

A Ship Deperming Coil System Using High Temperature Superconducting Cable Technology—Refrigeration—

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Abstract: The purpose of ship deperming is to reduce its permanent magnetism to avoid the threat of magnetic sea-mines which appeared first in battlefields in World War II and stored by many navies and unanimous groups since then. Magnetic fields for deperming are mostly generated by electric current through conductor cable and the intensity of such fields decreases with the distance from the cable. In order to impose sufficient field to the ship, the deperming cable is tightly wrapped around the hull of the ship. A cable with superconducting material as the conductor is expected to pass high electric current because of its zero-electric resistivity and has potential to make deperming coil system more separated from the ship hull. In the previous study, we designed superconducting coil system set flat on the seabed for ship deperming by calculating magnetic field generated by the coil based on the characteristic of HTS (high temperature superconducting) tape seen in published papers. This time we have kept our design to utilize HTS tape conductors that are existing and readily available in the open market. In addition, the limitations of the manufacturing potential and capacity of the HTS tape conductor industry have been taken into account for the design. Then we designed the refrigerating system which is to keep the superconducting property of the cable materials.

Key words: Deperming, magnetic, ship, refrigeration, helium, radiation, superconducting.

1. Introduction

After the discovery of superconducting phenomenon in 1911 by Kammering Onnes [1], its characteristics of zero-electric resistivity were expected to lead to many attractive applications, such as no loss electric current transmission. However, due to the sensitive characteristics of the superconducting material between its electric, magnetic and temperature characteristics, and also due to the low temperature requirement for the superconducting phenomenon, large-scaled systems were required to incorporate the necessary cooling capacity by means of using refrigerators. Electric power transmission is among the successful trial cases of using HTS cables, with extremely low power loss in long distance and overcoming refrigeration problem of long cable [2-4]. The use of superconducting cables in conjunction with high-field magnets has seen its application in multiple

areas such as nuclear fusion, material research and human diagnosis. This is due to its ultra-low power consumption requirements [5, 6]. HTS cable with current capacity of 100 kA has been developed for fusion reactor magnets [7].

Deperming of ship has been operated by many navies since World War II and although the magnetic fields required is as modest as a few milli-Tesla, in order to impose magnetic fields to specimens that are physically larger in scale such as ships, a system of a larger electric current cable and a power supply with higher capacity is needed. By using superconducting cable for ship deperming a reduction of the scale of power supply is expected even when its refrigeration is included. This is made possible with the system we designed, the HTS coil system flat on seabed by calculating magnetic field inside ship [8]. This design enabled that the electric current capacity of one cable is 100 kA, and one-unit coil of the length is 1,100 m set flat at the depth of 12 m. The calculation was based on the HTS materials' characteristic data found in

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published reports and target ship classes for calculation were taken as DDH (Hull classification symbol of Helicopter Destroyers) Izumo-class (248 L, 38 W, 7.1 D, units all in [m] and 19,500 tons of displacement) and SS (ibid., Submarines) with Soryu-class (84 L, 9.1 W, 8.5 D, 2,950 tons) of JMSDF (Japan Maritime Self-Defense Force).

2. Conventional Deperming System for Ship

A cable with conductor of copper is tightly wrapped around the ship hull which imposes electric current with alternating signature and decreasing the intensity [9]. The magnetic field intensity for deperming is decided by the saturation magnetic field of steel which makes up the ship's structure. The criterion of the top magnetic field is reported as 1,100 A/m [10] and magnetic shielding factor and inner field are decided by ship hull structure. Because of the electric resistance of conventional conductor, power supply limits the current to pass, this cable wrapping method requires huge resources in man-power and long time to spend for this operation. Furthermore, insufficient magnetic field is imposed on the hull surface just between the wrapped coils, which may result in an unexpected remnant magnetism of the ship. Fig. 1 shows an example of magnetic field intensity on the surface of the model cylinder generated by the wrapped coil on ship hull. The effect of this short spatial period inhomogeneity may be canceled out at a particular

distance over the period, but still expected to remain in near field signature of the ship.

Another problem of deperming with conventional cable is the large power supply necessary. In order to impose 1,100 A/m magnetic field at the center of DDH by wrapped coil on ship hull with 3 m space between wrapped coil, 3.3 kA of maximum current is required. When a copper cable with 100 mm² cross-sectional area is used, 15 MW power supply is required with 3.3 kA current source. This is only considering resistivity of the copper cables. In this coil case, resistivity of the conductor has the major effect on its power consumption.

3. HTS Coil System Derived from Magnetic Field Calculation

The magnetic field attenuation factor in transverse field to the keel is obtained by calculating the magnetic shielding factor from the size and weight of SS and DDH by using spheroidal shell model. The values were 0.36 and 0.81, respectively [8]. Considering the depth and height of each ship with the magnetic shielding factor, dimension of the unit deperming coil with racetrack shape on seabed was designed as shown in Table 1 and Fig. 2. The total length of the coil includes 200 m each way of lead cable to and from the shore.

Magnetic field generated by this three-coil set on the central vertical surface in Fig. 2 is shown in Figs. 3a and 3b for y -dependence and z -dependence, respectively.

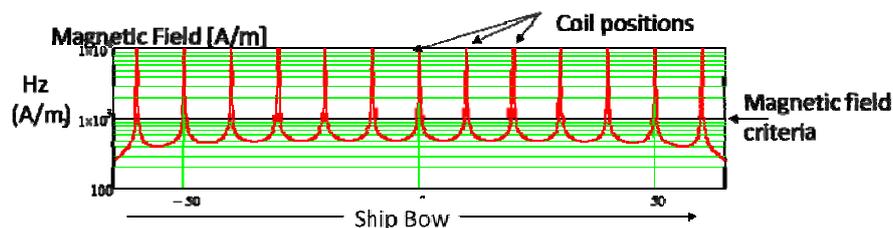


Fig. 1 Magnetic field on ship hull while deperming using wrapped coil.

Table 1 Coil dimensions.

No.	Width (m)	Length of straight line (m)	Total length of coil (m)
1	30	308	1,110
2	34	316	1,139
3	40	328	1,181

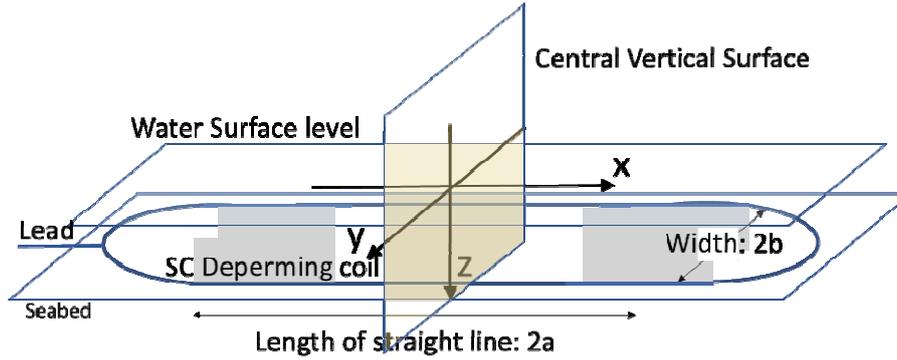


Fig. 2 Magnetic field by three-coil set on the Central Vertical Surface, (a), y-dependence and (b), z dependence compared to the required field.

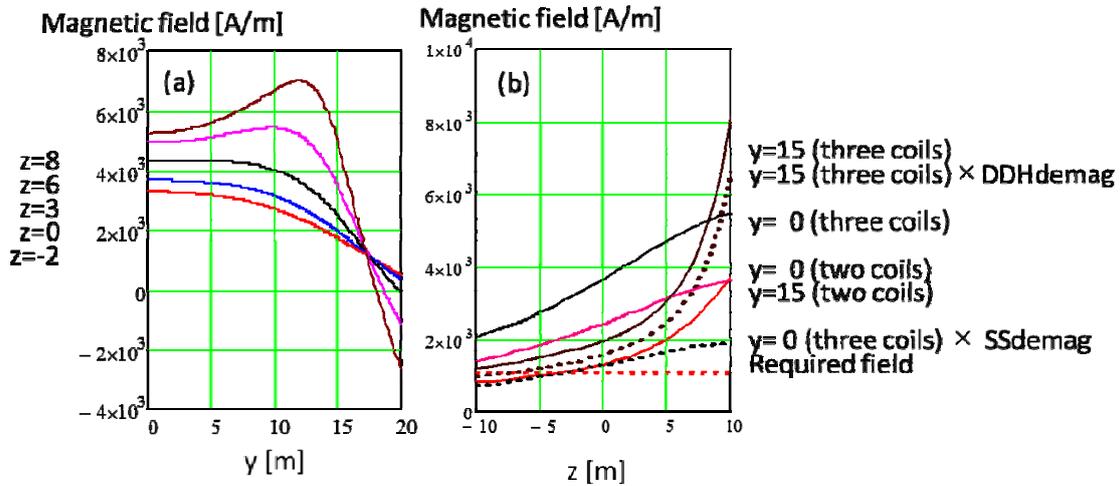


Fig. 3 Unit deperming coil set on seabed.

In Fig. 3b, z-dependence of magnetic field was shown considering the structure of DDH above the water surface level and demagnetization effect. The calculated magnetic fields of the three-coil set satisfy the required field. In case where the requirements can be lowered, calculated magnetic fields generated by two-coil set are also shown in Fig. 3b, for reference.

4. Conductor to Form 100 kA Cables

Recently, progress of HTS ReBCO (Rare-Earth, Barium, Copper, Oxide) tape combination to form high-current cable has been reported, such as TSTC (twisted stacked-tape cable) [11] and CORC[®] (cable on round core) [12]. In our previous studies [8, 13], we have designed the conductor of HTS deperming coil which conducts 200 kA and 100 kA at 77 K. Two types

of conductor cross-sections were designed based on the tape element fabricated by Fujikura [14], considering the balance of conductor size and maximum electric current. One of the conductor designs is closely packed TSTC, which enables to conduct a total current of 200 kA requiring 0.18 m of diameter of the conductor and maximum internal magnetic field is 0.42 T. The other design is a cylinder-type, which enables to conduct a total current of 100 kA requiring 0.14 m diameter of the conductor and maximum internal field is 0.21 T.

We designed a cable consisting of CORC which operates at 50 K and the maximum total current is 100 kA. CORC is commercially available and consists of tape-form conductors wound on a round core, and because it is flexible it is possible to form the conductor with existing technology. We plot the critical current (:

I_c) of two HTS-ReBCO tape conductors versus temperature based on the database by Wimbush [15]. Critical current is the maximum electric current below which the superconducting phenomenon appears, and the operational current (I_o) to reflect superconducting phenomenon is approximately 20% lower than the critical current.

Fig. 4 shows the temperature dependence of critical current of 4 mm-width tape-conductor under the magnetic field of 0.5 T, with respect to that at 77.5 K and 0 T. Figs. 4a and 4b are the data plots of commercially available HTS-ReBCO tapes, which are AMSC 8702 and SuperPower M4, respectively. Critical current is degraded by applied magnetic field mainly perpendicular to the surface of tape, which is indicated by 0-degree field. The temperature dependence of the critical current without imposing magnetic field is shown in Fig. 4 for reference.

As shown in Fig. 4, by lowering the temperature critical current increases, thus the amount of HTS tape element decreases to generate the same magnetic field. Under 0.5 T of perpendicular magnetic field, which is expected internal field of high current cable at 77.5 K, I_c of Super Power M4 tape is 24.8 A, which is 28% of I_c under 0 T, 77.5 K. At the temperature 50 K, its I_c is 184 A, that is 211% of I_c under 0 T, 77.5 K. This means that less than one seventh of quantity of tape is required for the deperming coil at 50 K. Not only by the cost of HTS

tape element, but additionally the production capability of the industry is limited at the present time. We designed the system to operate Super Power M4 tape at 50 K and expected 140 A of operational current through each tape.

The report issued by Advanced Conductor Technology indicates that CORC with 42 tapes of 4 mm width forms 7.5 mm diameter cable [12]. Assuming Super Power M4 tape is the wound element of CORC, one strand consists of six CORCs, therefore this CORC strand has 35.3 kA of total current. In turn, four strands of CORC, which is to be called hereinafter 4-6 CORC, result in 141 kA of operational current capacity.

5. Refrigeration Design

We designed HTS deperming cable to operate at 50 K by cooling with helium gas flow. Because of the fixed cable on seabed in fixed location and the extended length of the cable, we introduced a radiation shield cooled by liquid nitrogen to tolerate input heat as shown in Fig. 5.

5.1 Radiation Shield

Firstly, radiation shield is cooled from room temperature to 70 K by the flow of pressurized liquid nitrogen at 70 K. The time (t) to cool the radiation shield is calculated by Eq. (1),

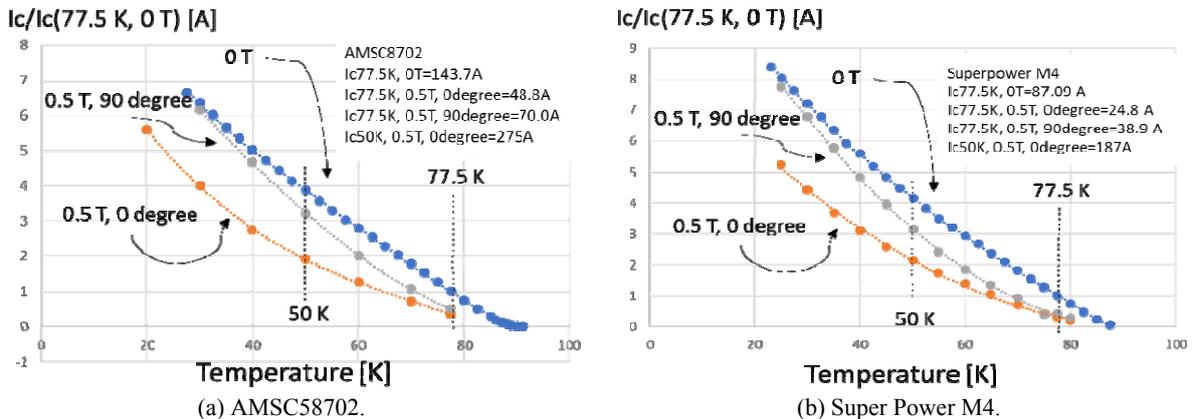


Fig. 4 Temperature dependence of critical current relative to that under 0 T, 77.5 K.

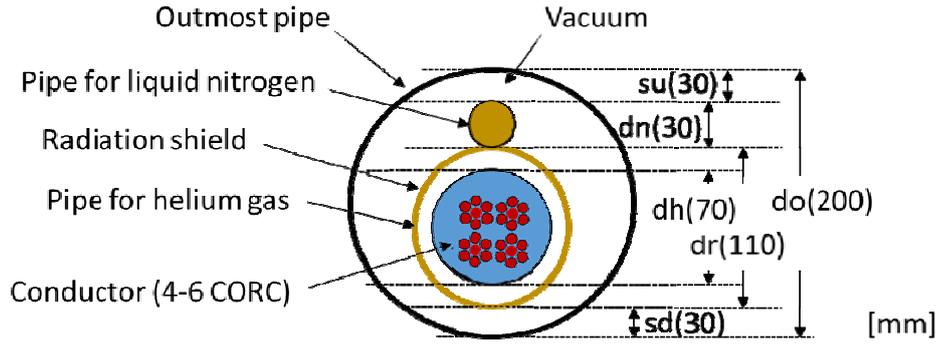


Fig. 5 Concept design of the deperming cable in cross-section.

$$C_{Cu}\rho_{Cu}(dn + dr) \cdot thick \cdot \pi \cdot length dT = [-\alpha\{(T - T_{70})C_{N2gas}V_{liqN2} + C_{N2ev} \cdot V_{liqN2}\} + 2\varepsilon(T_{rt}^4 - T^4) \cdot length]dt \quad (1)$$

where,

α : Heat exchange efficiency, where it is 0.6 in this calculation;

Thick: Thickness of pipe for liquid nitrogen and radiation shield. The material is assumed as copper with 1 mm of thickness;

Length: Cable length, which is 1,100 m in this calculation;

T_{70} : Temperature of nitrogen gas, which is evaporated from liquid at 70 K;

T_{rt} : Room temperature, which is 293 K.

The heat capacity of nitrogen gas, evaporation heat of liquid nitrogen and heat capacity of copper are written as follows,

C_{N2gas} : 29.2 [J/mol/deg], C_{N2ev} : 5,577 [J/mol], C_{cu} : 0.38×10^3 [J/kg/deg].

The parameter ε of radiation is calculated by Eq. (2) using the experimental data 2 W/m of heat invasion from the outmost pipe at room temperature [2]. In this case, the temperature of radiation shield pipe is 70 K.

$$\varepsilon = 2 / (T_{rt}^4 - T_{70}^4) = 2.7 \times 10^{-10} \quad (2)$$

Radiation heat in our design was doubled because of the conductor which is at T_{rt} this moment.

V_{liqN2} : Supplied quantity of liquid nitrogen, which is 30 liter/min [2] in this calculation.

The time dependence of the radiation shield temperature to cool, from the start of liquid nitrogen

flow, is shown in Fig. 6. With the above parameters, the time to cool the radiation shield to 70 K, which is the temperature of coolant, is calculated as 5.4×10^3 s. The heat invasion to the conductor is calculated as 5 mW/m when 70 K of radiation shield is set between the outmost pipe and the conductor. This enables lower effort in cooling of conductor to lower temperature than 70 K.

Other points of concern are, thermal stress of cable material and remaining gas inside the pipe pre-cooling which could slow the cooling of radiation.

The refrigeration system for this liquid nitrogen cooling was confirmed by the successful experiment of 1,000 m power transmission cable [2]. The difference between the power transmission cable case is that the deperming cable is one pass of coolant and no-return pass which is in the power transmission cable case.

5.2 Conductor

Next step is to cool the conductor down to 50 K. The

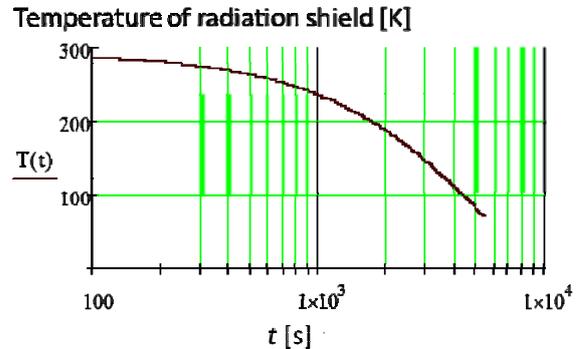


Fig. 6 Temperature of radiation shield vs. time from the start of cooling.

conductor is cooled by helium gas flow, which is pressurized and cooled to 40 K by a refrigerator before the inlet of deperming coil. The time to cool the conductor is calculated by Eq. (3).

$$C_{Cu}\rho_{Cu}(dC/2)^2\pi \cdot 7 \times 4 \cdot length dT = [-\alpha\{(T - T_{40})C_{Hegas}V_{Hegas}\} + \varepsilon(T_{70}^4 - T^4) \cdot length]dt \quad (3)$$

where,

dC : Diameter of each CORC line, which is 7.5 mm. The CORC line which consists of mainly copper and the layer of HTS tapes on the surface of the core is so thin that the effect of HTS tapes is neglected in thermal balance calculation. Six CORC lines are wound around a core line, which has no HTS layer, thus seven lines are stranded in one;

V_{Hegas} : Supplied quantity of helium gas, which is pressurized to increase the gas supply and cooled to T_{40} by refrigerator. T_{40} is assumed to be 40 K at the inlet of the deperming coil in this calculation;

Heat invasion to the conductor is calculated mainly radiation from radiation shield, which is at T_{70} , cooled by liquid nitrogen;

C_{Hegas} : Heat capacity of helium gas.

Time to cool the conductor to 50 K by a few cases of V_{Hegas} is listed in Table 2. The temperature of conductor against time from the start of cooling with 400 ℓ/min, 8 atm at room temperature is shown in Fig. 7. By the effect of radiation shield cooled by liquid nitrogen, the conductor can be cooled to 50 K by several days depending on the gas supply. However, in case of no cooled radiation shield, even with high gas supply of 1,000 ℓ/min, 8 atm at room temperature, the temperature of the conductor balances at 70 K, which is higher temperature than required to achieve our targeted critical current of the HTS tapes. This means that helium gas supply with actual amount is not enough to cool the conductor with 1,100 m length without liquid nitrogen cooled radiation shield.

Table 2 Time to cool conductor by helium gas.

α	V_{Hegas} : Helium gas supply			Temperature of radiation shield [K]	Time to 50 K [day]	Balanced temperature [K]
	[ℓ/min]	Pressure [atm]	[g/s]			
0.6	1,000	8	23.8	70	2.4	
0.6	1,000	8	23.8	rt	(3.5)*	70.6
0.6	200	2	1.2	70	42	
0.6	200	4	2.4	70	22	
0.6	200	6	3.6	70	15	
0.6	200	8	4.8	70	11	
0.6	400	8	9.5	70	6	

* Time to balanced temperature.

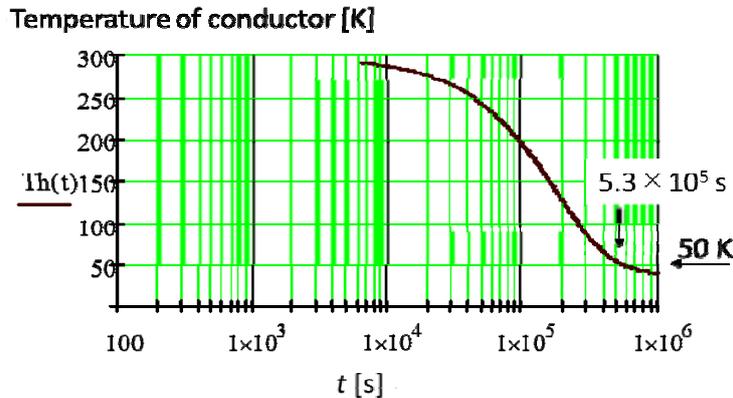


Fig. 7 Temperature of the conductor against time from the start of cooling with $V_{Hegas} = 9.5$ g/s.

5.3 Power for Refrigeration

The HTS deperming system using flat coil on seabed is only realized by superconducting cables using the benefit of its zero-electric resistivity and smaller power supply. However, refrigeration system is required for better superconducting property. We designed the HTS deperming system with liquid nitrogen cooled radiation shield and helium gas cooled conductor, and then estimated the power consumption for refrigeration.

According to Watanabe [2], refrigeration system to cool their conductor to 70 K consists of two TB (Turbo-Brayton) type cryocoolers, two Stirling type cryocoolers and three circulation pumps. Cooling power of one of the TB types is reported as 2 kW at 66 K. Other cryocoolers have similar capacities. The recent development of TB cryocooler for long power transmission line has 10 kW cooling capacity at 70 K with power consumption of 170 kW [16].

Helium gas cooling of the conductor of 1,100 m deperming cable to 50 K in a few days needs 23.5 g/s of helium gas at 40 K as listed in Table 2. The test results of variable temperature helium refrigerator/liquifier for nuclear fusion test facility are reported by Hamaguchi et al. [17], where the cooling capacity was estimated as 1.6 kW at 33 g/s with supply and return temperature 40 K/49.3 K, respectively. With reported power consumption of the main compressor to be 239 kW, we assume the refrigerator coefficient of performance to be 0.03. Overall, the power of helium gas cooling system is calculated to be 292 kW. In summary, we expect nearly 1 MW power consumption of cryocoolers and related equipment for a unit of deperming coil to be required. This is comparable to the estimated power consumption of the conventional deperming system.

6. Results and Discussion

The design of the HTS deperming system consists of a few units of HTS coil set flat on seabed, cryocooler, related equipment and power supply for each coil.

Maximum current is 100 kA and the length is 1,100 m for each coil cable. Our planned conductor of the cable consists of four strands of 6 CORC in one cable, operated at 50 K. As an optimum heat design of the cable, radiation shield is cooled by liquid nitrogen and the conductor is cooled by helium gas. Obtaining the parameters for heat exchange from the test results of 1,000 m HTS cable for power transmission line, cooling time of the conductor of our deperming coil radiation shield is calculated less than 2 hours. Similar calculation was conducted for cooling conductor by helium gas and cooling time. Duration of a few days was the result calculated when the supply of helium gas is 9.5 g/s at 40 K. The total power consumption for both cryocooler and related equipment was estimated at nearly 1 MW, which is comparable to the estimated conventional deperming system.

The advantages of HTS deperming system are easy deperming operation without heavy manual load of wrapping cable on ship and it is expandable to be used for larger ship than the size originally intended to be used for when the system is originally designed. Comparable power consumption for refrigeration system to the power consumption of conventional system concludes one of the problems of HTS deperming system. Starting from this concept design described here, real design of HTS deperming system will be proceeded considering costs, maintenance and market supply of each equipment.

One of the other problems of HTS deperming system is to design short connection between the supply inlet and return outlet of coolant at the cable. This is because the conductor forms a loop which is common structure of magnets. However, the length between the supply port of coolant and return for deperming system, careful design of the cooling in this part will be needed.

7. Conclusions

We designed a new HTS deperming system for naval ship, by first calculating from the magnetic field, and next from the refrigeration design. Our designed

system is to set flat on seabed, which has easy operational load but there are few experimental verifications on this status. Considering the market supply of HTS conductor, four strands of six CORCs in one were selected which is operated at 50 K. Cooling system of the conductor was calculated to be realized by pressurized helium gas at 40 K with radiation shield cooled by liquid nitrogen. The power consumption of the cooling system is estimated at nearly 1 MW, which is comparable to estimated conventional deperming systems. Having cleared one of the main problems of HTS deperming systems, we consider proceeding further with this project.

Acknowledgements

The authors appreciate the board of the Naval Ship Magnetic and UEP Research Committee for continuous support to the research, especially Kaiyo Denshi Kogyo Co., Ltd. for providing venues for our internal conferences. We appreciate Mr. Watanabe M., Sumitomo Electric Industries Ltd., Professor Kiss T., Kyushu University and Dr. Tachikawa K., National Institute for Material Science for their invaluable input to proceed our research. This work was collaborated by Mr. Mukoyama S., Mr. Fukushima H. and Mr. Takagi T. from Furukawa Electric Co. Ltd. and Dr. Yoshida S. from Taiyo Nippon Sanso Co.

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