Design and Thermal Analysis of Electric Motors of Electric Vehicles using Analytical and CFD Methods

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Abstract

In this paper, electro-magnetic design and thermal analysis of wheel hub motors, incorporated into the hub of a wheel and driven it directly, of electric vehicles were performed by using analytical and CFD methods. Since thermal management impacts the continuous power capability of electric machines, thermal analysis coupled electro-magnetic analysis are needed to reduce size and improve its performance. Mapping process for geometries and heat losses of rotor and stator was carried out separately and automatically with transfer of values form analytical code, electro-magnetic software to CFD code, STAR-CCM.

Keywords: Electric Motor, Design and Thermal Analysis, CFD Methods

1 Introduction

The following are demanded of drive motors used in electric vehicles (EVs): satisfaction of the output characteristics required to drive such vehicles; smaller size and lighter weight to be loaded on the vehicles; and high efficiency to decrease the power consumption rate. In addition, environment resistance is necessary because EVs are driven under vibrations and diverse environmental conditions. In-wheel motors, which realize independent driving of the wheels by mounting motors inside the wheels, as in Figure 1, do not require a transmission or differential gears, improve the torque transmission efficiency, and simultaneously make possible efficient space usage in terms of the entire vehicle. On this basis, a great deal of research has been conducted in this field. However, the high speed and smaller sizes of the drive motors of EVs have increased the output density and consequently the temperature inside the In-wheel motors has increased as well, thus making appropriate cooling systems necessary. In particular, because in-wheel motors are installed within the limited space of the wheels together with various components such as reduction gears, the passage of outside air is difficult without separate devices, and heat dissipation and cooling are difficult [1]. In the end, a temperature increase above the motors’ insulation grades leads to demagnetization of the magnet, and, as a result, the lifetime and the performance of the in-wheel motors is reduced [2]. As for cooling methods for in-wheel motors, the water-cooled method, which simultaneously cools control devices such as inverters by incorporating water jackets in the motor housing, and the oil circulation cooling method, which is based on air cooling and the use of lubricating oil, are mainly used.
The present study aims at cooling high-output in-wheel motors more effectively. In general, low-output motors can be sufficiently cooled by using the air-cooled cooling method. However, high-output motors must be cooled by using a water-cooled or oil-cooled cooling method, both of which have high cooling efficiency. Because they have high output density, in-wheel motors, the model examined in the present study, cannot be sufficiently cooled with the air-cooled cooling method [3]. The present study designed an in-wheel motor by using SPEED, a motor design program. The copper loss and iron loss of this in-wheel motor under nominal and maximum output conditions were predicted. In addition, research was conducted on the design of an in-wheel motor cooling system in consideration of motor loss. Finally, a cooling system for in-wheel motors both in the steady state under the nominal conditions and in the unsteady state under the maximum output conditions was reviewed.

2 Electric motor design

Because in-wheel motors are mounted inside the wheels and realize the independent drive of the wheels, design for high speed, a smaller size, and a lighter weight is necessary. The present study designed an in-wheel motor by using SPEED, a commercial motor design program, the results of which are shown in Table 1. The magnet and the coil consisted of 12 poles and 18 slots, respectively, and the DC link voltage was 320 V. In addition, the maximum output and torque were 17 kW and 80 N·m, respectively, and the base speed and maximum speed were 2,000 rpm and 6,000 rpm, respectively, calculated from the power requirement of EVs.

<table>
<thead>
<tr>
<th>Table 1: Specifications of in-wheel motor</th>
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<tbody>
<tr>
<td>Motor type</td>
</tr>
<tr>
<td>Magnet/Coil slot</td>
</tr>
<tr>
<td>Wheel size(inch)</td>
</tr>
<tr>
<td>Input voltage(V)</td>
</tr>
<tr>
<td>Max. power(kW)</td>
</tr>
<tr>
<td>Max. torque[N·m]</td>
</tr>
<tr>
<td>Current density[A/mm²]</td>
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Figure 2 shows an image of the in-wheel motor designed according to the design specifications of in-wheel motors. The outer diameter (OD) was 250 mm, and the axial distance was 50 mm. It was an interior permanent magnet synchronous motor (IPMSM), a structure where the magnet is inserted in the rotor.

Figure 3 is the TN characteristics curve of the in-wheel motor designed, and results that satisfied the maximum torque of 80 N·m or above and the maximum output of 17 kW were obtained at the base speed of 2,000 rpm. Figure 4 shows the
counter-electromotive force waveforms of the in-wheel motor designed. The counter-electromotive force demanded during rotation at 2,000 rpm was 42.5 Vrms, and when actual measurements were made based on this, 22.6 Vrms was derived during rotation at 1,000 rpm, thus being nearly identical to the results of the design and actual measurements. When the saturated density during the occurrence of the maximum torque of the in-wheel motor was reviewed using the results above, the magnetic flux density of the slot width of the stator was approximately 1.64 T and the magnetic flux density of the yoke of the stator was approximately 1.4 T, respectively, as in Figure 5, thus showing that there was no significant effect except for local saturation.

3 Thermal analysis

3.1 Numerical theories

In a numerical analysis, when rotating objects such as motors or turbines are analyzed, it is possible to use the dynamic mesh model (DMM) technique, which actually rotates the model. However, because the DMM technique makes use of the unsteady analysis technique, new modeling must be realized at each time step during the analysis. This method has the disadvantage of requiring considerable time and cost. To complement the disadvantage of the DMM technique, the present study used the moving reference frame (MRF) technique, where actual rotation does not occur, to simulate the rotation of the motor. In the MRF technique the flow field is divided into the rotation area and the non-rotation area and hypothetical force in non-inertial coordinate systems is added to momentum equations and calculated only for the rotation area. Contrary to the DMM technique, the MRF technique is capable only of a steady state analysis and can secure precise results with respect to the calculation time and cost.

As the governing equation for simulating the flow of the cooling water inside the housing, the Reynolds averaged Navier-Stokes (RANS) equation was used to increase the reliability of the results of the analysis at the wall with respect to the number of grids, and the continuity equation and the momentum equation were satisfied [4]. In addition, an analysis including turbulence was performed through the Reynold’s number, and the k-ε turbulence model was used to analyze the turbulence model.

3.2 Simulation model

The in-wheel motor used in the analysis was a 20 kW electric motor and was designed to consist of, proceeding from the inside, a shaft, a rotor, a magnet, a coil, a stator, and a housing, thus having the same shape as the inner rotors in general. Figure 6 shows the base housing model actually used in the analysis, and this was a motor using the water-cooled cooling method, where the motor is cooled as the cooling water passes through the flow channels of the 6 passes of the housing. Figure 7 is a 9-pass housing model designed to maintain the cross sections of the flow channels of the cooling water to be as uniform as possible to reduce pressure loss in comparison with the base housing. With this model an improvement in the cooling performance can be expected because of an increase in the number of flow channels, and
the cross sections of the flow channels are consistent and thus possible flow resistance is reduced.

As for the motor loss, which is the most important boundary condition in the heat dissipation and cooling analysis of motors, the loss was ascertained by using SPEED, professional electromagnetic analysis software, as presented in Figure 8, and the condition of extreme states was used.

In addition, pure water with a temperature of 55°C was used as the cooling water, and the ambient temperature around the motor was set at 40°C, thus conducting the analysis in consideration of the ambient temperature in summer, which is an extreme state. The material properties of the main components constituting the motor are given in Table 2.

### Table 2: Main material properties of in-wheel motor

<table>
<thead>
<tr>
<th>Part name</th>
<th>Density (kg/m³)</th>
<th>Thermal conductivity [W/mK]</th>
<th>Specific heat [J/kgK]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shaft</td>
<td>7850</td>
<td>72</td>
<td>449</td>
</tr>
<tr>
<td>Core</td>
<td>7600</td>
<td>22.9</td>
<td>470</td>
</tr>
<tr>
<td>housing</td>
<td>2700</td>
<td>166.9</td>
<td>903</td>
</tr>
<tr>
<td>coil</td>
<td>8890</td>
<td>348.9–395.42 (370)</td>
<td>387</td>
</tr>
<tr>
<td>Air(Solid)</td>
<td>1.18415</td>
<td>0.0260305</td>
<td>1003.62</td>
</tr>
</tbody>
</table>

The analysis was conducted by establishing four design variables, the base housing and the 9-pass housing improved to increase the cooling performance were analyzed according to the shapes, and the temperatures and differential pressures were compared. In addition, the flow rate of the cooling water was increased to 0.1 L/min, 1 L/min, 3 L/min, and 5 L/min and the temperatures and differential pressures were compared to determine the cooling characteristics according to the flow rate, and efforts were made to find the flow rate that is appropriate for cooling in the analysis model.

3.3 Simulation conditions

Both the steady state and the unsteady state were analyzed according to the output. An analysis of the rated power state was conducted as a steady state analysis because the maximum temperature of the system was predicted not to exceed 155°C, the allowable temperature of insulation grade F, and an analysis of the maximum power state was conducted as an unsteady state analysis to confirm both the maximum temperature and the time at which the allowable temperature was exceeded [5].
In addition, 10 W/m²K and 20 W/m²K were used to confirm the results to determine the effect of the heat transfer coefficient, and the loss as a function of the rotation speed of the motor was obtained to predict the temperature.

4 Simulation results

4.1 Effect of flow rate
Changes in the flow rate of the cooling water were studied to identify the effect of the flow rate on the temperature of the motor. The analysis was conducted in the rated power state, and the shapes of the base housing model and the 9-pass housing model were analyzed with respect to the numbers of motor rotations, 2,000 rpm and 6,000 rpm. As for the results of the analysis, the maximum temperature of the entire system decreased as the flow rate increased, as in Figure 9. However, when the flow rate of the cooling water exceeded 3 LPM, the cooling efficiency was confirmed to decrease. In addition, temperature differences caused by the shapes of the housings were not significant.

Figure 9: Maximum temperature change for flow rates

In Figure 10, the differential pressure in the flow channels can be confirmed. Because the pressure at the exits in the CFD analysis is generally hypothesized to be the atmospheric pressure when the analysis is conducted, the pressure at the inlets can be seen as being identical to the differential pressure of the system. According to the results of the analysis, the differential pressure in the inlets and exits of the flow channels of the cooling water increased gradually with an increase in the flow rate. In addition, the 9-pass housing was confirmed to have a differential pressure greater than that of the base housing. The differential pressure increased more for the 9-pass housing than for the base housing even though the shape was improved. This appears to be attributable to the increased lengths of the flow channels of the 9-pass housing and the reduced widths of the flow channels. Because an increase in the differential pressure signifies an increase in flow resistance in the flow channels, a pump with a higher output became necessary. When the effect of the flow rate of the cooling water on the cooling performance of the motor was confirmed, a flow rate of 3 LPM was deemed appropriate in terms of the cooling efficiency of the motor because the increase in the cooling efficiency was negligible at the flow rate of 3 LPM or above and the differential pressure of the cooling water increased dramatically when the flow rate was increased to 3 LPM or above.

Figure 10: Coolant inlet pressure for flow rates

The temperatures of the main components of the motor are shown in Figure 11. First, the 9-pass housing, redesigned to improve the cooling performance, did not exhibit as much improvement in the cooling efficiency as did the base housing. In addition, the temperatures at the rotor and the magnet were particularly higher in the results of the analysis under the 6,000 rpm condition, with considerable loss in the magnet, than in the results of the analysis under the 2,000 rpm condition, with little loss in the magnet. There appears to be a limit to the ability of the cooling water flowing along the contour of the motor to cool the motor all the way to the center.

Figure 11: Local temperature for flow rates
Figure 12 shows the temperature distribution in the cross section of the motor. Here, the temperatures of the rotor and the magnet placed in the center of the motor were high, and the stator and the coil, placed near the cooling water, exhibited comparatively low temperatures.

4.2 Effect of heat transfer coefficient

Even when the water-cooled cooling method is used, more cooling can occur because of convection on the surface of the housing. When analyzing cooling caused by convection, the value of the natural convection heat transfer coefficient is generally set at 5-20 W/m2K in a CFD analysis. In the present study, the analysis was conducted for two cases where the value of the convection heat transfer coefficient was 10 W/m2K and 20 W/m2K, respectively, and the temperatures of the respective components were compared.

According to the results of the analysis, the heat transfer coefficient in natural convection had nearly no effect on the motor in the water-cooled cooling method, as in Figure 13. This appears to be attributable to the effect of the cooling water on the cooling of the motor being so great in the water-cooled cooling method that cooling caused by convection did not have a comparable effect.

4.3 Effect of thermal conductivity

Thermal conductivity represents the ability of a material to transmit heat through conductance. The value of thermal conductivity is a material property, and the thermal conductivity of a fluid can change considerably because of the temperature of the object. However, the thermal conductivity of a solid does not change considerably because of the temperature, and there are many results of analyses that use representative thermal conductivity disregarding gradually changing temperature.

In the analysis of the unsteady state, because the analysis could not be conducted by using the MRF rotation technique, temperature changes could occur in comparison with the results of the analysis of the steady state to which the MRF technique had been applied. To correct such results, the analysis was conducted by changing the effective thermal conductivity of the air cap inside the motor. When the analysis was conducted after changing the effective thermal conductivity, the results of analyses exhibiting temperatures closest to the results of the analysis using the MRF technique were used to obtain the value of effective thermal conductivity that could yield results identical to those using the MRF analysis. In addition, this effective thermal conductivity was applied to the unsteady analysis.

For comparison with the results of the analysis using the MRF technique, the analysis was conducted by raising the value of the effective thermal conductivity by 1 time, 5 times, and 10 times, respectively. As a result, the effective thermal conductivity was between 5 and 10, as shown in Figure 14. The same equation as in Figure 15 was used to obtain more accurate effective thermal conductivity, and the maximum temperature of the system for effective thermal conductivity was predicted. As a result, the temperature became identical to that of the analysis using the MRF technique when the effective thermal conductivity increased by approximately 7.3 times under the 2,000 rpm condition, and the results of the analysis using the MRF technique were reached when the value of the effective thermal conductivity was increased by 8.6 times under the 6,000 rpm condition.
4.4 Unsteady analysis
An unsteady state analysis was conducted to confirm whether 155°C, the allowable temperature of insulation grade F, was reached when the motor was activated at the maximum output. The effective thermal conductivity predicted above was applied to the unsteady state analysis, and the heat transfer condition was hypothesized to be the same as that of the analysis to which the MRF technique was applied.

Although an unsteady state analysis was being performed, only heat transfer was taken into consideration and the analysis was aimed solely at confirming the temperature change. Consequently, the time step was set at 0.4 seconds, longer than in an unsteady state analysis in general, and the total time was set at 1,200 seconds. As in Figure 16, 155°C, the allowable temperature of insulation grade F, was not exceeded throughout the motor system under the 2,000 rpm condition and thus there were no problems with its use as the maximum output. As for the results of the analysis under the 6,000 rpm condition, the temperatures of all components except for the coil and the stator exceeded 155°C, as in Figure 17. Among these, the component that first exceeded the allowable temperature was the magnet, and 155°C was exceeded at approximately 66 seconds after activation. Consequently, the actual time of use under the 6,000 rpm condition was expected to be 1 second or less.

5 Conclusions
The purpose of the present study is to effectively cool the heat generated when activating high-output in-wheel motors. Because the output of the motor was high and cooling through convection was not easy, the water-cooled cooling method was adopted and the study was thereupon conducted. As for the detailed contents of the study, the optimal flow rate for cooling was determined through an analysis where the flow rate of the cooling water was changed, and the possibility of additional cooling using natural convection was confirmed in the water-cooled in-wheel motor. In addition, an unsteady state analysis was conducted to predict both the temperature of the motor, which was activated at the maximum output, and the possible activation time for the motor at the maximum output was predicted according to the insulation grade.

The conclusions of the present study are as follows.

- While the maximum temperature of the system decreased as the flow rate of the cooling water...
increased, the cooling efficiency decreased dramatically at a flow rate of 3 LPM or above.

- The differential pressures of the cooling water inlets/exits increased dramatically as the flow rate increased, and thus when the efficiency of the differential pressure with respect to cooling efficiency is taken into consideration, the most effective method was to cool the motor at a flow rate of approximately 3 LPM.
- While the shapes of the flow channels in the motor housing were improved, the temperature reduction effect was negligible and the differential pressure increased considerably.
- The base housing therefore appears to be a better model overall than the 9-pass housing. Because the cooling efficiency of the cooling water is very high, even when the cooling efficiency of heat transfer through convection on the surface of the motor housing is improved, there is not a significant effect on the cooling performance.
- When an unsteady analysis was conducted at the maximum output, the allowable temperature was exceeded at 6,000 rpm, thus requiring additional measures for cooling.

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References


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