

Hermetically Sealed Cooling Structure for Small High-current Density Motors

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ABSTRACT

A motor cooling structure for electrification vehicle drive motors capable of absorbing the increases in heat generation from miniaturization with high current has been developed. The conventional cooling method involves dripping refrigerant onto exposed parts of the stator coil, relying on thermal conduction to indirectly cool the coil inside the stator slots where the refrigerant cannot reach. In this study, we have established a technology that directly cools the entire coil by hermetically sealing the stator to immerse the entire coil in automatic transmission fluid. Using a prototype motor, the technology has been demonstrated to have more than twice the cooling performance of the conventional cooling method. It was also confirmed that further enhancements in cooling performance can be expected by increasing refrigerant flow rate.

1. Introduction

In recent years, electrification vehicles such as battery electric vehicles (BEVs) and fuel cell vehicles (FCVs) are rapidly growing in popularity due to demands to reduce CO₂ emissions during vehicle travel. In addition to the existing basic performance requirements of high power, high torque, and high efficiency, the authors see compactness as another important performance requirement for the traction motors used in electrification vehicles. With these electrification vehicle motors using rare metals and copper, which are of concern for material supply risk⁽¹⁾, smaller motors would lead to reductions in materials used.

There are two main methods of reducing motor size. First, motor rotating speed can be increased⁽²⁾. As motor output is the product of torque and rotating speed and torque is proportional to motor size, the motor size can be reduced while maintaining the same motor output by increasing the rotating speed⁽²⁾. Taking this route requires strengthening the rotating bodies in the reduction gear and rotor, which generally requires use of high-strength materials containing rare metals in quantity⁽³⁾. Also, the reduction ratio on the reduction gear will be increased, resulting in increased friction loss and reduced overall efficiency of the drive unit⁽⁴⁾. The other method is to increase torque density and output density by applying high current to the motor. Given the increased heat generation per unit area, this method requires higher cooling performance than offered by

conventional cooling methods^{(5),(6)}.

Given the supply risks of rare metals and other materials, in this study, we propose a hermetically sealed cooling structure with more than twice the conventional cooling performance to achieve a smaller motor by increasing current density. Using the hermetically sealed cooling structure, we succeeded in increasing motor torque density and output density to approximately double their conventional values⁽⁷⁾.

Traction motors are generally cooled using one of two main methods: water cooling, in which refrigerant in the form of Long Life Coolant (LLC) flows through channels formed in the housing, and oil cooling, in which Automatic Transmission Fluid (ATF) as the refrigerant is dripped directly on exposed portions of the coil to cool the motor⁽⁵⁾. In water cooling systems, as the system uses thermal conduction to cool the motor through the stator core, cooling performance is high for the windings inside the slots but weaker at the coil ends outside the stator core⁽⁵⁾. Meanwhile, in oil cooling systems, the coil ends can be cooled directly, but the windings inside the slots where the refrigerant does not reach are cooled by thermal conduction in the conductor itself⁽⁵⁾. Both systems depend on thermal conduction to cool certain sites and struggle at handling the increase in heat generation per unit area needed when reducing motor size. Therefore, in this study, we have developed a method based on oil cooling to directly cool the entire coil, including the slot interior. This paper will open with an overview of the

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cooling technology application. Next, a proof of concept of the cooling effects on a test piece will be explained, followed by challenges with the hermetically sealed cooling structure and how to handle these challenges. Finally, results confirming the effects will be shown from test measurements with an actual prototype motor.

2. Cooling Technology Application

2.1. Target Cooling Performance

The goal of this study was to double existing cooling performance. The following represents the estimated impact that a twofold enhancement in cooling performance would have on motor performance.

First, so as to help ensure sufficient drive power for an electrification vehicle with a single motor, taking into account the ratio of reduction gears and balance of friction, the assumed motor for development was given a maximum torque of 280 Nm, maximum power of 150 kW, and maximum rotating speed of 15,000 rpm. If cooling performance can be doubled from existing levels, current density will also at least be doubled, resulting in torque density and output density of at least 1.7 times existing levels. With this, existing motors could be reduced in volume by 40%.

2.2. Cooling Method Concept

To enhance cooling performance, it is important to reduce thermal resistance between the heating element, or coil, and the refrigerant using heat transfer Eq. (1). According to Eq. (2), thermal resistance is determined by the heat transfer area and heat transfer coefficient. The heat transfer coefficient can be expressed by Eq. (3) using a Nusselt number, a dimensionless quantity indicating whether the heat transfer is convective or conductive. Nusselt numbers positively correlate with Reynolds numbers, which indicate the ratio of inertial force to viscous force. According to Eq. (4), the Reynolds number is proportional to the flow velocity of the fluid. Thus, the heat transfer coefficient can be enhanced by increasing flow velocity. Based on the above, the aim of the proposed structure will be to increase the heat transfer area and, by increasing flow velocity, to enhance the heat transfer coefficient.

$$Q = \frac{(T_{\text{coil}} - T_{\text{ATF}})}{R} \quad (1)$$

$$R = \frac{1}{Ah} \quad (2)$$

$$Nu = \frac{hL}{k} \quad (3)$$

$$Re = \frac{UL}{\nu} \quad (4)$$

Q : Amount of heat removed (W)

R : Thermal resistance (K/W)

T_{coil} : Temperature of coil (K)

T_{ATF} : Temperature of ATF (K)

A : Heat transfer area (m^2)

h : Heat transfer coefficient ($\text{W}/\text{m}^2\text{K}$)

Nu : Nusselt number

L : Characteristic length (m)

k : Thermal conductivity (W/mK)

Re : Reynolds number

U : Flow velocity (m/s)

ν : Dynamic viscosity (m^2/s)

Figure 1 shows a sectional view and overview of a conventional cooling structure⁽⁶⁾, and Fig. 2 shows a sectional view and overview of the proposed cooling system for development. In the conventional cooling structure, ATF refrigerant is dripped on the coil ends from directly above to cool the coil. In the conventional structure, thermal conduction from the coil ends, not the ATF, is used to transfer heat to the coil inside the slots, and the heat transfer area of the coil ends is limited to the surface area where ATF is applied. This limits the total amount of heat removed from the coil as a whole.

As shown in Fig. 2, in the hermetically sealed cooling structure in this study, the entire coil, including inside the slot as well as the coil ends, is immersed in ATF to help ensure a heat transfer area 2.2 times larger than the conventional heat transfer area. Furthermore, the ATF is pressure-fed along the axis of rotation from one coil

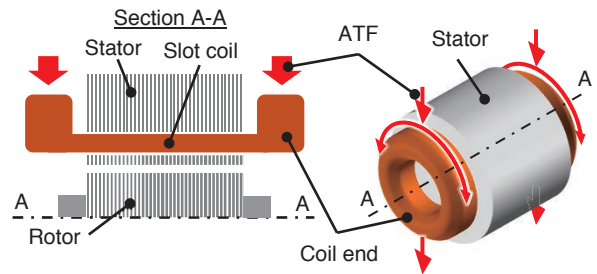


Fig. 1 Conventional motor cooling structure

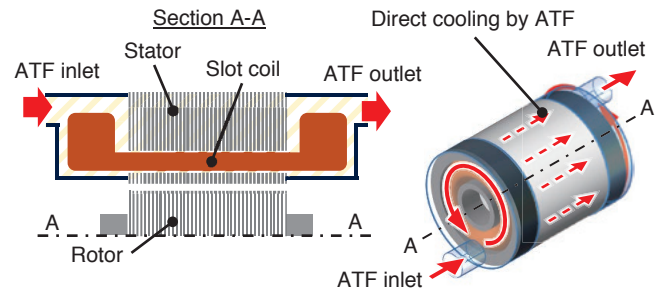


Fig. 2 Proposed cooling method

end through the inside of the slot and discharged out the opposite coil end, increasing the flow velocity of ATF in contact with the coil and enhancing the heat transfer coefficient.

3. Proof of Concept for Cooling Effect

3.1. Thermal Fluid Analysis

The results of a thermal fluid analysis simulating part of the cooling concept described above are given in Fig. 3. Thermal fluid analysis was performed through CFD simulations. The analysis model is a reproduction of a single slot in the motor stator. The ATF flows in from one coil end and through the slot interior to be discharged from the opposite coil end. For the boundary conditions, flow velocity at the inlet was constant, discharge at the outlet was by atmospheric release, and heat flux on the outer surfaces of the stator yoke and covers were set to zero. To simulate heat release from the coil, the coil wall surfaces were given a heat flux equivalent to twice the heat generated by the motor used in the conventional cooling system.

The CFD results show that the maximum temperature is below the heat resistance temperature of the coil.

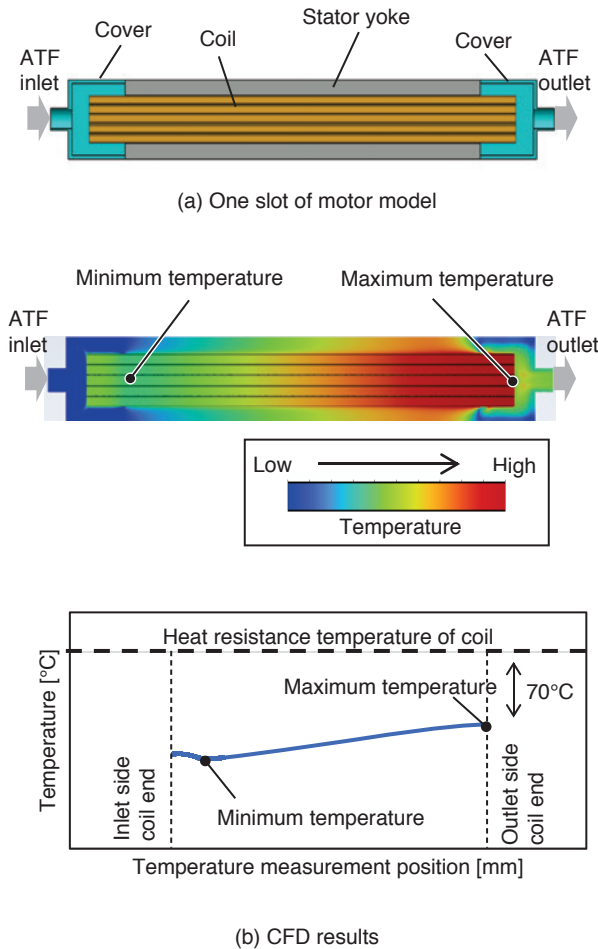


Fig. 3 Fluid analysis

Additionally, the maximum temperature for the coil was at the ATF discharging coil end, not inside the slot as in the conventional system. By using the hermetically sealed cooling structure to enable direct cooling of the entire coil with ATF, including the coil in the slot interior, it was confirmed that the maximum temperature of the coil is located at the coil end exposed from the stator.

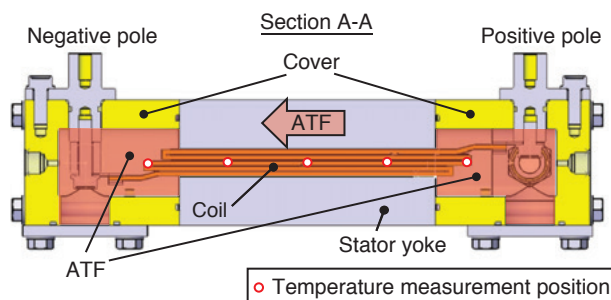
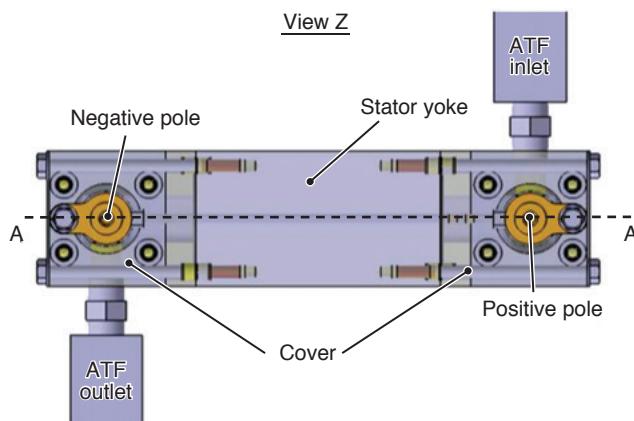
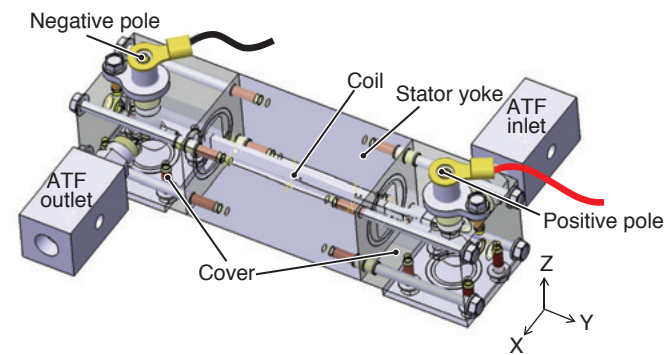
3.2. Verification Test with Test Piece

A test piece simulating a 1-slot section of the stator was fabricated based on the CFD model described above. The test piece is shown in Fig. 4. The test piece is equipped with a power supply terminal for energized heating of the coil. The test piece is built with the ability to simulate both a conventional cooling structure, dripping refrigerant on the coil ends, and the hermetically sealed cooling structure devised for this study. The conventional cooling structure was simulated by dripping refrigerant from the cover at both coil ends. With it, refrigerant could be discharged by partially releasing the cover. The hermetically sealed cooling structure was simulated by supplying refrigerant from the inlet, running it through the gaps in the coil within the slot, and discharging it out the outlet side. Inside the slot, the conventional cooling structure is composed of a coil, insulating paper, and varnish. By contrast, the hermetically sealed cooling structure is composed of the coil and insulating paper, using no varnish.

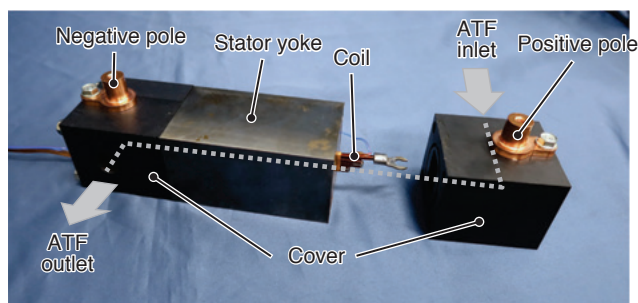
In the test system, coil temperature is measured when the coil is energized and heated to compare between the conventional cooling structure and hermetically sealed cooling structure. For the test conditions, the same temperature and flow rate for the refrigerant ATF and input power for the coil were used for both cooling structures.

Figure 5 shows the relationship between current density and coil temperature during coil heating for each cooling structure. Coil temperature was measured at equal intervals in the coil longitudinal direction using five thermocouples, plotting the maximum temperature of these measurements. Coil temperature was lower for the hermetically sealed cooling structure than in the conventional cooling structure. Even at twice the current density of the conventional structure, which is the input power with the motor reduced to 40% the conventional volumetric size, the maximum temperature is confirmed to be below the coil heat resistance temperature.

In conventional cooling structures, only the exposed parts of the coil is directly cooled by ATF. Thus, the coil ends are directly cooled, but the middle of the coil in the slots is relatively hard to cool. By contrast, as the hermetically sealed cooling structure can directly cool the entire coil with ATF, including the spaces within the slots, this greatly increases the heat transfer area and should increase the cooling effect. The hermetically sealed cooling structure was successfully reproduced according to the concept in testing with the test piece.



(a) CAD model



(b) Actual model

Fig. 4 Test piece

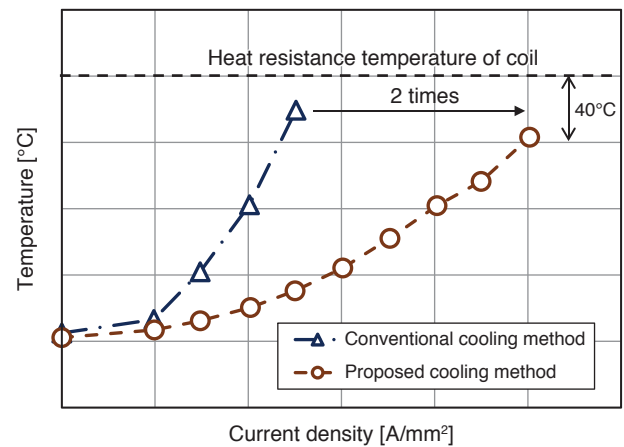


Fig. 5 Relation between current density and coil temperature

4. Challenges and Their Measures with Hermetically Sealed Cooling Structures

In the hermetically sealed cooling structure, the entire coil is immersed in ATF, which is circulated throughout the system. To apply the structure to an actual motor, upon insulating the system, the following three technical issues will need to be addressed:

- (1) Fix the coil and stator yoke in the slot
- (2) Create oil channels in the slots
- (3) Seal the coil ends with a cover to make them oil tight

First, figures will be used to explain technical issues (1) and (2) in detail. Figure 6 is a sectional drawing of a slot in a conventional motor. The coil and stator yoke are insulated from one another by wrapping insulating paper around the

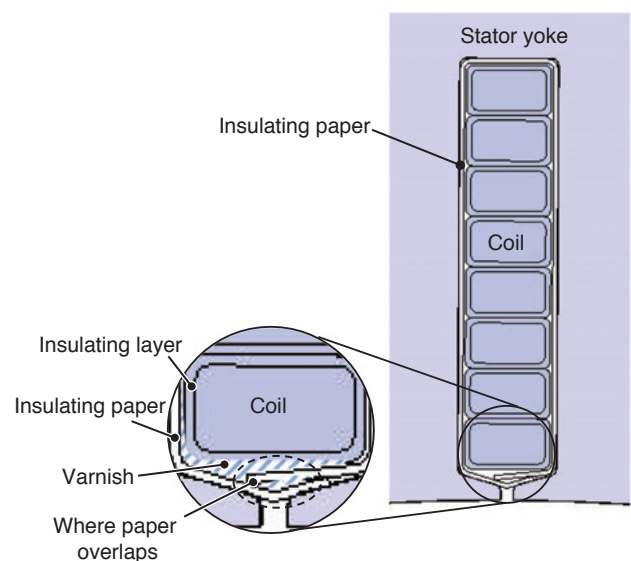


Fig. 6 Cross section of slot for conventional motor

coils inside the slots. When the proposed cooling system is applied to this structure, ATF will need to flow between the insulating paper and coils, meaning that ATF will leak through where the insulating paper overlaps. In conventional motors, the gaps between the slot coils, insulating paper, and stator yoke are impregnated in varnish to fix each part in place, thus blocking the space that will serve as the ATF flow path required for the proposed cooling method.

An overview of the structure devised to address issues (1) and (2) is shown in Fig. 7. A sheet with a foam adhesive layer is applied to the surface of newly developed insulating paper, modifying the seal where the insulating paper overlaps and sufficiently affixing the coil without using varnish. Coil fixing force and ATF channels are ensured in the slots by adopting a coil shape with straight sides for a wide contact area where facing the stator yoke and arc-shaped corners for large spaces on the sides between coils.

A detailed view of the internal slot configuration is shown in Fig. 8. The slot is composed of a coil with a

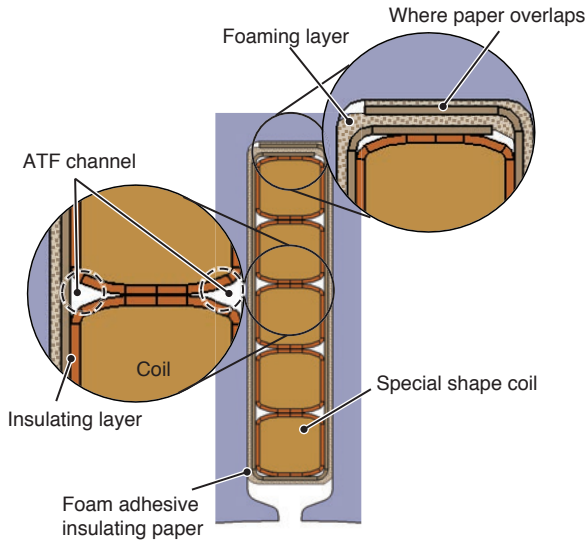


Fig. 7 Cross section of slot for proposed motor

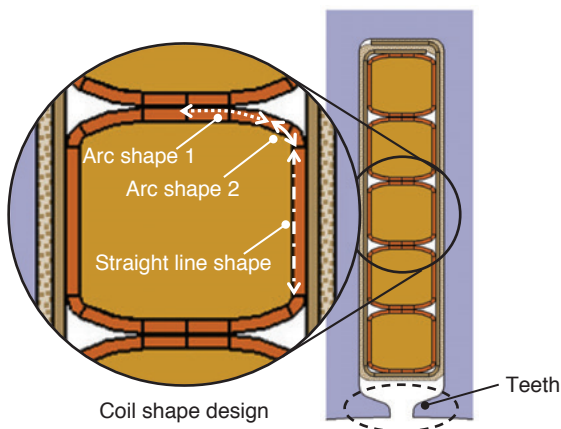


Fig. 8 Slot configuration

special sectional shape with multiple arcs forming its corners, surrounded by insulating paper with heat-attached foam adhesive. The coil corners are shaped with double arcs in the vicinity of the coils to create space for ATF channels between the conductors, and the straight sections are made longer on the sides contacting the insulating paper than the sides contacting an adjacent coil to provide a wide adhesional surface area with the insulating paper.

Finally, the following is an explanation of technical issue (3). In the conventional structure, refrigerant is dripped onto the coil ends, so no coil end seals are necessary. However, in forming the hermetically sealed cooling structure described in this paper, no refrigerant can be allowed to leak from the coil ends. The coil end sealing structure used for this motor is shown in Fig. 9. Along the inner diameter of the stator are multiple teeth, as shown in Fig. 8. To seal these teeth, a resin cuff support is positioned on the end face of the stator. The gaps between the cuff support and insulating paper are filled with a foam adhesive sheet to help ensure a good seal. The sealing structure was formed by applying an O-ring between the coil cover and cuff support.

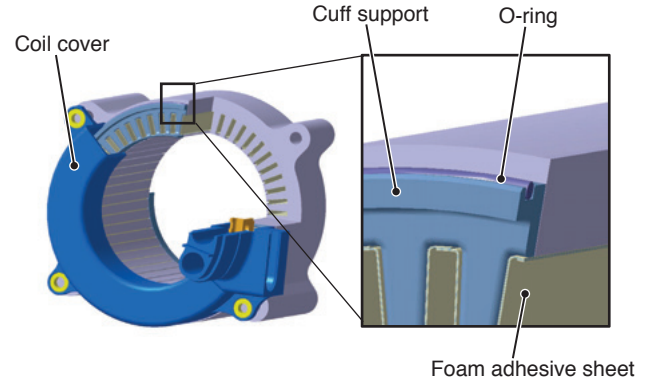


Fig. 9 Sealing structure (coil is not shown)

5. Demonstration Testing with the Hermetically Sealed Cooling Structure

5.1. Overview of the Prototype

Figure 10 is an external view of the prototype. A prototype motor using the hermetically sealed cooling structure was fabricated to confirm the pressure loss and cooling performance characteristics of the cooling structure.

5.2. Basic Specifications

Table 1 shows the basic specifications of the motor. The current density is double the conventional values to produce equivalent torque at 40% the conventional size. By reducing the area occupied by the coil, the specification allows for the appropriate number of turns to be set even with the smaller diameter.

Table 1 Motor specifications

Motor type	IPMSM
System voltage	350 V
Number of poles	8
Number of turns / slot	5
Current density	Twice conventional density
Coil type	Segment conductor



Fig. 10 Prototype motor

Figure 11 is a sectional view of the magnetic circuit applied for the motor. The motor stator has a smaller outer diameter than in conventional motors. As a result, the magnetic torque, which depends on the magnet flux, is limited. The motor adopts a multilayer arc magnet shape to maximize reluctance torque while ensuring the magnet amount.

5.3. Pressure Loss Characteristics

As the cooling structure is hermetically sealed, pressure is lost when pressure-feeding the ATF. Running the ATF into the slight spaces inside the slots requires an electric oil pump to pressure-feed the ATF. If pressure loss when feeding is high, a high-flow electric oil pump will be required, which would impact the overall drive unit efficiency.

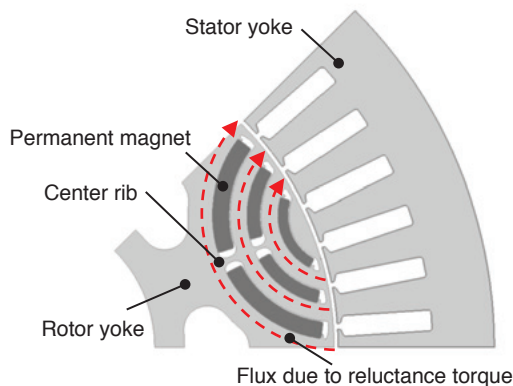


Fig. 11 Magnetic circuit model

Pressure loss in the cooling structure was measured to confirm the feasibility of establishing the cooling channels. Figure 12 shows the relationship between flow rate and pressure loss, and the rated output curve of the electric oil pump. The electric oil pump had an output of 40 W and volumetric efficiency of 50%, which is typical for automotive applications⁽⁸⁾. With the pressure loss at each target flow rate falling below the oil pump output curve, this confirms that the cooling structure can be fed with a typical automotive use electric oil pump.

5.4. Cooling Performance Characteristics

This section will compare the cooling performance of the prototype motor and a conventional motor. Given the many differences between the conventional cooling structure and hermetically sealed cooling structure, including motor structure, an evaluation method capable of comparing the cooling performance was used. For the test conditions, temperature and flow rate were set equal for the refrigerant ATF, and cooling amount was evaluated as copper loss of the power applied until the coil temperature reached equilibrium at a controlled temperature. Thus, greater copper loss means higher cooling performance. Figure 13 shows sample time series data for measurements of actual coil temperature and copper loss.

Figure 14 shows a graph of the relationships between cooling performance and refrigerant flow, comparing the proposed motor and conventional motor. The results confirmed that the proposed cooling method achieved more than twice the cooling performance of the conventional method. They also show that cooling amount increases relative to refrigerant flow differently than with the conventional cooling method. With the conventional method, the cooling amount tends to become saturated relative to refrigerant flow. Presumably, this may be due to refrigerant dripped on the coil ends being reflected and

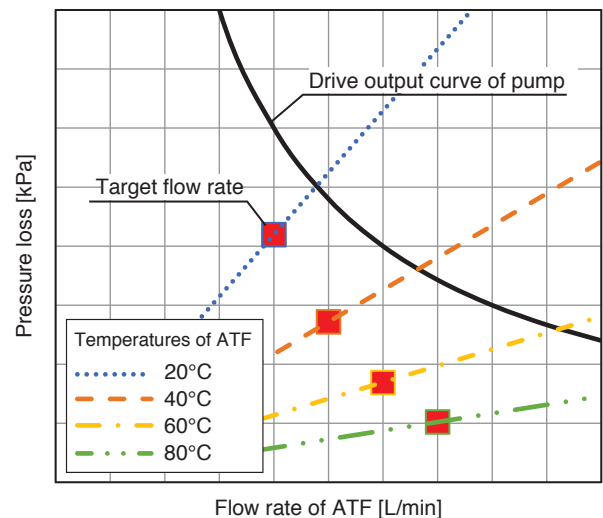


Fig. 12 Relation between flow rate and pressure loss

scattered at increased flow rates, meaning that the added refrigerant does not contribute to cooling. Meanwhile, in the proposed cooling structure, the cooling amount tends to increase linearly with refrigerant flow. As the structure is ATF immersed, an increase in refrigerant flow should increase flow velocity, which in turn should lead to an increase in heat transfer coefficient. In this test, the maximum cooling performance was confirmed to be quadruple that of the conventional motor.

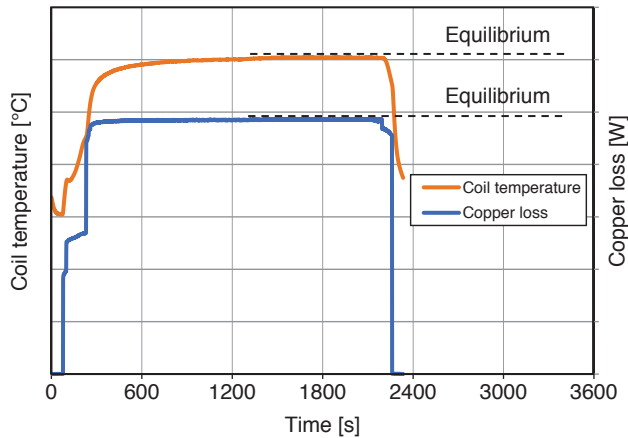


Fig. 13 Time series measurement data

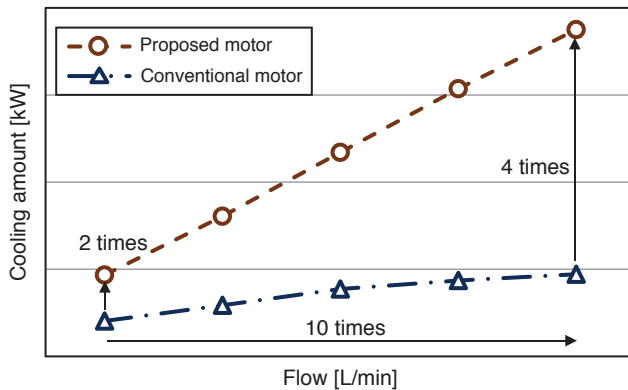


Fig. 14 Measurement of cooling capacity

6. Conclusions

A hermetically sealed cooling structure was developed to achieve a compact motor with high current density. A test piece and prototype motor applying this structure were fabricated to demonstrate the cooling performance.

- (1) More than twice the cooling performance of conventional cooling was achieved by immersing and circulating ATF throughout all windings to directly cool the coil, expanding the heat transfer area, and increasing the heat transfer coefficient.

- (2) The hermetically sealed cooling structure is highly sensitive to refrigerant flow, and cooling performance can be further enhanced by increasing refrigerant flow.

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