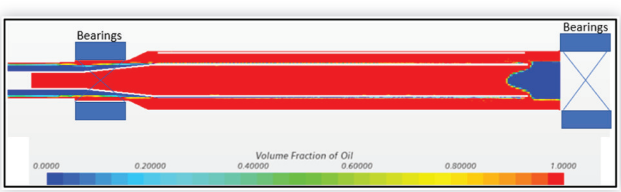


FIGURE 13 Design change to improve bearing heat transfer.

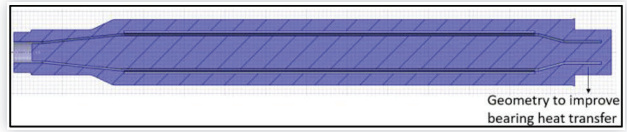
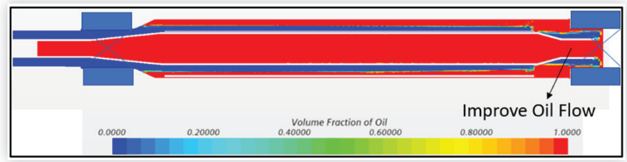


FIGURE 14 Improved oil flow to extract heat from the bearings.



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.

References

1. Mizuno, S., Noda, S., Matsushita, M., Koyama, T. et al., “Development of a Totally Enclosed Fan-Cooled Traction Motor,” *IEEE Transactions on Industry Applications* 49 (2013): 1508-1514, doi:10.1109/TIA.2013.2256872.
2. Herbert, W.A., “Totally Enclosed Fan-Cooled Squirrel-Cage Induction Motor Options,” *IEEE Transactions on Industry Applications* 50 (2014): 1590-1598, doi:10.1109/PPIC.2013.6656038.
3. Ponomarev, P., Polikarpova, M., and Pyrhönen, J., "Thermal Modeling of Directly-Oil-Cooled Permanent Magnet Synchronous Machine," in *XXth International Conference on Electrical Machines*, 2012,1882-1887, doi:10.1109/ICElMach.2012.6350138.

4. Woods, J.L., and Morris, W.D., “An Investigation of the Laminar Flow in Rotor Windings of Directly Cooled Electric Machines,” *IMechE*,16,1974,408-417, https://doi.org/10.1243/JMES_JOUR_1974_016_075_02.

5. Morris, W.D., “Laminar Convection in a Heated Vertical Tube Rotating about a Parallel Axis,” *Journal of Fluid Mechanics* 21 (1965). https://doi.org/10.1243/JMES_JOUR_1974_016_075_02.

6. Mori, Y. and Nakayama, W., “Forced Convective Heat Transfer in a Straight Pipe Rotating about a Parallel Axis (Laminar Region),” *International Journal of Heat and Mass Transfer* 10 (1967): 1179-1194. https://doi.org/10.1016/0017-9310(67)90083-X.

7. Morris, W.D., “An Experimental Investigation of Laminar Heat Transfer in a Uniformly Heated Tube Rotating about a Parallel Axis,” Ministry of Technology, A.R.C., C.P. No. 1055, 1969, https://reports.aerade.cranfield.ac.uk/handle/1826.2/1068.

8. Le Feuvre, R.F., “Heat Transfer in Rotor Cooling Ducts,” *Proceedings of the Institution of Mechanical Engineers, Conference Proceedings* 182, no. 8 (1967): 232-240, doi:10.1243/PIME_CONF_1967_182_234_02.

9. Humphreys, J.F., Morris, W.D., and Barrow, H., “Convective Heat Transfer in the Entry Region of a Tube Which Revolves About an Axis Parallel to Itself,” *International Journal of Heat and Mass Transfer* 10 (1967): 333-347. https://doi.org/10.1016/0017-9310%2867%2990150-0.

10. Reich, G. and Beer, H., “Fluid Flow and Heat Transfer in an Axially Rotatingpipe-l. Effect of Rotation on Turbulent Pipe Flow,” *International Journal of Heat and Mass Transfer* 32, no. 3 (1989): 551-562. https://doi.org/10.1016/0017-9310(89)90143-9.

11. Weigand, B. and Beer, H., “Fluid Flow and Heat Transfer in an Axially Rotating Pipe Subjected to External Convection,” *International Journal of Heat and Mass Transfer* 35 (1992): 1803-1809.

12. Borisenko, A.I., Kostikov, O.N., and Chumachenko, V.I., “Experimental Investigation of Turbulent Flow Characteristics in a Rotating Channel,” *Inzhenerno-Fizicheskii Zhurnal* 24 (1973): 1103-1108.

13. Murakami, M. and Kikuvama, K., “Turbulent Flow in Axially Rotating Pipes,” *Journal of Fluids Engineering* 102 (1980): 97-103. https://doi.org/10.1115/1.3240633.

14. White, A., “Flow of a Fluid in an Axially Rotating Pipe,” *Journal of Mechanical Engineering Science* 6 (1964): 47-52, doi:10.1243/JMES_JOUR_1964_006_010_02.

15. Zhu, D., Pritchard, E.G.D., and Silverberg, L.M., “A New System Development Framework Driven by a Model-Based Testing Approach Bridged by Information Flow,” *IEEE Systems Journal* 12, no. 3 (Sept. 2018): 2917-2924, doi:10.1109/JSYST.2016.2631142.

16. Kumar, V., Zhu, D., and Dadam, S., “Intelligent Auxiliary Battery Control - A Connected Approach,” SAE Technical Paper 2021-01-1248 (2021), doi:10.4271/2021-01-1248.

Contact Information

Driveline | ATDC
1840 Holbrook Ave., Detroit, MI 48212
bangalore.yashwanth@aam.com

ISSN 0148-7191