RESULTS FROM A 14T SUPERCONDUCTING MHD PROPULSION EXPERIMENT

Luguang Yan, Ciwen Sha*, Yan Peng, Kuo Zhou, Aihua Yang, Qiujuan Qing
Institute of Electrical Engineering Academia Sinica, P. O. Box 2703 Beijing 100080, China

Kazu Nishigaki, Minoru Takeda, Daiki Suyama
Kobe University of Mercantile Marine, Fukae-minami, Higashinada-ku, Kobe-shi 658-0022, Japan

Tsukasa Kiyoshi, Hitoshi Wada
National Institute for Materials Science, Sakura, Tsukuba-shi 365-0003, Japan

ABSTRACT

Institute of Electrical Engineering, Academia Sinica (IEEAS) and Kobe University of Mercantile Marine (KUMM), research teams have jointly conducted a high-field MHD propulsion experiment with about 14 tesla superconducting magnetic field, in cooperation with the National Institute for Material Science (NIMS), in September of 1999, using the NIMS’s existing 15T class superconducting magnet. The goal of the test is to investigate the MHD thruster performance in much high field and the other phenomena such as the influence of high field on the electrical conductivity of seawater and so on. A helical MHD thruster and a seawater closed-loop duct system were designed, built up and coupled to the 15T magnet system to create a test facility especially suited for investigating MHD thruster performance. The inner diameter of the thruster is 0.346m, and the effective length is 0.6m, the helical pitch number is 3.8. During the experiment, the magnetic field were increased step by step with six stages 3, 5, 8, 10, 12 and 14T, and electrodes currents were changed from 10 to 700A whereby seawater pressures, temperatures and flow rates were measured and collected by a data acquisition computer system. One of the results, the thruster electrical efficiency increases in association with the increase of the magnetic field and the maximum efficiency is greater by one order than that of the YAMATO-1. This paper will present in more detail the objectives structure of the helical MHD thruster, experimental facility and the results.

INTRODUCTION

The superconducting magnetohydrodynamic (MHD) propulsion is essentially an electro-magnetic pump operating in seawater. It is a potentially attractive technology for ship due to such system eliminate the conventional propellers, as well as other rotating shaft-gear components. Two technical approaches have been mainly developing in the recent decade. One is the liner MHD channel thruster combined with the dipole superconducting magnet such as the world's first superconducting MHD propulsion ship—YAMATO-1 of Japan, and the other is the helical MHD channel thruster combined with the solenoid superconducting magnet such as the experimental MHD propulsion ship—HEMS-1 of China\(^1\).

The MHD propulsion force and efficiency are strongly related to the intensity of the magnetic field. The conclusion from the results reached by YAMATO-1 seems that ships with such propulsion systems would be justified for commercial operation, if we could raise the magnetic field magnitude of the MHD thruster to 20 to 30T \(^2\). The magnetic field of existing experimental MHD propulsion mentioned above are not high enough, the YAMATO-1’s 3.5T and HEMS-1’s 5.0 T. So the performances of the MHD propulsion in the high-field conditions are very interested. Unfortunately, so far no experimental data was presented.

For the first approach, the dipole magnet over 10 tesla with enough large warm bore is very hard to make in present years, however for the second approach, the solenoid magnets with extreme high field and large size are exist, one 15 Tesla superconducting magnet \(^3\) is exist in the National Institute for Material Science (NIMS) at Tsukuba of Japan. For investigating the performance of MHD propulsion in high field condition, the Institute of Electrical Engineering Academia Sinica (IEEAS) and Kobe University of Mercantile Marine (KUMM),

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* Corresponding author. Tel/fax: +86-10-62542029
E-mail: cwsha@mail.iee.ac.cn

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jointly applied to conduct a closed loop MHD propulsion experiment using the 15 Tesla superconducting magnet of NIMS.

The experimental MHD thruster was designed and manufactured by IEEAS according to the conditions coupled to the 15 T magnet, and shipped to NIMS by the end of August of 1999. The experimental closed loop was designed and provided by KUMM. Measurement and data acquisition systems were prepared by both. The NIMS supplied the superconducting magnet system, electrode power source and test operation. The tests began on Sep. 15th and last for 3 days. 75 sets of data were collected. The experimental results demonstrated that the characteristics and performance of the thruster is much more advanced than HEMS-1's and YAMATO-1's.

**TEST FACILITY LAYOUT**

Fig.1 shows the general arrangement of the test facility. It consists of the 15 tesla superconducting magnet, the assembled MHD thruster, an external closed loop system including the connecting pips, tank, soft joints, the measuring instruments, the data acquisition system and electrode power source and so on. The MHD thruster served as the pump for the facility, no auxiliary mechanical pump is used. A propelling force \((F = j \times B)\) is created by the MHD thruster, whereby seawater is circulated within the closed loop. The applied currents and voltages of the thruster were recorded with the electrometers of the power. The flow rates were measured with flow meters, and the pressures with sensors, and the temperatures with thermometers.

![Fig. 1: General Arrangement of Test Facility](image)

**SUPERCONDUCTING MAGNET**

The 15T superconducting solenoid magnet is the background magnet of the existing 40 tesla hybrid magnet system \(^3\), and sets vertically up. Its axial distribution of the magnet field is shown in Fig.2. The central section of the warm bore with diameter 365mm and length 600mm was used for coupling with the thruster in this experiment. The structure at the bottom of the magnet limits the diameter of the circulating pipe no larger than 164mm. The highest magnitude of the magnet field during the test reached to 14T.

![Fig.2: Magnetic Field Distribution](image)

**MHD THRUSTER**

The assembled helical thruster is shown in Fig. 3. It consists of the flow-guide at the entrance and the flow-rectifier at the exit, the coaxial cylindrical inner and outer electrodes, the helical insulation wall, current leads, and the inlet and outlet sections. The thruster design principle is that it could be inserted smoothly into the warm bore of the magnet, and has the best usage of the magnetic field and the highest efficiency of propulsion. The diameter of the thruster channel was designed as large as possible, and the effective length is 300 mm, from the center of the magnet for working in stronger and uniformed magnetic field. The most important point is the helical pith/climb angle selection optimization that has to consider the effective Lorenz force, the flow pressure increase, flow rate and the hydraulic loss in the whole closed loop system. After model analysis study, the structure parameters of the thruster are listed in Table 1.

**Table 1 Main Parameters of Thruster**

<table>
<thead>
<tr>
<th>Name</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>MHD Effective length</td>
<td>m</td>
<td>0.6</td>
</tr>
<tr>
<td>Diameter of cathode (outer electrode)</td>
<td>m</td>
<td>0.346</td>
</tr>
<tr>
<td>Length of cathode</td>
<td>m</td>
<td>1.0</td>
</tr>
<tr>
<td>Diameter of anode (inner electrode)</td>
<td>m</td>
<td>0.1</td>
</tr>
<tr>
<td>Length of anode</td>
<td>m</td>
<td>0.6</td>
</tr>
<tr>
<td>Thickness of helical insulating wall</td>
<td>m</td>
<td>0.012</td>
</tr>
<tr>
<td>Helical pitch</td>
<td>m</td>
<td>0.155</td>
</tr>
<tr>
<td>Loop number</td>
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<td>3.8</td>
</tr>
<tr>
<td>Climb angle</td>
<td>Degrees</td>
<td>16</td>
</tr>
<tr>
<td>Flow Vanes</td>
<td></td>
<td>5</td>
</tr>
<tr>
<td>guide</td>
<td>Length</td>
<td>m</td>
</tr>
<tr>
<td>--------</td>
<td>--------</td>
<td>----</td>
</tr>
<tr>
<td>Rectifier</td>
<td>Vane</td>
<td>5</td>
</tr>
<tr>
<td>Rectifier</td>
<td>Length</td>
<td>m</td>
</tr>
</tbody>
</table>

Fig. 3 (a) General Arrangement of the Thruster

Fig. 3 (b) Assembled Thruster (Installing in NIMS, Tsukuba)

The inner electrode (anode) is made of stainless steel with 100 mm outer diameter and 600 mm length. Its surface is coated in a layer of platinum with thickness of 4 μm to avoid the electro-chemical corrosion. The helical insulation wall, made of nylon, is fixed into the helical groove on the surface of the anode with the pitch length of 155 mm and depth 2 mm. The flow guide and rectifier with vane number of 5 and length of 240 mm are fixed at the both ends of the anode. Inside the anode, a copper bar contacted well with the anode is used to lead the electrical current. The assembled inner part of the thruster is shown in Fig. 4. The outer electrode (cathode) is a stainless steel pipe with 356 mm outer diameter and 5 mm thickness.

Fig. 4 Inter Structure of Thruster

SEAWATER CLOSED LOOP

The seawater closed loop comprises the seawater/air separation tank, piping and the separation tank is made of FRP and has a capacity of 1500 liters. The piping material is vinyl chloride with the inner diameter of 0.194 m. The man-made seawater is produced by solving sodium chloride in tap water. The electric conductivity of this man-made seawater was measured with an electrical conductivity meter model DS-12 and the specific gravity with a standard hydrometer. The measurements show the electrical conductivity: 4.92 s/m – 4.94 s/m, and the specific gravity: 1.020 kg/m³.

INSTRUMENTATION AND DATA ACQUISITION SYSTEM

To enhance the reliability of experimental data, two individual data measurement and collection systems supplied by IEEAS and KUMM were used. Fig. 5 is the interface display of the DAS supplied by IEEAS. During the experiment, all parameters were treated as analog signals by transducers and transferred through AD/DA converter to the PC computer in the controlling room which is over 8 meters from the test facility platform to realize a real time display of all parameters, storing of historical data, and selection of all experimental functions in order to protect the data from the strong magnetic field affect.

In the experiment, the measured parameters are the electrodes current, electrodes voltage, flow rate in the loop (FRM), pressure at the entrance and exit of the thruster (P₁, P₂), loop pressure (P₃, P₄), temperature at the entrance and exit of the thruster (T₁, T₂), and conductivity of the working fluid. Table 2 lists the instruments used in the experiment.
TEST RESULTS AND DISCUSSIONS

1. Fig. 6 shows the hydraulic varying with the flow rate between point P1 and P2 in the thruster. The pressure losses include the losses in the flow guide at the entrance, the MHD effective section and the rectifier at the exit. As expected, the pressure losses increase with the flow rate increased.

Fig. 6 Hydraulic Losses of Thruster (Between P1 and P2)

2. Fig. 7 shows the voltage and current characteristics and the relation between the back electromotive potential and current. The electrodes voltage includes the seawater voltage-drop, the back-electromotive potential and the voltage drop on the surface between the electrodes and seawater. The back-electromotive potential was calculated as:

\[ U_{\text{back}} = (R_{\text{outer}} - R_{\text{inner}}) \times V_{\text{MHD}} \times B \times \cos \theta \]

Where, \( U_{\text{back}} \): back-electromotive potential, \( V_{\text{MHD}} \): seawater velocity in the thruster, B: magnetic field, \( \theta \): helical climb angle of the thruster, \( R_{\text{outer}} \): inner radius of the outer electrode, \( R_{\text{inner}} \): outer radius of the inner electrode.

![Fig. 7: Relationship Between Voltage and Current of Electrodes](image)

3. Fig. 8 shows the seawater conductivity variation with the current under the different magnetic field. The conductivity was calculated by using U-I characteristics, and the conductivity was measured directly to be 4.93 s/m with an...
conductivity meter, model DS-12.

Fig. 8: Conductivity Variation with Current in Different Magnetic Field

4. Fig. 9 shows the pressure increase $P_{\text{MHD}}$ and $P_{\text{net}}$ created by the MHD effect.

Fig. 10 and 11 indicate electromagnetic force and effective electromagnetic force variation with the electrical current of the electrodes and the magnetic field.

Fig. 12 shows the electromagnetic force density with the current density.

These curves show that the electromagnetic force is proportional to the current. The typical data are that when the magnetic field is 14T, and the electrode current is 700A, the electromagnetic force of 1030 N was created with electromagnetic force density of 24300 N/m$^2$.

$$P_{\text{MHD}} = P_{\text{net}} \cdot P_{\text{loss}}$$

where, $P_{\text{MHD}}$ : pressure increase created by MHD effect

$P_{\text{net}}$: pressure difference between points P1 and P2 measured

$P_{\text{loss}}$: Pressure loss between points P1 and P2, shown in Fig. 5

$$F_{\text{eff}} = P_{\text{MHD}} \times A_{\text{MHD}}$$

$$F = F_{\text{eff}} / \cos \theta$$

$$f = F / V_{\text{eff}}$$

where, $F_{\text{eff}}$: the effective electromagnetic force

$F$: the electromagnetic force created by the MHD effect

$f$: the electromagnetic force density

$A_{\text{MHD}}$: flow cross-area of helical channel of the thruster

$V_{\text{eff}}$: volume of helical channel of the thruster

Fig. 9: $P_{\text{MHD}}$ and $P_{\text{net}}$ with Current

Fig. 10: Electromagnetic Force with Current

Fig. 11: Electromagnetic Force V Variation with Magnetic Field

Fig. 12: Electromagnetic Force Density with Current Density

5. Figure 13 shows the duct thrust, which is proportion to the electrode-current. The duct thrust is defined as:

$$T = \rho Q (V_2 - V_1) + P_2 A_2 - P_1 A_1$$

where, $V_1$, $A_1$ and $V_2$, $A_2$ are the velocity and cross-area and in the point $P_1$ and $P_2$, respectively. For this case, $A_1$ and $A_2$ are the same value, and $V_1$ equals to $V_2$, $Q$ is the flow rate.
6. Fig. 14 shows the flow rates, which increase with the electrode current and magnetic field. In this test, the maximum flow rate was measured to be 343 m³/h, and the corresponding velocity in the thruster was about 5.5 m/s and the electrode current of 700A and magnetic field of 14 T.

7. Figure 15 shows the efficiencies varying the load factor $K$ in the magnetic field of 14 T. The thruster efficiency is defined as:

$$\eta_t = \eta_m \eta_c \eta_r \eta_{\text{end}}$$

$$\eta_m = \frac{1}{K}$$

$$\eta_c = 1 - \frac{\Delta U}{U_0}$$

$$\eta_r = \frac{P_{\text{net}}}{P_{\text{MHD}}}$$

8. Fig. 16 shows the electromagnetic efficiency with the current density, and comparison with the data of YAMATO-1's.
Fig. 16: Electromagnetic Efficiency with Current Density in Different Magnetic Field

The following factors will relate to the efficiency of the thruster:

- The NIMS’s magnet is not designed for MHD propulsion and the well-distribution of magnetic field will benefit to the efficiency.
- The effect of the electrode voltage drop and the frictional loss with the boundary layer will decrease with the size increase of thruster.
- The effect of electrical end loss, as well as the effect of the hydraulic losses in the flow guide and the flow rectifier will decrease with the length increase of the effective section of the thruster. The thruster in this experiment has the total length of the flow guide and the flow rectifier of 480 mm and the length of the effective section of the thruster of 600 mm. It is leaded the relative large of the pressure losses at the flow guide and the flow rectifier section, and for the practical use, the effective section will be much longer than the flow guide and the flow rectifier, and the climb angle also will be great than 16 degree. According to the analysis above, the efficiency in the practical use could be expected in much greater than the data obtained in this thruster[4].

CONCLUSION

- The joint experiment on the helical channel MHD seawater thruster under the strong magnetic field was carried out jointly by IEEAS, KUMM and NIMS. The experimental results show that the pressure rising caused by the electromagnetic force increases with the magnetic field, and is linearly proportional to the electric current.
- Thruster force and thruster force density increase with the magnetic field, and are linearly proportional to the electric current density. The thruster force density reaches 20600 N/m² under the condition of the magnetic field of 14T at the electric current density of 2033 A/m², which is much stronger than the earlier works, such as in Yamato-I and HEMS-1.
- The flow rate gradually increases with the electric current and magnetic field.
- The electromagnetic efficiency and thruster efficiency increase with the magnetic field, and decrease as the electric current density increases. The highest thrust efficiency reaches 13% under the magnetic field of 14T, the current density of 2033 A/m², which is approximately ten times that of YAMATO-I under the magnetic field of 2T at current density of 4457 A/m².
- Several efficiencies are separated from the experimental data, and it is found that the frictional and local losses including the losses in the flow guide, rectifier and the MHD effective section, are the main losses. One of main tasks in the future is, therefore, to improve the helical channel structure to decrease the losses.
- The experiment has demonstrated that the helical-type superconducting electromagnetic thruster is superior, in terms of duct thrust density and thruster efficiency, than that of earlier works such as Yamato-I and HEMS-1. This is important for the marine machinery and equipment in which the lighter weight and smaller size have particular significance, and it is concluded that the superconducting MHD thruster with the helical channel is better suited to commercial applications.

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