

Application of superconductor technology to electromagnetic ship propulsion system

Seung-Hwan Lee*

* MOMAF Sea Grant Model College Center, Korea Maritime University, Busan 606-791, Korea

Abstract : *The superconducting electromagnetic propulsion system has been proposed as one of new alternative propulsion systems. Especially, the helical-type propulsion system has the greatest merit that is able to use the solenoid-type superconducting magnets with high magnetic fields. In this study, calculations of characteristics of the large scale helical-type thruster are carried out on the basis of our experimental results. As a couple of results of calculations, it is found that the thruster efficiency quickly increases with the length of electrode up to about 5 m and then goes up to about 0.9. The thruster efficiency peaks at a certain point (~ 0.6 m) and then falls as length of pitch increases.*

Key words : *Superconducting electromagnetic propulsion, Electromagnetic ship, Magnetic field, Helical-type, Thruster efficiency*

1. Introduction

The importance of high-speed transport systems in coastal and international shipping has been lately recognized from the viewpoints of their impacts upon the global environment, transport efficiency and speed. It is, however, unrealistic to achieve ships with speeds higher than those available at present, as far as screw propellers are employed as the propulsion system. As an alternative propulsion system, the superconducting electromagnetic propulsion system has been proposed (Iwata *et al.*, 1980 ; Tamama *et al.*, 1991). Unlike ships with screw propellers, a superconducting electromagnetic ship is less susceptible to the adverse effects of cavitation and is capable of developing higher speed. What is more, when compared with Techno-Superliner (TECHNO MARINE, 1994), it has multiple advantages, such as reduced levels of operational noise, vibration and exhaust gas emission, coupled with the added advantage of easier speed regulation including the reversing functions from going ahead and astern or vice versa. As a result, the superconducting electromagnetic ship is promising as one of next-generation ships.

Prof. Y. Saji and his co-researchers of Kobe University of Mercantile Marine (hereafter "KUMM") commenced its research into electromagnetic ships using superconducting magnets in the early part of the 1970's (Saji *et al.*, 1978). They built a ship model, ST-500 of the external field type, using racetrack-type superconducting magnets with an effective magnetic field of 2 Tesla (T) in 1979, and successfully carried out experimental trial runs for the first

time in the world (Iwata *et al.*, 1980).

KUMM researchers took over the further studying to put to commercial use, and the research group supported by the Ship & Ocean Foundation built YAMATO-1 (Tamama *et al.*, 1991), an internal field type superconducting electromagnetic ship with a displacement of 185 tons, in 1992, using dipole-type superconducting magnets with a magnetic field of 4 T. YAMATO-1 uses two thrusters, each comprising six annular superconducting magnets. With this testcraft, trial runs were carried out where the maximum electric currents flowing between the electrodes were approximately 24000 A at maximum, and the electric current density, approximately 4500 A/m². In the trial run, the ship successfully registered a propelling speed of approximately seven knots. It is, however, difficult to manufacture dipole-type superconducting magnets of a larger size than the test-manufactured one. The system of YAMATO-1 uses six pairs of unit dipole coils to form a lotus-like ring, requiring an input electric current as large as six times, which is not practical for a commercial propulsion system.

In parallel with research work using YAMATO-1, on the other hand, the Institute for High Temperature Academy of USSR (Baskatov, 1991) started research into the helical insulation wall type superconducting electromagnetic propulsion ships of the internal magnetic field type (hereafter "helical-type"). Then, the Institute of Electrical Engineering, Chinese Academy of Sciences (hereafter "IEE") (Sha *et al.*, 1996 ; Yan *et al.*, 2000) joined the R&D with the intent of further development.

* Corresponding Author : Seung-Hwan Lee, shlee@bada.hhu.ac.kr 051)410-5137

The greatest feature of the helical-type, in a relative sense, is that the use of the solenoid-type superconducting magnets permits a wide range of high magnetic fields to be readily used (Baskatov, 1991 ; Sha *et al.*, 1996 ; Yan *et al.*, 2000). If this feature is fully utilized, the only one unit of the helical-type superconducting magnet can produce a greater power output than the propelling force of YAMATO-1, providing the same electrical power as the case of YAMATO-1. In fact, however, these research projects failed to develop a propelling power output greater than that of YAMATO-1. We consider the reasons just below.

The magnetohydrodynamic forces developed by the Institute of USSR with a magnetic field of 5.8 T and those by IEE, 5 T, which are too small for producing a power output greater than in the case of YAMATO-1. Moreover, the dimensions of the electrodes were too small.

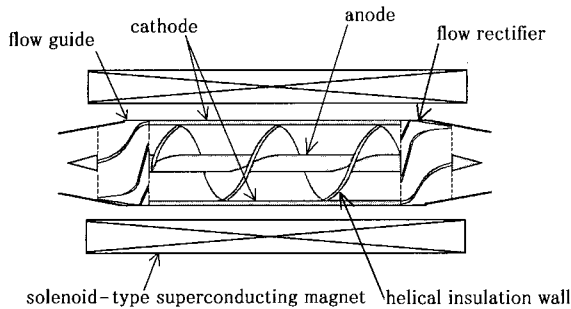


Fig. 1 Conceptual plan of helical-type superconducting electromagnetic thruster.

Taking the above into account, we have carried out the joint experimental test of the helical-type superconducting electromagnetic ship performance in cooperation with IEE and National Research Institute for Metals. In this study, a couple of newly obtained calculation as well as experimental results are presented.

2. Principles of superconducting electromagnetic ship

By conducting an electric current through seawater in the presence of a magnetic field, a Lorentz force will act to move the seawater in the directions normal to both magnetic field and electric current. This is a principle of electromagnetic thruster.

Fig. 1 shows an outline of the helical-type superconducting electromagnetic thruster, and Fig. 2 and 3 show the operating principles. The helical-type is configured with a solenoid-type superconducting magnet, coaxial cylindrical electrodes, a flow-guide, a flow-rectifier, and a helical insulation wall.

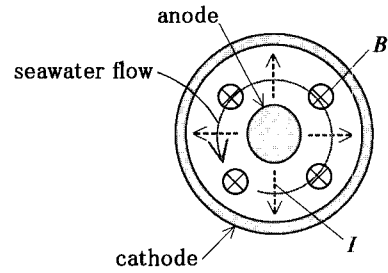


Fig. 2 Principle of helical-type superconducting electromagnetic thruster (Sectional view).

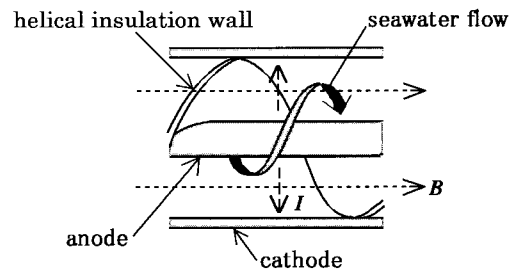


Fig. 3 Principle of helical-type superconducting electromagnetic thruster (Side view).

Magnetic field B is impressed onto seawater by the solenoid-type superconducting magnet, and electric current I flows via the seawater between the coaxial cylindrical electrodes. Under the Fleming's left hand rule, the seawater is subjected to the electromagnetic force per unit length below,

$$F = I \times B \quad (1)$$

and rotates around the anode. This revolving flow of seawater is converted into an axial flow using the helical insulation wall and the flow rectifier, in this way a propelling force is produced.

The provision of the flow guide helps seawater to rapidly flow into the thruster through the conversion from an axial flow into circumferential flow, and the provision of the flow rectifier converts the circumferential flow into an axial flow, whereby utilizing the power produced by the thruster as an effective propelling force. The helical-type insulation wall forcibly changes the flow direction of seawater with the flow guide and the flow rectifier.

3. Experiments and Results

Fig. 4 shows the system of the experimental arrangement of this study. The main system components are the thruster, seawater circulating system and various measuring instruments.

In this experimental arrangement, a propelling force is created by the thruster, whereby artificial seawater is circulated within the seawater circulating system. The artificial seawater flows in the directions shown by arrows. At the same time, the flow rate of the simulated seawater is measured with flowmeters (Q_1 and Q_2), pressures with pressure gauges (P_1 , P_2 , P_3 and P_4), and temperature with thermometers (T_1 and T_2).

During the experiment, magnetic fields were changed to 3, 5, 8, 10, 12 and 14 T with electric currents changed at each strength stage of magnetic field, whereby seawater pressures (P_1 , P_2 , P_3 and P_4), temperatures (T_1 and T_2) and flow rates (Q_1 and Q_2) were measured. Electric currents were changed to nine stages from 10 to 600 A, when strength stages of magnetic field were 3 and 5 T; to nine stages from 10 to 600 A when strength stages of magnetic field were 8, 10, 12 and 14 T.

Particular precautions taken for measuring pressures and flow rates were determination of zero points for all measuring instruments. The pressure and flow rate of the simulated seawater in its stationary state were measured to make these parameters zero before and after the simulated seawater started moving due to the propelling force generated.

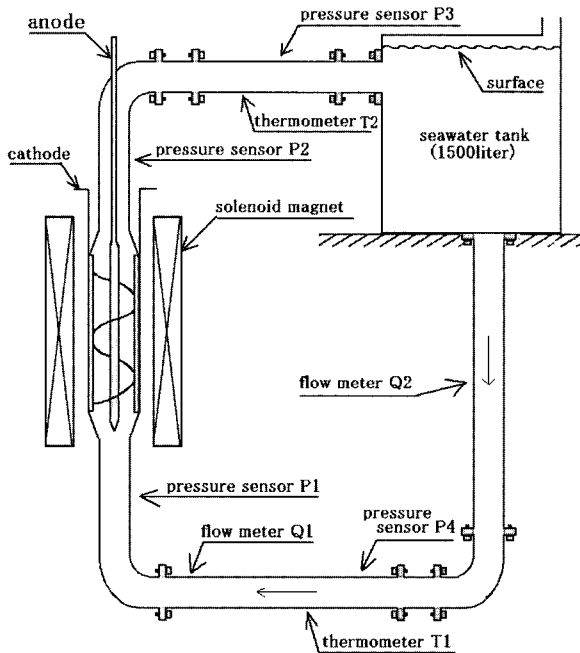


Fig. 4 System diagram of experimental arrangement.

Fig. 5 shows the relationship between duct thrust density and electric current density, as a parameter of the magnetic field. Equation (2) was used to compute duct thrust density D ,

$$D = T / V_{th} \quad (2)$$

where T is duct thrust, and V_{th} is volume of the entire thruster.

It can be seen from Fig. 5 that duct thrust density is in linear proportion to electric current density. It can also be seen that, if electric current density is constant, duct thrust density increases in association with the increase of the magnetic field.

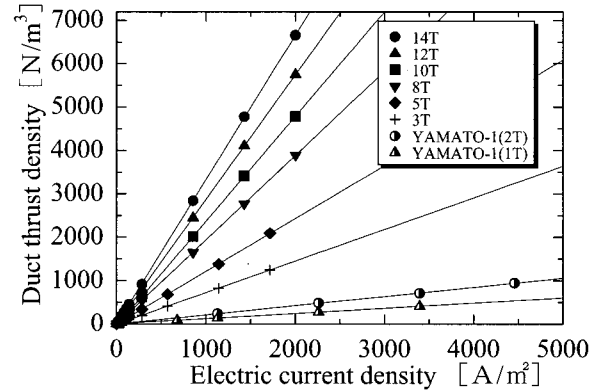


Fig. 5 Dependence of electric current density on duct thrust density as a parameter of the magnetic field. The solid lines show the approximate curves using the least squares method.

Data on YAMATO-1 in the figure represent those plotted on the basis of measurements on one thruster comprising six superconducting magnets. To compare thrusters alone, while neglecting hull resistance, bollard-pull test data were used (Sasakawa *et al.*, 1993). Electric current density data were obtained by dividing the measured electric currents flowing through the six electrodes by the sectional area of the electrodes. Duct thrust density of the magnetic field of 14 T at electric current density of 2003 A/m² was seven times that of YAMATO-1 with a magnetic field of 2 T at electric current density of 4457 A/m².

Fig. 6 shows the relationship between thruster efficiency and electric current density, as a parameter of the magnetic field. Data on YAMATO-1 in the figure were obtained under the same conditions as above. Equation (3) was used for computing the thruster efficiency η ,

$$\eta = T v_{MHD} / IV \quad (3)$$

where v_{MHD} is seawater speed at pressured zone, I is the electric current, and V is the voltage.

It can be seen from Fig. 6 that the thruster efficiency peaks at a certain point and then falls as electric current

density increases. Multiple reasons are considered to be ascribable to this phenomenon, i.e., hydrodynamic losses increase as the electric current density increases, and the electromotive forces generated in the reverse direction to the direction of electric current flow under Faraday's rule causes an electric resistance between electrodes as the electric current density increases. It can also be seen that, if the electric current density is constant, then the thruster efficiency increases in association with increase of the magnetic field. The thruster efficiency when the magnetic field is 14 T and electric current density is 2003 A/m² is approximately ten times that of YAMATO-1 of a magnetic field of 2 T at electric current density of 4457 A/m².

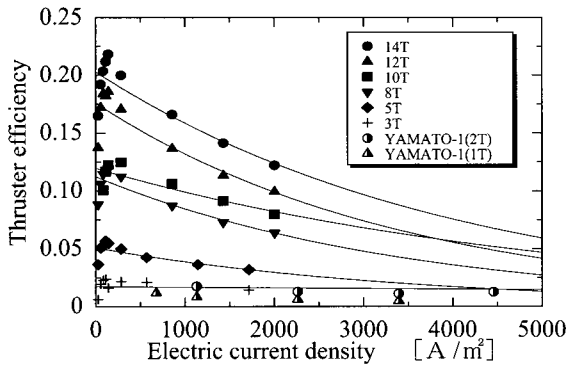


Fig. 6 Dependence of electric current density on thruster efficiency as a parameter of the magnetic field. The solid lines show the approximate curves using the least squares method.

4. Calculations

Fig. 7 shows the calculating region of helical-type superconducting electromagnetic thruster, which is composed of an inlet, a flow guide, a working space, a flow rectifier, and an outlet. Assuming that (1) seawater (27 °C) is incompressible, (2) voltage drop at the surface of electrode and electrolysis products are negligible, and (3) magnetic field and electric current are uniform inside the thruster, we made calculations of characteristics of the large scale helical-type thruster performance.

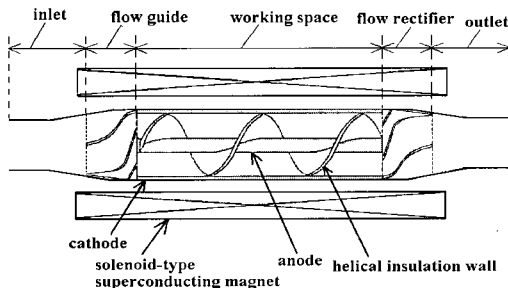


Fig. 7 Calculating region of helical-type superconducting electromagnetic thruster.

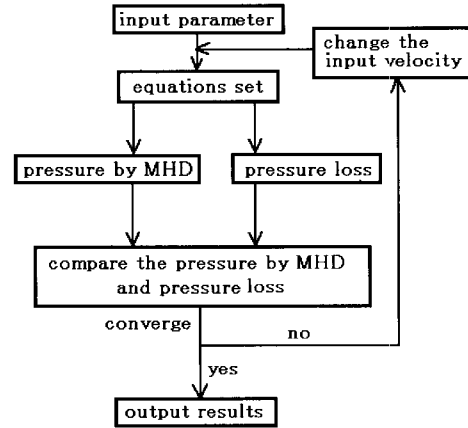


Fig. 8 Flow chart for calculation of seawater velocity.

Equation (4) was used for computing seawater velocity flowing by the thruster.

$$\frac{IBn}{L_{MHD} - n\delta} = \sum_i \lambda_i \frac{L_i}{d_i} \frac{1}{2} \rho v_i^2 + \sum_j \zeta_j \frac{1}{2} \rho v_j^2 \quad (4)$$

where L_{MHD} is length of electrode, n is pitch number concerned with the length of pitch, δ is thickness of the partition plate, λ is friction coefficient (the subscript i and j stand optional positions), d is diameter, ρ is density, v is velocity and ζ is the local loss factor.

A flow chart for calculation of seawater velocity by using Eq. (4) is shown in Fig. 8. The seawater velocity was calculated from the hydrodynamic equation based on Bernoulli theorem on condition that the electromagnetic pressure (pressure by MHD) equals to the hydrodynamic

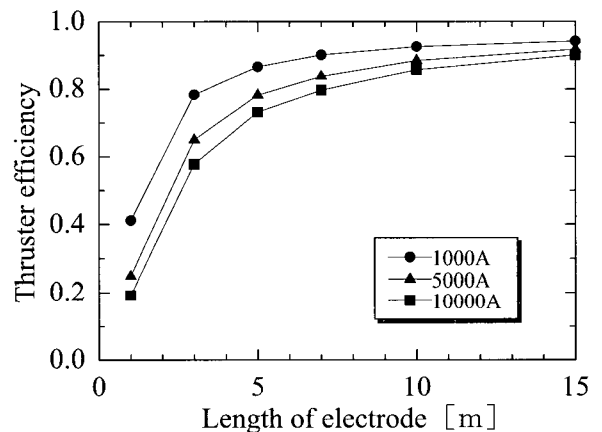


Fig. 9 Dependence of length of electrode on thruster efficiency as a parameter of the electric current.

loss (pressure loss). The thruster efficiency was obtained from the seawater velocity, using Eq. (3).

Fig. 9 shows the relationship between thruster efficiency

and length of electrode for the thruster with a length of pitch of 0.8 m under the magnetic field of 15 T, as a parameter of electric current. On the calculation, similar figures to the test thruster were supposed; V_{th} is about 0.7 m^3 for the thruster with a length of electrode of 1 m and is about 700 m^3 for 10 m. As is seen in this figure, the thruster efficiency quickly increases with the length of electrode up to about 5 m and then goes up to about 0.9. This may be attributed to low electric resistance between electrodes with increasing the length of electrode.

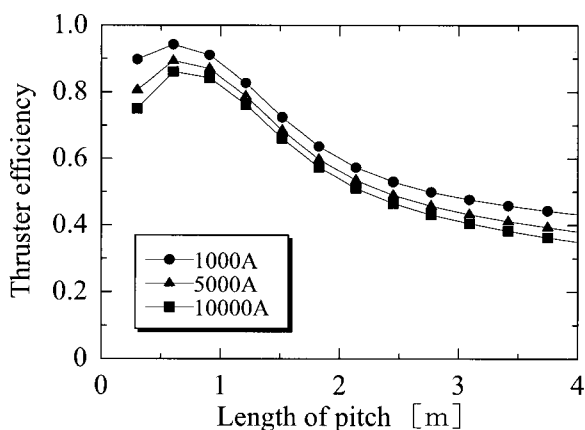


Fig. 10 Dependence of length of pitch on thruster efficiency as a parameter of the electric current.

Fig. 10 shows the relationship between thruster efficiency and length of pitch for the similar thruster with a length of electrode of 10 m under the magnetic field of 15 T, as a parameter of electric current. It can be seen from this figure that the thruster efficiency peaks at a certain point ($\sim 0.6\text{m}$) and then falls as length of pitch increases. The reason why the thruster efficiency shows the maximum value is qualitatively explained on the basis of competition between hydrodynamic loss and net electromagnetic force. Calculations of relationship between thruster efficiency and length of pitch will be made, as a parameter of magnetic field, length of electrode and so on.

5. Conclusions

We presented the latest calculations of the helical-type superconducting electromagnetic ship as well as experimental results. As results of calculation for the large scale helical-type thruster performance, the thruster efficiency quickly increases with the length of electrode up to about 5 m and then goes up to about 0.9. In addition, the thruster efficiency peaks at a certain point ($\sim 0.6 \text{ m}$) and then falls as length of pitch increases.

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