Development of the cryo-rotary joint for a HTS synchronous motor with Gd-bulk HTS field-pole magnets

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Abstract. We have studied a prototype of an axial-gap type synchronous motor with Gd-bulk HTS field-pole magnets since 2001. At the liquid nitrogen temperature, these bulks have trapped over 1 T inside the motor after being applied the pulsed field magnetization method. Increasing the flux of the field poles is the most straightforward way of improving the output power of the motor. Cooling down the bulk HTS magnets below the liquid nitrogen temperature provides an effective alternative to increase the magnetic flux trapping. In 2007, we exchanged the cryogen from liquid nitrogen to condensed neon. The key technology of this challenge is a rotary joint, introducing a fluid cryogen into the rotating body in the motor from the static reservoir. We have successfully developed a compact rotary joint which is smaller and lighter than the existent one (1/10 volume, 1/3 length and 1/12 weight). The present joint was manufactured and evaluated with liquid nitrogen and condensed neon. We presume a total heat loss of this rotary joint of less than 10 watts. Successful cooling and rotating tests of the bulk-HTS motor with this novel rotary joint are conducted.

1. Introduction

Since 2001, an axial-gap type high-temperature superconductor (HTS) rotating machine for ship propulsion system with Gd-123 bulk-HTS field-pole magnets has been studied in our laboratory [1]. The bulk-HTS magnets are cooled down below the superconducting transition temperature ($T_c$) with circulating liquid nitrogen. The pulsed field magnetization (PFM) method is employed to magnetize bulk-HTS magnets inside the motor. A pair of vortex-type coils of copper is adopted as magnetizing coils instead of a conventional solenoid-type coil separately prepared. Thanks to the above PFM, at the liquid nitrogen temperature, the maximum trapped magnetic field density reached 1.04 T in 2004 [2]. This enabled 10 kW at 720 rpm operation in our motor [3].

Enhancing total flux of the field poles is necessary to improve the output power of this prototype motor. Generally speaking, the trapped flux density of a bulk-HTS magnet increases with decreasing temperature. A bulk-HTS magnet traps and keeps over 17 T at 29 K [4]. Consequently, to improve the output power of the bulk-HTS motor, we changed the refrigerant from liquid nitrogen to condensed neon to decrease the temperature of the bulk-HTS magnets [5].

A problem caused by the change of cryogen makes necessary the cryo-mechanical design of a rotary joint. Generally, a rotary joint is used for high-temperature fluids as steam. An experimental rotary joint applied to low-temperature fluids such as liquid nitrogen and condensed neon has been
realized in our group in 2007 [6]. However, cryogen leakages and a large heat invasion are inevitable, drastically decreasing the cooling efficiency.

Here, we try to fix three major specifications to develop the new rotary joint: to prevent a leakage of the cryogen, to preserve the mechanical movement from freezing and to reduce the heat invasion from outer parts. According to the above requirements, we designed a novel cryo-adapted rotary joint (cryo-RJ) using a FEM software (ANSYS), and manufactured it.

In this present study, we report the design specifications and the results of the evaluation of the present cryo-RJ.

2. Specifications
The present cryo-RJ was not only designed for HTS but also LTS rotating machine like motors and generators. The design concept is lighter, smaller and offers a lower heat loss compared with the previous experimental ones. This cryo-RJ is aimed at allowing liquid and/or gaseous cryogens such as nitrogen, condensed neon and helium. Figure 1 shows the overview of the present cryo-RJ.

![Figure 1. Overview of the manufactured cryo-RJ.](image)

A commercial Magnetic-Fluid Sealing (MFS) unit is employed to prevent a leakage of the cryogen. The structure of the present cryo-RJ is composed of a multilayer tube and a vacuum insulation. Thanks to the choice of these components, this present cryo-RJ was successfully reduced in volume, weight and heat invasion. Compared to the previous experimental rotary joint used with liquid nitrogen, the present cryo-RJ represents 1/10 volume, 1/12 weight and 1/3 heat invasion. Table 1 shows design specifications of the present cryo-RJ.

**Table 1.** Dimensions and properties of the cryo-RJ.

|                        |     |                        |     |
|------------------------|-----|------------------------|-----|
| Length [mm]            | 348 | Diameter [mm]          | 126 |
| Weight [kg]            | 12.6| Heat loss (designed) [W]| < 6 |
| Maximum rotating speed [rpm] | 1000| Maximum pressure [MPa]  | 0.45|
| Acceptable cryogen     | Liquid and/or gaseous N₂, O₂, Ar, Ne and He |

3. Experimental details

3.1. Facilities
A performance test was carried out to investigate the properties of the present cryo-RJ. The test facilities are composed of the cooling system, the cryo-RJ, the driving device and the data acquisition system, as shown in figure 2.
3.1.1. Components. With the present experiment, we used two different kinds of cryogens to evaluate the characteristics of the cryo-RJ. One is circulating liquid nitrogen (77 K), which is supplied from a Dewar vessel under pressure. On the other hand, the condensed neon (27 K), which is condensed by using a closed-cycle thermosyphon, is employed as shown in figure 2.

The neon gas is introduced in the condenser via an input gas pipe. The pressure inside the thermosyphon is monitored by a pressure gauge and maintained below 0.45 MPa due to the limit from the MFS unit.

In this present study, the cryo-RJ has no power unit to drive itself, so a conventional Permanent-Magnet (PM) synchronous motor is employed. A timing belt and a pulley transmit drive power from the PM motor to the drive shaft. And the rotating speed is controlled by using a commercial inverter. The drive shaft is jointed to the evaporator which is connected at the end of the cryo-RJ, with a thin rod for insulation from heat invasion.

For the experiment with liquid nitrogen, we removed the thermosyphon cooling system. The liquid nitrogen is supplied from the top of the cryo-rotary joint directly as shown in figure 3.

3.1.2. Sensors. Three kinds of temperature sensors are employed for the present experiment as following: the silicon-diode sensor (DT-670/LakeShore), the Chromel versus Alumel (Type-K) thermocouples and the Normal-Silver versus Au-0.07 % Fe thermocouples are attached to measure the transit of the temperature during the experiment. The silicon-diode sensor and the heater are attached to the exchange plate which is placed between the cold head of the cryo-cooler and the top plate of the condenser, to maintain the temperature of the condenser at 25 K, thus preventing the freezing of the neon gas.
Cold-cathode vacuum gauges (PKR-251/Pfeiffer) are attached to both upper and lower vacuum vessels to check the pressure transition. The PKR-251 has a wide measurement range allowing from $1 \times 10^5$ Pa to $5 \times 10^{-7}$ Pa.

### 3.1.3. Measurements.
The load torque is collected to compute the mechanical loss of the present cryo-RJ by using a spring balance. The spring balance is connected to the driving pulley attached to the drive shaft, and measures the load. The load torque is calculated from the radius of the pulley and the load.

To check the leakage of the cryogen, we measured the pressure inside the lower vacuum vessel, because the vacuum pressure of the lower vacuum vessel would increase in case of leakage from the MFS unit inside the cryo-RJ. In addition, we also measured the cryogen pressure inside the thermosyphon. If the cryogen leaks from the MFS unit, then the cryogen pressure will decrease.

Finally, we especially focused on the temperature of “vi”, as shown in figure 4. The temperature of “vi” leads to the heat generation of the MFS unit; considered to be the largest heat load of the cryo-RJ, it is an important value to design thermal insulation.

### 3.2. Position of the thermocouples
The detailed inner structure of the evaluation apparatus and the position of the thermocouples are shown in figure 4. Temperature transit of the cryo-RJ is measured by Chromel versus Alumel thermocouples as shown in the right side of the figure 4. Normal-Silver versus Au-0.07 % Fe thermocouples are placed around the evaporator and the cryogen tube as shown in the left side of the figure 4.

![Figure 4](image)

**Figure 4.** The schematic evaluation apparatus where the numbered items are: 1- Connecting flange to the cooling system, 2- Stationary part of the cryo-RJ, 3- Upper vacuum vessel, 4- Magnetic-Fluid Sealing (MFS) unit, 5- Rotary part of the cryo-RJ, 6- Lower vacuum vessel, 7- Connecting flange to the rotating machine, 8- Evaporator, 9- Drive shaft, 10- Driving pulley, 11- Electrode.

### 4. Results and discussion

#### 4.1. Mechanical loss
In this section, we discuss about the mechanical loss of the present cryo-rotary joint. The primary origin of the mechanical loss comes from a viscous friction of the magnetic fluid inside the MFS unit. The magnetic fluid is usually composed of oil and magnetic powder, thus the viscosity is decreased with the increase of temperature of oil. Hence, we predict that the mechanical loss will decrease when increasing the temperature of the MFS unit in the cryo-RJ.

While measuring the value of the load torque of the cryo-RJ, we vary the rotating speed and the type of cryogen. Figure 5 shows a transit of the load torque during a rotation. Even if initial load torque varies widely, the values of the load torque reach almost similar values about 30 minutes after...
rotation has started. This leads to the conclusion that the load torque has no relation with the type of cryogen.

Figure 6 shows the relationship between the average load torque, calculated from the stabilized load torque, and the temperature of the MFS unit. According to the solid line in figure 6, the average load torque decreases when the MFS unit’s temperature increases. Note: the cause of error of the solid line comes from the measuring scale because of the accuracy of the spring balance.

4.2. Cryogen leakage
This section deals with leakages of the cryogen. The vacuum pressure inside the lower vacuum vessel and the cryogen pressure inside the thermosyphon are measured. If the cryogen leaks from the MFS unit, then the first pressure will increase while the second will decrease. Figure 7 shows the results of the transition of the vacuum pressure as a function of rotating speed. The pressure increment is kept low until a rotating speed reaches 300 min⁻¹. Though, when the rotating speed goes over 300 min⁻¹, the pressure increases slightly. We suppose this phenomenon is caused by a degassing of the magnetic fluid, since the cryogen pressure inside the thermosyphon remains constant during the rotation. Also, the figure 8 shows the variation of the pressure increment and temperature of the MFS unit as a function of rotating speed. This figure shows that the pressure increment increases when the temperature of the MFS unit increases. We can see with the above mentioned that no leakage of cryogen is achieved.

Figure 5. Transit of the load torque as a function of time during rotation.

Figure 6. Relationship of the average load torque and the temperature of the MFS unit.

Figure 7. Transit of the vacuum pressure inside the lower vacuum vessel as a function of time during rotation.

Figure 8. Relationship of the pressure increment with the temperature of the MFS unit.
4.3. Heat invasion

A dummy apparatus which has the same dimensions, except the cryo-RJ, is prepared to investigate the load characteristics of the thermosyphon without the cryo-RJ. We applied a heat load to the evaporator and measured the variation of the heater output which is attached on the exchange plate.

![Figure 9. Variation of the heater output and heat loss of the cryo-RJ. The horizontal line represents the no-load heater output without cryo-RJ. The solid line with circles represents the transit of heater output with cryo-RJ as a function of the rotating speed. The heat invasion of the cryo-RJ is plotted as the solid line with squares.](image)

The no-load heater output without the cryo-RJ is 41.5 W. The heater output with cryo-RJ decreased from 37.1 W at 0 min⁻¹ to 32.4 W at 700 rpm. The heat invasion of the cryo-RJ as a function of the rotating speed is computed from the difference of the no-load and loaded heater outputs. The transit of these values is shown in figure 9. The maximum heat loss with rotation is 6.4 W, and the increment between 0 and 700 rpm is about 3.5 W.

5. Conclusion

With the present study, we have successfully developed a lighter, smaller and efficient cryo-RJ for HTS rotating machines. This present cryo-RJ achieved the design objective in terms of heat invasion.

About the average load torque, the aggregated average value during a rotation is 0.044 Nm. The load torque does not depend on the type of cryogen. Compared with the output torque of the sub-MW class HTS rotating machine (usually having ~400 Nm torque), the mechanical loss originating from the cryo-RJ is within 0.01%.

The most important problem of previous studies on the rotary joint has been the leakage of the cryogen. In the present study, the pressure inside the lower vacuum vessel increased slightly. However, the maximum increment is less than 1x10⁴ Pa only. Considering the cryogen pressure inside the thermosyphon remains constant during the rotation up to 700 rpm, therefore, the pressure increase of the vacuum vessel is thought to come from a degassing of the magnetic fluid. Consequently, if the MFS unit is cooled down by using water or air, then the increase of the vacuum pressure can be avoided.

Thermal insulation properties were also efficiently achieved thanks to an optimal design of the present cryo-RJ. The calculated value of heat invasion is sufficiently low compared to the previous experimental one.

The present cryo-RJ will be applied not only to HTS and/or LTS systems but also to other analysis systems such as, among others, LT-STM (low-temperature scanning tunneling microscope).

6. References

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