Development of Helium Transfer Coupling of 1 MW-Class HTS Motor for Podded Ship Propulsion System

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Abstract. Research and development of 1 MW superconducting motor are being made aiming at the efficiency improvement for the podded type ship propulsion. The basic machine configuration is similar to steam turbine generators, having a rotating horizontal shaft. As for the motor composed of rotating superconducting field, one of the most critical issues is to provide a technically viable helium transfer coupling (HTC). The field winding of 1 MW motor is cooled with cryogenic helium gas. The HTC needs to supply the cryogenic helium gas with an appropriate flow rate from the stationary part to the rotating field winding region through a hollowed shaft in order not to lose superconducting state of the winding. A full size prototype of HTC was developed prior to the actual one to demonstrate its technical acceptability. The fundamental data with regard to the supply of the refrigerated helium gas were successfully obtained at the rated speed. This work has been supported by New Energy, and Industrial Technology Development Organization (NEDO).

1. Introduction
Kawasaki Heavy Industries LTD., and cooperative research groups have been developing 4 P-1 MW- HTS motor for a merchant ship [1]. A helium transfer coupling (HTC) is a device that supplies the cryogen to the rotor of the HTS motor and return it to the cooling system [2]. In order to maintain the superconducting state of the field winding of the HTS motor, helium gas is supplied at the temperature of 25 K and returns it to the cooling system approximately at 30 K. The adopted pressure of supply helium gas is 0.4 MPa to make the helium gas refrigerator compact. The helium gas flow of 1.5 m³/h is needed to refrigerate the electrical losses and the thermal losses of the HTS rotor. A developed sealing concept for rotating pipes of the HTC targets at a small amount of gas leak. The gas leak flow was clear based on CFD (Computational Fluid Dynamics) analyses and fundamental experimental data. The CFD analyses and tests were made concerning the two types of seal structure of the ejector nozzle and the grooved nozzle. This HTC model has aimed at the confirmation of the validity of the integrated HTC structure and the seal performance. The analyzed results and test results were almost the same. The HTC design and fabrication with higher performances became possible for an actual machine by means of above achievements.

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2. HTC (Helium transfer coupling) design

2.1. HTC Requirements for 1 MW-class HTS motor

Specification requirements for the HTC are listed in Table 1. The total heat loss at the HTS rotor is about 100 W because of the electrical loss and the thermal loss of conduction as well as radiation from the normal temperature region. The above heat loss is removed with 25 K helium gas supplied through the HTC, which in turn cooled by the helium gas refrigerator set up outside. The temperature rise of the gas in the rotor is assumed to be around 5 K, and the flow rate of the helium gas 4 g/s. The helium gas with the pressure of 0.4 MPa is supplied to the rotor at the speed of 190 rpm. One of the critical technical issues of the HTC is a gas sealing performance in the gas seal composition, otherwise that might leak to the stationary part without cooling the field windings. A ferrofluid seal unit is effectively employed at the stationary part of the HTC. The HTC is installed at the anti-driving side and a multiple thin tube is inserted axially into a multiple tube at the rotating side. In this HTC model, the supplied helium gas returns to the recovery line through a U-shape tube connected at the end of the HTC, since the model is tested without an HTS motor. The HTC prototype structure for 1 MW-class HTS motor is shown in Figure 1.

Table 1. HTC Requirement

| Parameters          | Value |
|---------------------|-------|
| Heat to be removed  | 100 W |
| Supply pressure     | 0.4 MPa |
| Gas flow            | 4 g/s |
| Inlet temperature   | 25 K  |
| Rated speed         | 190 rpm |
| Gas leak            | < 5%  |
| Heat loss           | < 5 W |

2.2. CFD Analysis of structure

The optimal design of the prototype HTC can be made by using Computational Fluid Dynamic (CFD) technologies. Two types of seal composition, namely, the ejector nozzle and the grooved nozzle were taken into consideration which is shown in Figure 2. Test results as to these nozzles agreed pretty well with the analyses. The analyzed result of the ejector nozzle is shown in Figure 3.
3. Assembly and leak test

3.1. Assembly and leak test

Each of the thin-walled tubes was kept under vacuum by welding on a 0.5 mm thick tube of SUS316L to reduce the heat leak. The bending rigidity and weldability were also studied. The dimensional accuracy, gas leak and the pressure proof test were performed at each production stage of the HTC model. The deformation of the pipe after welding was 0.07 mm or less. There was no helium leak. The pressure proof test was conducted for 30 minutes with 0.4 MPa of helium gas pressure with respect to the assembled multiple vacuum pipe line together with the ferrofluid seal device and no leak was confirmed. Figure 4 shows the pressure test of HTC. Two RTD temperature elements were attached to measure the temperature at the inlet and outlet of the HTC. The gas pressure was also measured. The helium supply pipe and the return pipe were connected with the U-shape pipe at the end of the piping, where the 50 W of heater as well as RTD’s were attached to measure the gas flow rate as shown in Figure 1.

3.2. HTC performance evaluation

The performance verification test was performed at the state of both stand still and rotation. The seal characteristics were studied on two conditions of the supplied helium gas with regard to temperature, pressure and gas flow of 80 K, 0.4 MPa and 0.5 g/s and 25 K, 0.05 MPa and 0.03 g/s respectively. The HTC test arrangement is shown in Figure 5. The test procedure of the gas leak is shown below. The gas flow in the pipe is calculated by the aid of both temperature measurement and heater wattage. For this purpose, first, the perfect mechanical sealing is made intentionally to produce no leak and therefore the flow characteristics with this measurement tool are obtainable. The temperature difference $\Delta t$ of helium gas flow across the heater is measured on the condition of the complete sealing. Figure 6 exhibits the gas flow vs. $\Delta t/W$. Next, the intentional complete mechanical sealing is set back to the normal state. The gas flow rate of main path is obtained by means of above mentioned flow characteristic curve. The supply gas flow rate minus the gas flow rate of main path provides the actual gas leak amount. The grooved nozzle exhibited 5% of gas leak for the total flow of 1.54 g/s, while the ejector nozzle exhibited 24% of gas leak. It is clear from Table 2 that the analyses and the test results are almost the same. Figure 7 indicates the test of prototype HTC. Figure 8 is an example of measurement.

![Figure 4. Pressure test of HTC](image)

![Figure 5. HTC test at 80 K He gas and 25 K He gas](image)
Figure 6. Test result of ejector seal performance

Table 2. HTC Seal Performance test:
Leak flow/Total flow (%)

| Seal structure | Test result | CFD Analysis |
|----------------|-------------|--------------|
| Ejector nozzle | 24          | 25           |
| Grooved nozzle | 5           | 6            |

Figure 7. Prototype HTC testing
Figure 8. An example of measurements

4. Conclusion
The full size prototype HTC was developed prior to the actual one to demonstrate its technical acceptability. The fundamental data with regard to the supply of the refrigerated helium gas to the HTS rotor were successfully obtained at the rated speed. The heat insulation of HTC was effective throughout the test. It took less than 30 minutes to cool down the HTC with helium gas from room temperature to 25 K. The HTC model displayed the usefulness of its structure as well as the seal performance. The test results agreed pretty well with the analyses. The HTC design and fabrication for the 1 MW motor are conducted according to these achievements.

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