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Thermal evaluation of direct cooling technology for in-wheel drive system

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ABSTRACT: We are developing a small and lightweight direct-drive system to develop in-wheel electric vehicles (EVs). In conventional oil-cooled motors for driving EVs, it is necessary to minimize the amount of cooling oil that enters between the rotor and stator to suppress fluid friction losses. In this study, we focused on the low-speed rotation of direct drives and developed a direct oil cooling system in which the entire motor magnetic circuit, including the rotor, is immersed in oil. We measured frictional loss and conducted a continuous heat-run test and a short-time rating test on a test bench. The results demonstrated that direct cooling is effective and continuous operation is possible. In this paper, we report on the concept of direct cooling and the results of the measurements.

KEY WORDS: electric vehicle, motor drive system, in-wheel motor, direct cooling

1. INTRODUCTION

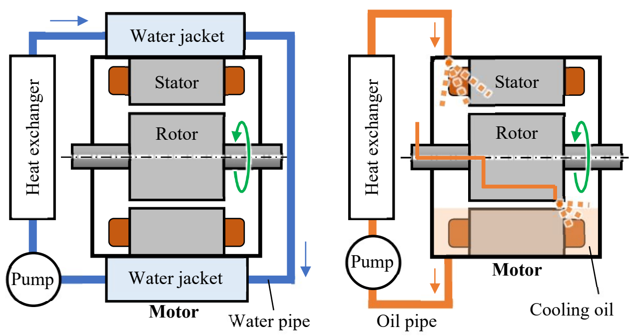
There has been increasing investment and technological development towards the realization of a decarbonized society, and in the automotive field in particular, there has been a shift from gasoline vehicles to electric vehicles (EVs).

Conventional EVs use the drive technology of gasoline-powered vehicles, replacing the engine with a drive motor and driving the wheels through a drive shaft. In contrast, in an in-wheel motor, the motor is mounted inside the wheel and directly driven.(1) This results in high efficiency and flexibility of control achieved by directly driving the wheels. In addition, the design of the body frame is flexible because the entire drive system is housed inside the wheels, and the cabin space is expanded. In-wheel motors have advantages such as increased battery mounting space and reduced mechanical loss.(2) These also improve cruising range, which is often limited in conventional EVs.(3) However, there are also drawbacks such as increased mass in the wheels and extensive modifications to the existing brakes and suspension.(4)(5)

Therefore, we have been developing a compact and lightweight in-wheel motor, the Direct Electrified Wheel (DeW), which integrates a motor, inverter, and brake. Conventionally, to prevent the cooling water from adhering to the power semiconductors that make up the inverter and causing electrical leakage, a space for a dedicated cooling water channel that is electrically insulated was required.(6) To save space in the cooling pipe, the motor and inverter are integrated, the power semiconductor is directly cooled using highly insulating cooling oil, and the cooling oil is circulated through the motor to directly cool the coil. Furthermore, we aim to improve cooling efficiency, downsize the motor, and improve output density by constantly immersing all coils densely arranged in cooling oil and directly cooling them with pumped cooling oil.

2. DIRECT COOLING

EV drive motors are generally cooled using liquid cooling instead of air cooling to achieve high power density. There are two liquid cooling methods, water (Fig. 1(a)) and oil (Fig. 1(b)). As shown in the figure, the water cooling method has a water channel called a water jacket in the motor housing that cools the motor. The oil cooling method cools the coils, cores, and magnets directly in contact with the cooling oil. Compared with water cooling, oil cooling is more efficient as the heat is transferred directly from the heating parts to the cooling oil. In conventional oil cooling, cooling oil is flowed by a high speed rotor or is sprayed into the coils.



(a) Conventional water cooling (b) Conventional oil cooling

Fig. 1. Examples of conventional liquid cooling methods.

We are aiming to develop a direct cooling technology with a power density greater than that of conventional oil cooling. Fig. 2 shows the concept.[7] In direct cooling, the inside of the motor is filled with the cooling oil, and the heating parts are completely immersed in the oil. The heat transfer rate from the heating parts to the cooling oil is increased by pumping the oil, and the contact area between the heating site and the oil is also increased. This results in a higher cooling efficiency than that of conventional oil cooling.

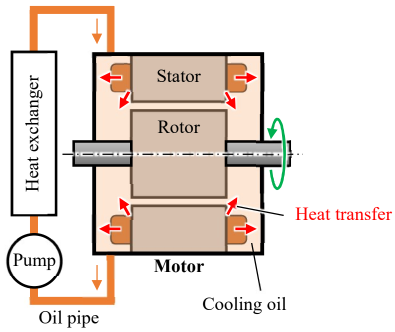


Fig. 2. Direct cooling method.

3. OVERVIEW OF DIRECT ELECTRIFIED WHEEL

Fig. 3 shows an image of the developed in-wheel motor DeW, and Table 1 lists its specifications. The DeW is a direct drive that does not use a speed reducer and is sized to fit a 19-inch wheel. The maximum output is 60 kW, and the maximum torque is 960 Nm. The motor power density at maximum output is 2.5 kW/kg.

Direct-drive in-wheel motors often use an outer rotor to increase the gap diameter and torque.[8][9] In this development, we implemented an inner rotor by taking into account the connection with the peripheral parts. In addition, we increased the gap diameter by arranging the coils densely and thinned the stator arranged on the outer circumference.

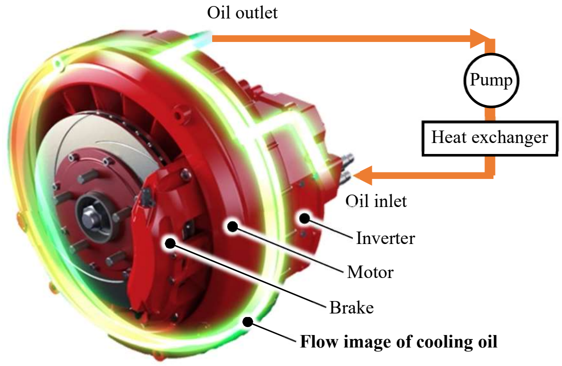


Fig. 3. Direct-cooling motor DeW.

Table 1. Specifications of DeW.

No.	Item	Unit	Number
1	Power density of motor	kW/kg	2.5※1
2	Wheel diameter	mm	19 inch
3	Tire size	mm	235/35R19
4	Maximum output	kW	60
5	Maximum torque	Nm	960
6	Maximum rotation	min^{-1}	1200
7	Supply voltage	V_{dc}	420
8	Maximum current	A_{rms}	280

※1: Weight includes the motor housing and driveshaft.

4. Prototype test

4.1. Oil friction loss

We removed the three-phase wires of the inverter to open the phases of the motor and externally drive the in-wheel motor with the motor on the test bench. The flow rate of the cooling oil is 0, 2, and 5 L/min, and the rotational torque is measured up to 1200 min^{-1} every 100 min^{-1} at 2 L/min and every 200 min^{-1} at 0 and 5 L/min.

Due to accurately separate fluid friction loss from iron loss, copper loss, and mechanical losses such as bearings and oil seals, an externally-driven no-load rotation test is performed with the inside filled with cooling oil including the fluid friction loss and with the inside without cooling oil without the fluid friction loss, and the fluid friction loss is calculated from the rotation torque differences of the two.

Fig. 4 shows the actual measurement results of the fluid friction loss. In the cooling oil flow rate range of 0 to 5 L/min, changes in the flow rate have little effect on the fluid friction loss. The calculated results agree well with the theoretical formula, indicating that it is possible to estimate the fluid friction loss even with theoretical formula-based calculations[10].

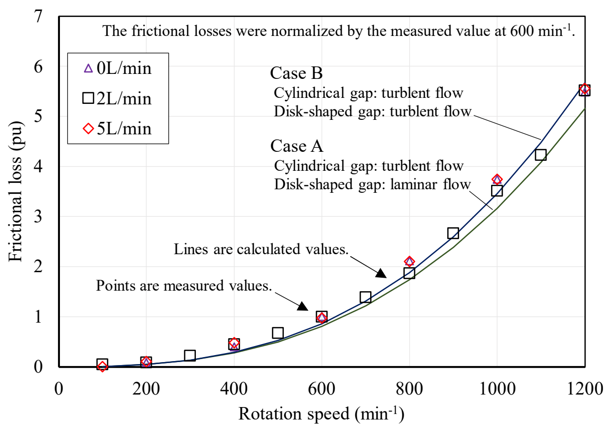


Fig. 4. Measurement results of frictional loss.

4.2. Continuous heat-run test

The heat-run test of the actual in-wheel motor was carried out on the test bench. The motor circulates while cooling oil is cooled by the oil circulation system, and it is energized until the outlet temperature of the cooling oil and the coil end temperature are saturated.

Fig. 5 shows the temperature increase of the coils in a continuous heat-run test. When the temperature of each part is saturated, the copper loss is increased by increasing the current and continuing the energization until the temperature is saturated again.

Fig. 6 shows the relationship between the loss and temperature increase. The loss and increase in coil end temperature are proportional, and even under operating conditions equivalent to 50% of the maximum output, the temperature of the coils did not increase by more than 50 K, thus demonstrating the cooling effect of direct cooling.

Fig. 7 shows the relationship between the flow rate and temperature increase. In motors such as direct drives, in which a large percentage of the total loss is copper loss, we found that the flow rate and coil temperature of the cooling oil were inversely related.

4.3. Short-time rating test

Finally, we measured the increase in coil temperature at the short-time rated maximum output of 60 kW. The flow rate of the cooling oil is set to 0 L/min and 2 L/min, and the temperatures of the coil end and cooling oil are measured.

Fig. 8 shows the measurement results of the short-time rating test. The temperature of the coil end increases proportionally with time and was not affected by the cooling oil flow rate. The increase in the cooling oil temperature was less than 0.5 K. Therefore, in short-time ratings, it is difficult to control the coil temperature by the flow rate of the cooling oil even with direct oil cooling, and the rate of temperature increase is determined by the heat capacity of the coil and surrounding components.

4. CONCLUSION

The concept of direct oil cooling, in which the inside of a motor is filled with cooling oil and the heat-generating parts such as the coils and core are directly cooled by the pumped cooling oil, was developed. The following conclusions were obtained by measuring the characteristics of an actual in-wheel motor on a test bench.

(1) Oil friction loss

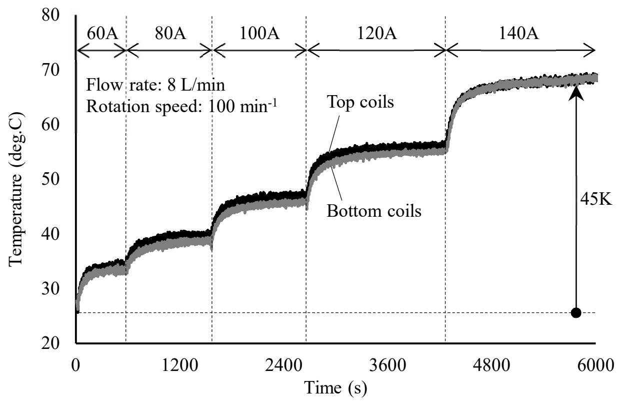


Fig. 5. Temperature rise of coils at continuous heat-run test.

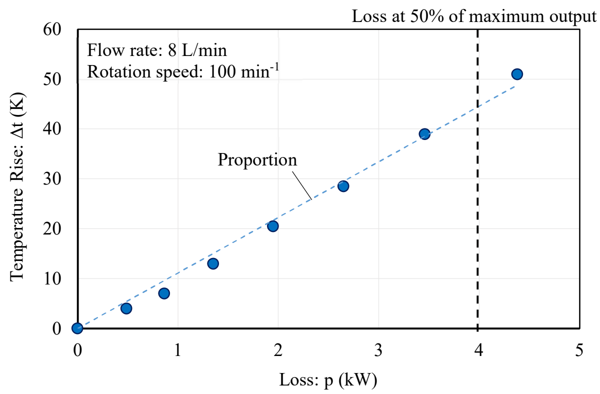


Fig. 6. Relationship between loss and temperature rise.

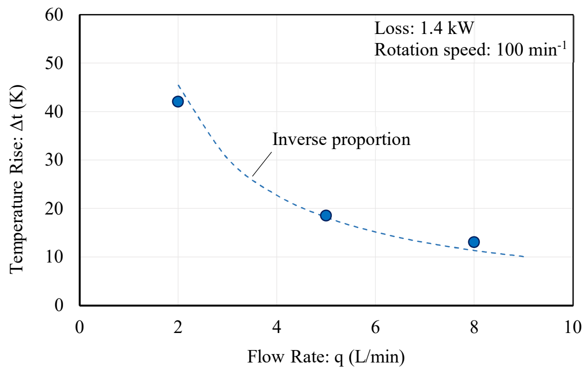


Fig. 7. Relationship between flow rate and temperature rise.

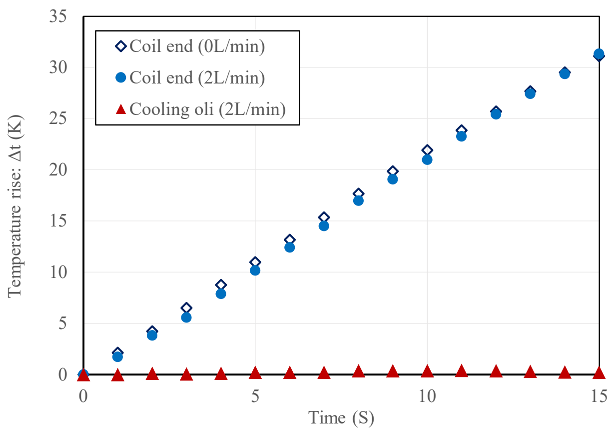


Fig. 8. Coil temperature during short-time rating test.

Through calculations and actual measurements, we determined that oil friction loss depends on the rotation speed. The calculated and measured results are in good agreement, indicating that the oil friction loss can be manually calculated. In addition, although there was a large increase in oil friction loss at the maximum rotation speed of 1200 min^{-1} (approximately 150 km/h), in the practical speed range of 400 min^{-1} and below (approximately 50 km/h), it was less than 1% of the maximum output.

(2) Continuous heat-run test

Even under operating conditions equivalent to 50% of the maximum output (assuming continuous output), the temperature increase of the coil ends was at most 50 K, which demonstrates the cooling effect of direct oil cooling. In addition, the cooling oil flow rate and the increase in coil temperature are inversely proportional in a direct drive motor in which the DC copper loss accounts for a large proportion of the total loss.

(3) Short-time rating test

The temperature of the coil ends increased proportionally with time and was not affected by the cooling oil flow rate. Thus, the temperature increase cannot be controlled by the cooling oil and depends on the heat capacity of the surrounding parts.

In the future, we will mount the in-wheel motor DeW on the EV prototype shown in Fig. 9 and verify its performance.

Fig. 9. EV prototype with in-wheel motor.

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