Development of 1 MW-class HTS motor for podded ship propulsion system

K Umemoto¹, K Aizawa¹, M Yokoyama¹, K Yoshikawa¹, Y Kimura², M Iizumi², K Ohashi³, M Numano³, K Okumura⁴, M Yamaguchi⁴, Y Gocho⁴ and E Kosuge⁴

¹Kawasaki Heavy Industries LTD., 673-8666, Hyogo, Japan
²Tokyo University of Marine Science Technology, 135-8533, Tokyo, Japan
³National Maritime Research Institute, 181-0004, Tokyo, Japan
⁴Japan Super-conductivity Organization Co. LTD., 135-8533, Tokyo, Japan

E-mail: umemoto@ati.khi.co.jp

Abstract. To reduce fuel consumption and lead to a major reduction of pollution from NOx, SOx and CO2, the electric ship propulsion system is one of the most prospective substitutes for conventional ship propulsion systems. In order to spread it, innovative technologies for the improvement of the power transmission are required. The high temperature superconducting technology has the possibility for a drastic reduction of power transmission loss. Recently, electric podded propulsions have become popular for large cruise vessels, icebreakers and chemical tankers because of the flexibility of the equipment arrangement and the stern hull design, and better maneuverability in harbour, etc. In this paper, a 1 MW-class High temperature superconducting (HTS) motor with high efficiency, smaller size and simple structure, which is designed and manufactured for podded propulsion, is reported. For the case of a coastal ship driven by the optimized podded propulsion in which the 1MW HTS motor is equipped, the reductions of fluid dynamic resistance and power transmission losses are demonstrated. The present research & development has been supported by the New Energy and Industrial Technology Development Organization (NEDO).

1. Introduction
Kawasaki and cooperative research groups have developed an HTS motor for the podded propulsion system of a merchant ship since 2007, while receiving the support of New Energy and Industrial Technology Development Organization; NEDO. In this paper, the overview and the current status of this project will be reported.

It is widely known that an HTS motor can have higher efficiency than conventional motors and greatly decrease its weight and size [1], [2]. Such characteristics become advantageous further in large torque and slow rotation rate. From such reasons, a ship propulsive motor is the most suitable application for an HTS motor. The design of a conventional motor is an advanced engineering
problem itself, which becomes possible by integrating a lot of technical fields such as electrical engineering and mechanical engineering. It is expected that to apply superconductivity technologies to such a complex industrial product becomes a very important thing to spread them in the future. On the other hand, it is becoming possible for many complex engineering problems to reach an optimum solution or a solution near the optimum solution in very short time by wide-ranging spread of Computer Aided Engineering (CAE) technologies in recent years. Under the above background, the role of CAE technologies in R&D on an HTS motor will be shown in this paper.

2. HTS motor specifications
The specifications of the present HTS motor are listed in Table 1. In Kawasaki, the podded propulsion with built-in conventional electric motor of 1MW has already been produced as shown in Figure 1, and various land base tests were completed. The final objective of this project is to make this podded propulsion more effective and smaller by HTS technologies. The design and the production of main portions of the prototype of a 1MW-class HTS motor like rotor, stator, cooling systems, cryogenic helium gas coupling device and electric power control equipment, etc. have ended almost. They are being finally assembled now in preparation for the rotating test in this autumn. The photographs of main components of the present 1MW-class HTS motor are shown in Figure 2.

| Table 1. HTS motor specifications |
|-----------------------------------|
| **Output** :1,000kW              |
| **Rotation speed** :190Rev./min  |
| **Pole number** :4               |
| **Voltage** :1200V               |
| **Armature current** :675A       |
| **Phase** :3                     |
| **Frequency** :60Hz              |
| **Stator cooling** :Liquid water |
| **Field coil current** :200A     |
| **Cryogen** :Helium gas          |
| **HTS Conductor** :BSCCO-2223 tape |
| **HTS operating temperature** :30K |
| **Design total efficiency** :98% |

**Figure 1. Kawasaki “PODPELLER”**

**Figure 2. Main components of 1MW-class HTS motor (a) Stator; (b) Rotor**
3. HTS motor design

As previously described, the design of an HTS motor is a typical trade-off problem. The CAE tools allow to decrease the necessary time period of the turning design spiral greatly. Some examples of these CAE approaches will be demonstrated in the following sections.

3.1. Electrical design

The electrical design is an important design process in which dimensions and the performance of an HTS motor are practically decided. However, it is necessary to do an electrical design that takes structural strength design, cryogenic design, and vacuum design into consideration from the initial stage of electrical design because all design factors are more interacting than a conventional motor. Moreover, the manufacturing easiness and the total cost of producing an HTS motor become very important factors for practical purpose, too. Especially, a shorter length of HTS tape is more preferable from the viewpoint of cost. Figure 3 shows the optimization process of field-pole HTS coil geometry considering the minimization of length of HTS tape, the structural strength of the rotor-core, manufacturing etc.. In this process, the iteration of electromagnetic field analysis is the most efficient means to approach the correct and optimal design.

Regarding the present HTS motor, the stator is composed of copper coils. The minimization of copper loss is achieved by thinning the teeth, which supports the stator coils against electromagnetic forces, as much as possible, and increasing the sectional area of the stator coils. Nonmagnetic material is used for the teeth material to prevent magnetic flux density being saturated. Moreover, to minimize eddy current loss generation in the copper stator coils by magnetic flux linkage, the cross section of the copper stator coil is divided into many rectangular sub-coils. An example of the estimation of eddy current generation in such divided stator coils by electromagnetic field analysis is shown in Figure 4.

3.2. Cryogenic design

The rotor core is cooled initially by liquid nitrogen and cryogenic helium gas circulation cooling to the HTS operation temperature, 30K. The cryogen piping is axially passed through the rotor core. The field-pole HTS coils are cooled via copper mounting plates inserted between the bottom and top plane of the coil holder in the rotor core and the field-pole HTS coils, and between the field-pole HTS coils each other by the thermal conduction. To improve the heat exchange between cryogenic helium gas and the rotor core, turbulence promoters are installed on the inner surface of the cryogen piping. The turbulence promoters of the equally spaced internal rib type are adopted, and they allow fastening the turbulent transition by generating the cavity flow in the cryogen piping. The arrangement of the cryogen piping and the detailed dimensions of the turbulence promoters were entirely decided by Computational Fluid Dynamics, CFD.

Figure 3. Iteration of electromagnetic field analysis

Figure 4. Eddy current density estimation by numerical analysis
Figure 5 shows the set-up of cooling tests of the rotor unit. The cooling power of the cryogenic helium gas circulation system is approximately 100Watts at 30K. Figure 6 shows the time histories of the surface temperatures on the rotor core. About three days and nights were required until the overall temperature of the entire rotor core arrived at 30K, the operating temperature of this field-pole HTS coil. As for any stages of temperatures of the rotor core, because the heat exchange efficiency was improved by turbulence promoters, the cooling of the rotor core, which reflected the maximum power of this cooling system, could be carried out.

3.3. Structural Strength design

The field pole HTS coils can generate very high magnetic flux density, over 5Tesla. In order to make the size of an HTS motor much smaller by effective using strong electromagnetic forces generated from HTS coils, the structural strength design of the rotor core where electromagnetic forces can be supported and the output power can be transmitted becomes important. The result of the thermal stress analysis of the rotor core in initial cooling process is shown in Figure 7, as one example of structural strength analysis by Finite Element Method (FEM). In the numerical simulation, the material non-linearity and the geometrical non-linearity of the rotor core at cryogenic temperature are taken into account. The estimated time period by this analysis that the rotor-core is cooled down to liquid nitrogen temperature is about 8 hours, and this has the good agreement with the experimental time period shown in Figure 7.

Thermal conductivity through the coil decreases because the amount of shrinking in the bottom of the coil folder is growing as shown in Figure 7 (a). Therefore, the outer surface temperature of the rotor core of the part where the coil is installed becomes warm compared with the part without the coil in initial stage of the cool down as shown in Figure 7(b). The distortion and the generating stress in the rotor core estimated by this analysis become important indices to decide the way of the initial cooling operation by liquid nitrogen.
3.4. Field-pole HTS coil design

In Figure 8, the double pancake coils for the present 1MW-class HTS motor are shown. It is well known that the superconductivity of BSCCO HTS tape is broken under lateral magnetic field more easily than under parallel one. The critical condition for the field-pole HTS coil under the large lateral magnetic field was evaluated by using the small test coil with the same bending radius as the coil for the HTS motor. In Figure 9 (a), the test set-up is illustrated. The small test coil is equipped vertically in the cryostat and the surrounding magnet gives it lateral magnetic field until 4Tesla. The critical currents of the various lateral magnetic fields and temperatures of the small test coil are compared with the critical currents of HTS tape itself in Figure 9(b). From these results, under 2-2.5Tesla of estimated maximum lateral magnetic field subjected to the stack of coils, the critical current for the whole field–pole HTS coils can be expected to be larger than 200A of the design operating current. In this paper, we defined the critical current is the average voltage drop with 1 µV/cm whole HTS winding because the voltage rise around critical current is very large at 30K and HTS wire length is short (32 m)[3]. In near future, we will develop the estimation method of critical current, n-value and heat generation from the stack of coils under the practical multi-directional magnetic fields. The comparison of the calculated heat generation with the measured one is planning in this project.

3.5. Helium transfer coupling design

A Helium Transfer Coupling (HTC) is a device that puts the cryogen in and out in the stationary cooling system and the rotating part of the HTS motor. It is one of important equipments in the HTS motor because it maintains field-pole HTS coils at the operating temperature during rotation. A prototype of HTC is shown in Figure 10. The internal cryogen flow in the HTC is very complex as

![Figure 7. FEM analysis for initial cooling process by liquid nitrogen (a) Temperature distribution contour (b) Shrink distribution contour](image)

![Figure 8. Field-pole HTS coils](image)

![Figure 9. The characteristics of the small test coil under lateral magnetic field (a) Test set-up, (b) Test results](image)
described in Figure 11 because the thermodynamic property of cryogen is non-linear and the turbulence effect must be taken into account. CFD analysis is a powerful tool to visualize and to understand such complex internal flow. It is demonstrated at high accuracy by comparison between test results and these numerical simulations that CFD can simulate the loss to the cooling power in the HTC. The HTC was designed by using this verified analysis tool so that the loss to cooling power might become within several percent or less to the total cooling power.

The detailed description of HTC and the test and simulation results are presented in [4].

4. Ship propulsive efficiency improvement estimation

For the examination of the applicability of the present HTS motor, a podded propulsion system for a coastal container ship is demonstrated. The pod radius is chosen from two radius based on the estimation of the propulsive efficiency while the propeller radius is changed with three diameters. The restrictions for the equipment of the present propulsion system are also considered. The hull shape is designed for the present propulsion system, especially near stern of the ship. Figure 12 shows the computational results of flows around the present pod propulsion system. The in-house CFD code is used for the present examination. The measurements of propulsive efficiency in towing tank test are also carried out as shown in Figure 13, and finally 21% reduction of engine output from the conventional propulsion system is estimated, considering the electrical and mechanical transmission loss, the HTS benefit and the hydrodynamic efficiency improvement.
5. **Conclusion**

Kawasaki and cooperative research groups have started the prototype development of an HTS motor with low rotating rate for commercial uses since 2007. Designing and manufacturing a 1MW-class HTS motor have been completed almost. The performance tests on the land base scheduled in November are being prepared now. At any design stages of the present HTS motor, the fundamental design and the detailed design, CAE tools were widely applied to obtain practical engineering solutions. Some examples of them were presented in this report.

Podded ship propulsion with an HTS motor becomes slenderer than that with a conventional motor. The reduction of hydrodynamic resistance due to the optimization of podded propulsion itself and the modification of the stern hull form adjusted to it was evaluated by CFD analysis and towing tank tests. It was expected to be 21 % reduction of engine output for the present propulsion system from the conventional one, considering the mechanical and electrical transmission loss, the HTS benefit and the hydrodynamic efficiency improvement.

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