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Thermal performance of oil spray cooling system for in-wheel motor in electric vehicles

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HIGHLIGHTS

- An oil spray cooling system was developed for in-wheel motor in electric vehicles.
- The shape of the channel was optimized for efficient delivery of the cooling oil in hollow shaft.
- The thermal performances of the oil spray cooling system and the conventional models were compared.

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ABSTRACT

The cooling of the motor in an in-wheel system is critical to its performance and durability. In the present study, the shape of the channel in the hollow shaft for the oil spray cooling of a high-capacity 35 kW in-wheel motor was optimized, and the thermal performance of the motor was evaluated by numerical analysis and experiments. The thermal flow was analyzed by evaluating the thermal performance of two conventional cooling models of in-wheel motors under conditions of continuous rating base speed. For conventional model #1, in which the cooling oil is stagnant in the lower end of the motor, the maximum temperature of the coil was 221.7 °C. For conventional model #2, in which the cooling oil circulates through the exit and entrance of the housing and jig, the maximum temperature of the coil was 155.4 °C. Both models thus proved to be unsuitable for in-wheel motors because the motor control specifications limit the maximum temperature to 150 °C. We designed and manufactured an enhanced model for in-wheel motors, which we equipped with an optimized channel for the oil spray cooling mode, and evaluated its thermal performance under continuous rating conditions. The maximum temperatures of the coil at the base and maximum speeds, which were set as the design points, were below the motor temperature limit, being 138.1 and 137.8 °C, respectively.

1. Introduction

Recently, a great deal of effort has been put into replacing conventional internal combustion engine vehicles with electric power-based vehicles owing to increasing awareness of environmental pollution and energy depletion around the world [1–3]. The in-wheel system, which is an electricity-driven mode, is a method of directly driving a wheel by mounting a driving motor to the wheel of a vehicle. This method has the advantages of improving driving performance through optimized mass distribution and enhancing the degree of freedom in terms of vehicle layout or design [4]. On the other hand, since an in-wheel system should accommodate a number of parts with complicated structures in a limited space, the parts need to be miniaturized. In particular, the motor, which is a critical part of the system, requires efficient cooling for efficient miniaturization and high power output and to ensure durability [5,6].

The driving motors for electric vehicle (EV) have different cooling modes depending on the operating fluid: air-cooled [6], oil-cooled [7], and liquid-cooled [8]. The most suitable mode is selected based on the capacity and mounting environment of the motor. For the air-cooled mode, while it has the advantage of a simple cooling system configuration, its cooling capacity is relatively small, which makes application to a miniaturized high-capacity motor difficult. The present study selected a high-capacity 35 kW in-wheel motor operating in oil-cooled mode. Although the oil-cooled mode generally has lower cooling capacity than the water-cooled mode, its advantage is that it can cool and lubricate at the same time.

Many studies have reported that the spray cooling method provides better thermal performance than existing methods using

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Nomenclature

B	magnetic flux density (T)
C_p	specific heat at constant pressure (J/kg K)
D	outside diameter (m)
g_i	gravity (m/s^2)
I_{eff}	effective phase current (A_{rms})
$i_{\max}$	maximum current (A)
K	thermal conductivity (W/m K)
L	length (m)
m	mass (kg)
N	rotational speed (rpm)
n_{sp}	number of spires by phase
n_r	number of bearings
P	energy loss (W)
P_{cu}	copper loss (W)
P_{iron}	iron loss (W)
P_{mec}	mechanical loss (W)
p	pressure (Pa)
R	electrical resistance (Ω)
S_c	spire section (m^2)
T	temperature (K)
t	time (s)
u_i	flow velocity in x_i direction (m/s)
v_i	simulation grid velocity (m/s)
x_i	coordinates (m)

Greek letters

α	coefficient of volume expansion (1/K)
β	Steinmetz constant
μ	viscosity (kg/m s)
ρ	density (kg/m^3)
ω_s	angular frequency (rad/s)

Subscripts

cu	copper
e	eddy current
fr	friction
h	hysteresis
mec	mechanical
ph	phase
rot	rotor
sp	coil spire
0	reference condition

oil cooling channels. Lin et al. [9] evaluated the heat transfer performance of spray cooling with respect to various fluids, while Kim [10] measured the cooling efficiency of spray cooling on surfaces with various fin shapes. In addition, Mudawar et al. [11] measured the performance of power electronics in a hybrid electric vehicle (HEV) using a two-phase spray cooling method, while Bostanci et al. [12] studied the thermal management of an inverter through spray cooling of high-temperature cooling water. As demonstrated by these examples, the EV/HEV industry has applied spray cooling to power electronics and inverter cooling rather than to motors.

In the present study, we developed a cooling system in which an oil spray was used to cool a 35 kW in-wheel motor. The shape of the channel was optimized for efficient delivery of the cooling oil to parts requiring lubrication and cooling, and the system was applied to an in-wheel motor. The thermal performance was experimentally evaluated to determine the effects of changes in the operating conditions. Numerical analysis was used to compare the performance of the system with that of conventional cooling methods.

2. Optimum design of cooling structure

2.1. Cooling system for in-wheel motor

Fig. 1(a) shows the shape and structure of an in-wheel motor module with a cooling system. It comprises a motor for driving the wheel, a jig for fixing the motor, and an oil tank and pump that store/radiate and circulate the cooling oil. Fig. 1(b) shows the circular structure for the cooling oil. The cooling oil stored in the oil tank is delivered to the shaft of the motor via the pump. The shaft includes a hollow flow channel with multiple outlets to distribute cooling oil to motor parts where lubrication and cooling are required; a spray mode is used for the transmission. The sprayed cooling oil absorbs generated heat from the motor parts, moves to the oil tank via the housing and jig, and is radiated outside from there.

The cooling flow channel positioned in the hollow of the shaft performs an important function of distributing and delivering the cooling oil to each part. The shape of the cooling channel is shown in Fig. 2. The cooling oil introduced into the hollow of the shaft is sprayed into the respective outlets for the coil/stator core, bearing, and reduction gear and is thus delivered to each part. Here, the cooling channel should have low pressure-drop characteristics considering the performance of the cooling system. In particular, a sufficient oil flow to the coil and stator core should be ensured; this is closely related to the performance level and service life of the motor and should be suitable for the manufacturing processes.

2.2. Cooling channel optimization method

The Taguchi method was employed to optimize the shape of the cooling channel. The Taguchi method is an experimental design used for parts and process design. It has the advantages of reducing time and cost by minimizing the number of experiments as well as meeting the requirements for robustness against noise that design variables should exhibit [13,14]. The Taguchi method uses signal-to-noise (S/N) ratios in order to consider the effects of parametric and noise factors on the target performance simultaneously. The S/N ratios are divided according to the nominal-the-best (NTB) characteristic (specific target value), smaller-the-better (STB) characteristic (lowest possible target value), and larger-the-better (LTB) characteristic (highest possible target value), as shown in Table 1. In this study, the pressure drop was set as the STB while the flow rate in the coil/stator core was set as the LTB for optimization.

The design parameters and levels that were set for the optimal design of the cooling channel are outlined in Fig. 3 and Table 2. The fact that the cooling channel was located in a shaft in order to avoid interference with other parts and facilitate mechanical stiffness due to the high rotational speeds placed constraints on the length and shape of the cooling channel. Therefore, the diameter and number of main cooling channels in the circumferential direction were set as design parameters. These design parameters can adjust the pressure drop and distribution of the fluid by flow-resistance adjustment in the internal channels and exits. They were divided into three levels—minimum, maximum and medium values—to reflect the actual manufacturing and processability.

In order to analyze the effect of the design parameters, an L9 Taguchi orthogonal array was used with the minimum number of tests for three levels and four parameters, as shown in Table 3.