Analytical and experimental study on the feasibility of rotor cooling with thin gas for fully superconducting rotating machines

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Abstract. Rotor cooling with thin gas in air gap was considered for fully superconducting rotating machines. This does not require designing coolant channels in the rotor, so the rotor structure can be simplified. The aim of this study is to verify the feasibility of this cooling system with thin gas. In this paper, at first, steady state thermal analysis with the finite element analysis software COMSOL® was conducted to investigate whether it would be possible to observe cooling characteristics of thin gas in our experiment. The analytical result suggests an enhancement of cooling due to convection can be observed in an experiment with liquid-nitrogen cooling by increasing helium gas pressures to 5000 Pa and above. Then an experiment device including a helium gas vessel was fabricated and an experiment without rotation was performed. The temperature of the rotor which was in the vessel cooled by liquid nitrogen was apparently decreasing after feeding helium gas. Therefore, it was confirmed that the rotor was cooled by heat conduction through the helium gas. In the future, to verify whether rotor cooling with thin gas is enhanced by convection, the experiment will be conducted at various rotational speeds and pressures of helium gas.

1. Introduction
Fully superconducting rotating machines can be smaller in size and weight than conventional machines, so they are expected to be applied to electrified aircraft [1] or wind power generators [2]. However, it is necessary to cool both the rotor (field windings) and stator (armature windings) in these machines. In particular, designing the flow path in the rotor to supply coolant requires complicated structures.

To simplify the rotor structure, rotor cooling with thin gas in the air gap was considered [3-6]. Figure 1 shows a conceptual diagram. The stator, which has armature windings made of MgB2 wire, is cooled to 20 K with coolant, such as liquid hydrogen. On the other hand, the rotor, which has field windings made of REBCO tape, is cooled to below 50 K with heat conduction and convective heat transfer through the gas, typically helium or hydrogen. However, the feasibility of this cooling system is still unknown for the fully superconducting rotating machines, so the purpose of this study is to verify its feasibility by both numerical analysis and experiment.

In this paper, numerical analysis and an experiment were described. At first, the numerical analysis was performed to investigate whether it would be possible to observe the cooling characteristics of the thin gas in our experiment. Then the experiment without rotation was conducted to observe the cooling effect due to heat conduction through helium gas.
2. Numerical analysis

2.1. Method

Steady state thermal analysis was performed with the finite element analysis software COMSOL®. Figure 2 shows a 2D axisymmetric model and analytical conditions. This model consisted of the rotor and air gap (helium gas) domain. In addition, the model size was same as the experimental device size as shown in Figure 2.

As a condition of heat transfer between the rotor and the stator, empirical formulas of convective heat transfer between concentric rotating cylinders [7] were applied. They are given by

\[
Nu = \begin{cases} 
2 & (Ta < Ta_c) \\
0.42(TaPr)^{0.25} & (Ta_c < Ta < 10^8) \\
0.092(TaPr)^{1/3} & (10^8 < Ta < 5 \times 10^{12}) 
\end{cases}
\] (1)

where \( Nu \) is the Nusselt number, \( Ta \) is the Taylor number, and \( Pr \) is the Prandtl number. These dimensionless numbers are defined as below.

\[
Nu = \frac{hD_h}{k}
\] (2)

\[
Ta = \frac{\omega^2 r_1}{\nu^2} \left( \frac{D_h}{2} \right)^3
\] (3)

\[
Pr = \frac{\nu}{\alpha}
\] (4)

Here, \( h \) is the heat transfer coefficient, \( D_h \) is the hydraulic diameter, \( k \) is the heat conductivity, \( \omega \) is the angular velocity, \( r_1 \) is the rotor radius, \( \nu \) is the kinematic viscosity, and \( \alpha \) is the thermal diffusivity. \( h \) was calculated by equations (1) to (4) and used as the heat flux condition to reflect the cooling characteristics of helium gas in the air gap.

In addition, windage loss \( (Q_w) \) which was calculated with reference to [8] was set as a heat generator on the rotor’s side face. It was not included in \( q_1 \) or \( q_2 \). The stator temperature \( (T_s) \) was set to either 80 K or 20 K, for the cases of stator cooling with liquid nitrogen and liquid hydrogen, respectively. Heat invasion from the rotor ends was also considered. In this section before the experiment, it was assumed 1 W regardless of the stator temperature, but it will be adjusted to the experimental result.
In this analysis, the rotational speed ($N_{\text{rot}}$), and pressure of the helium gas in the air gap ($P$) were varied as parameters. Then the rotor surface temperature was calculated to investigate whether it would be possible to observe the cooling characteristics of the thin gas in the experiment.

**2.2. Result and discussion**

Figure 3 shows the maximum temperature of the rotor surface as a function of the rotational speed at different pressures of helium gas (a) $T_s = 80$ K (b) $T_s = 20$ K

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**2.2. Result and discussion**

Figure 3 shows the maximum temperature of the rotor surface as a function of the rotational speed at different pressures of helium gas. Figure 3(a) shows the case where the stator temperature is 80 K and Figure 3(b) shows the 20 K case. The horizontal axis extends up to 1200 rpm because the maximum rotational speed in the experiment is planned to be around 1000 rpm.

To check the validity of this numerical analysis, the rotor temperature was approximately calculated based on the heat equivalent circuit. Figure 4 shows the circuit. The rotor temperature is given by,

$$T_1 - T_s = Q(R_{h1} + R_k + R_{h2}) \tag{5}$$

where $R_{h1}$, $R_k$, and $R_{h2}$ are heat resistivities caused by heat convection between the rotor and helium gas ($R_{h1}$), heat conduction of helium gas ($R_k$), and heat convection between helium gas and the stator ($R_{h2}$), respectively. These are defined as below.

$$R_{h1} = \frac{1}{2\pi r_1 l h} \tag{6}$$

$$R_k = \frac{1}{2\pi lk} \ln\left(\frac{T_2}{T_1}\right) \tag{7}$$
When the stator temperature was 80 K and the rotational speed was 0 rpm, the rotor temperature at Figure 3(a) was 106.8 K regardless of the pressure. On the other hand, the rotor temperature applied the heat conductivity of helium gas at 95 K and calculated by equation (5) to (8) was 107.5 K. Therefore, it can be said that the numerical analysis is valid.

The higher the pressure of the helium gas becomes, the lower its kinematic viscosity becomes, so the Taylor number increases. Therefore, it is expected that the higher the pressure is, the more the cooling is enhanced by convection caused by the rotation. Enhancement of the cooling means a temperature drop with increasing rotational speed. In Figures 3(a) and (b), this effect appeared when the pressures were 5000 Pa and 1000 Pa, respectively. This result suggested enhancement of cooling due to convection can be observed in the experiment with liquid nitrogen by increasing helium gas pressures to 5000 Pa and above.

3. Experiment

3.1. Method
To perform the experiment, an experimental device was made. Figure 5 shows its photograph. The stator wall was cooled, and a rotor made of stainless steel was rotated in helium gas and its temperature was observed. The pressure of the helium gas and the rotational speed were also measured. Then the result was compared to the numerical analysis under the same parameters.

Figure 6 shows a schematic diagram of the experimental device. For the stator, a helium gas vessel was fabricated. In addition, the device consists of some other parts, including a rotor, shaft, bearings and a slip ring. However, no superconducting materials were used because this experiment focused on the cooling characteristics of thin gas in the air gap.

The vessel was immersed in liquid nitrogen (LN$_2$) to cool the stator wall as shown in Figure 6(a). In the future it will be cooled to a lower temperature. Temperature sensors were placed at 6 points as shown in Figure 6(b). T1 is on the side face of the rotor to measure its temperature. T2 and T3 are on the end face of the rotor and the shaft in room temperature area, respectively. From the temperature difference between T2 and T3, the heat invasion to the rotor through the shaft was estimated. T4 is on the side face in the vessel to measure the stator’s temperature. T5 and T6 are on the top and bottom sides of the stator to estimate the effect of rotor cooling from the end face. To reduce this effect, a bakelite board, which has low thermal conductivity, was set on the bottom of the vessel.

In this paper, the temperatures were measured under a no rotation condition. Firstly, the stator was cooled while vacuum drawing was done with an oil rotary vacuum pump. Then, helium gas was fed in the vessel after closing the pump valve and removing the pump. Finally, the cooling effect due to heat conduction was verified by the results of the temperature measurements.
3.2. Results and discussion

Figure 7 shows the results of the temperature measurements after pouring the liquid nitrogen coolant during vacuum drawing. The rotor temperature (T₁) decreased slightly. After 75 minutes when the stator temperature (T₄) reached about 85 K, helium gas was fed.

Figure 8 shows the results of the temperature measurements after feeding helium gas into the vessel at a pressure of 0.032 MPa and presents values of T₁ and T₄ at 150 minutes. Compared to Figure 7, T₁ markedly decreased. This was because cooling was enhanced by the heat conduction of the helium gas.

The steady state numerical analysis as described above was conducted under the same parameters: \( P = 0.032 \text{ MPa}, \ N_{\text{rot}} = 0 \text{ rpm}, \) and the heat invasion estimated based on T₂ and T₃ was 0.31 W. The calculated temperature at the same point as T₁ was 87.448 K, whereas the measured result of T₁ was 89.12 K 150 minutes after feeding the helium gas. Therefore, it can be said that the experimental result nearly agrees with the numerical analysis. However, it is supposed that T₁ should become lower than the analytical result over time. This is because there is a cooling effect from the end face which was not considered in the numerical analysis. This is illustrated by T₅ and T₆, as they were also falling after the helium was fed gas as shown in Figure 8. Hence, in the future, this influence will need to be considered to compare the experiment with the numerical analysis.
4. Conclusion
In this paper, steady state thermal analysis and an experiment were done to verify the feasibility of rotor cooling with thin gas for fully superconducting rotating machines. The analytical results which had been calculated before the experiment suggested that an enhancement of cooling due to convection should be observed in the experiment cooled with liquid nitrogen by increasing the helium gas pressures to 5000 Pa and over. Moreover, the cooling effect due to heat conduction by the helium gas was observed by the experiment conducted without rotation.

However, not only static state experiments but rotational states must be conducted to verify the feasibility. In the future, the experiment will be performed at various rotational speeds and pressures of helium gas to investigate the cooling effect of thin gas. At that time, the cooling from the end face will be needed to be considered to compare the experiment and the numerical analysis.
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