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# PERFORMANCE AND FLOW CHARACTERISTICS OF MHD SEAWATER THRUSTER

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## SUMMARY ACCOMPLISHMENTS

The main goal of the research is to investigate the effects of strong magnetic fields on the electrical and flow fields inside MHD thrusters. The results of this study is important in the assessment of the feasibility of MHD seawater propulsion for the Navy.

To accomplish this goal a three-dimensional fluid flow computer model has been developed and applied to study the concept of MHD seawater propulsion. The effects of strong magnetic fields on the current and electric fields inside the MHD thruster and their interaction with the flow fields, particularly those in the boundary layers, have been investigated. The results of the three-dimensional computations indicate that the velocity profiles are flatter over the sidewalls of the thruster walls in comparison to the velocity profiles over the electrode walls. These nonuniformities in the flow fields give rise to nonuniform distribution of the skin friction along the walls of the thrusters, where higher values are predicted over the sidewalls relative to those over the electrode walls.

Also, a parametric study has been performed using the three-dimensional MHD flow model to analyze the performance of continuous electrode seawater thrusters under different operating parameters. The effects of these parameters on the fluid flow characteristics, and on the thruster efficiency have been investigated.Those parameters include the magnetic field (10-20 T), thruster diameter, surface roughness, flow velocity, and the electric load factor. The results show also that the thruster performance improves with the strength of the magnetic field and thruster diameter, and the efficiency decreases with the flow velocity and surface roughness. .

## 1. BACKGROUND

There has been recently considerable renewed interest in the possibility of using MHD for propelling seawater ships and submarines. There are many reasons for such renewed interest; mainly the advantages that MHD seawater propulsion offers over conventional mechanical propellers. The absence of a conventional mechanical propeller system will lead to a reduction of the vibration level and therefore in the mechanical noise generated. Also with a conventional propeller, its speed is limited by cavitation. MHD propulsion does not have such a restriction. Therefore there is a potential to operate submarines and ships at higher speeds. Quieter and faster ships or submarines are desirable for commercial as well as military applications. MHD seawater propulsion has the potential to achieve these goals at high propulsion efficiencies.

MHD seawater propulsion depends on the cnductivity of the seawater to carry the electric currents. Energy is supplied to the duct of the thruster by applying an external electric field. The resulting electric current J, interacts with the applied magnetic field, B, to produce a driving (JxB) Lorentz force that pushes the seawater through the duct. Therefore the MHD thruster can be viewed as an electromagnetic pump that ejects the seawater at a higher velocity than the intake velocity; thus providing the thrust. Figure 1 shows a schematic diagram of the concept of MHD seawater thruster.

It has been established by several investigators [Refs. 1-4] that in order to achieve higher thruster efficiencies, strong magnetic fields (10-20 Tesla) are required. Recent development in high temperature superconducting materials is one of the main drives for the renewed international interest in the concept of electromagnetic seawater propulsion. However, in most previous studies, simple physical relationships have been used in the analyses. Some basic losses in the thruster have been ignored. In reference [4] by Doss and Geyer, some basic losses, such as frictional losses and end effects have been included in a one-dimensional MHD thruster model. The results of this study also established the need for high magnetic fields (10-20 Tesla) in order to achieve higher thruster efficiencies above 50%. In all the above studies, three-dimensional effects have been neglected.

During the past year, the effects of strong magnetic fields on the current and electric fields of an MHD thruster have been investigated and their interaction with the flow fields, particularly those in the boundary layers have been discussed. A three-dimensional MHD flow model has been used in this analysis. Those results were documented in References [5 & 6].

Work has progressed further where a parametric study has been performed to analyze the performance of continuous electrode seawater thrusters for different operating parameters. This parametric study has been carried out using the three-dimensional MHD flow model. A description of the model is discussed and the results of the parametric study are presented in this paper.

## 2. THREE DIMENSIONAL THRUSTER MODEL

A three-dimensional MHD generator model incorporating fully the interaction between the flow and the electrical fields inside the channel has been adapted for the application of seawater propulsion [6]. The flow fields are represented by the parabolic form of the three-dimensional compressible, turbulent Navier-Stokes equations and their solution is coupled to the solution of the electrical fields in the cross-flow direction.

The equations solved in this model consist of the mass conservation equation, the three momentum equations, the equations for temperature, turbulence kinetic energy and dissipation rate, the Maxwell and Ohms law equations. This set of coupled equations is solved by the use of a finite-difference calculation procedure. The turbulence is represented by a two-equation model of turbulence in which partial differential equations are solved for the turbulence kinetic energy and its dissipation rate. Full descriptions of the equations and the method of solution are given in Refs. [6,7].

A continuous electrode configuration has been used in this application where the electric field $E_x$ is assumed to be zero. This assumption is reasonable since the Hall parameter, $\beta$, for seawater is negligible. An applied electric field, in terms of a load factor, is specified as the boundary conditions for the electrode walls, while the sidewalls are assumed to be insulators. The electrical fields are computed at each crossectional plane perpendicular to the flow. Locally the axial variation of the electrical fields and current densities are assumed to be negligible in comparison with their variations in the cross-plane. This assumption may not be accurate where there are strong variations of the magnetic field, flow velocity, or where there are abrupt changes in the boundary conditions. Such situations may exist near the ends of the MHD thrusters in the fringing regions of the magnetic field.

## 3. OPERATING CONDITIONS

A parametric study has been performed using the three-dimensional model for MHD thruster operating in the continuous electrode mode with insulating sidewalls. The general operating parameters for the computational cases considered are listed in Table I. The thruster is assumed 10 m long, with a constant cross sectional area. The magnetic field is assumed to be constant along the duct. The flow at the entrance of the thruster is assumed to be that of a plug flow.

Table I

Operating Condition for the Illustrated Examples

| | | |
|---|---|---|
| Thruster geometry: | | |
| • length (L) | 10 | m |
| • height and width (d) | 1 x 1, 2 x 2 | $m^2$ |
| • wall roughness ($\varepsilon$) | 0,1,2 | mm |
| Wall temperature | 300 | K |
| Fluid temperature | 300 | K |
| Working fluid | Sea water | |
| • electrical conductivity ($\sigma$) | 4.8 | S/m |
| • mass density ($\rho$) | 1025 | $Kg/m^3$ |
| • viscosity (m) | 1.1 10-3 | Kg/(m.s) |
| • specific heat (C) | 3994 | $J/(m.s.^oC)$ |
| Flow velocity (U) | 5,10,20,30 | m/s |
| Magnetic field (B) | 10,20 | T |
| Duct loading | continuous electrode with insulating sidewalls | |
| • average electric load factor (K) | | 1-10 |
| • load potential (V) | 0 - 6000 | V |

The physical properties of seawater are documented in Ref. [8] and the values used are for a temperature of $20^oC$.

The average load factor, K, is defined as

$$K = \langle E_y \rangle / \langle UB \rangle$$

where $E_y$ is the electric field across the duct between the two electrode walls.

No restrictions have been imposed on the flow conditions at the exit of the thruster. The computations proceed to compute the flow fields and the pressure increase along the thruster regardless of the actual ambient pressure. Practically, for steady-state conditions, the flow velocity inside the thruster is a floating parameter that will be determined by the input and boundary conditions of the propulsion system. The cruise velocity and the flow velocity in the thruster will be reached when there is a balance between the total thrust generated and the total surface drag of the ship or submarine.

## 4. RESULTS AND DISCUSSIONS

This section covers two parts. The first part covers the effect of strong magnetic fields on the flow and electric fields of an MHD thruster. This part is covered here briefly, for completeness, because it has been discussed in more detail in Ref. [5]. For this part, a 29x29 grid network was used in the computation for the thruster cross section with a 2 cm stepsize in the flow direction. The second part covers the effects of different parameters on the performance of the MHD thrusters in terms of its electrical efficiency. More than 200 cases were covered in the parametric study. A coarser grid network (15x15) was used in this part of the computations with a 5 cm stepsize along the flow direction.

### Three-Dimensional Effects

Figure (2) presents the axial velocity profile between the electrode walls and the sidewalls for the thruster at x = 10 m for the following operating conditions: U = 30 m/s, B = 20 T, d = 1 m, $\varepsilon$ = 0.002 m, and K= 2. As shown on this figure, there is a difference between the shape of the velocity profile along the electrode wall and that along the sidewall. The velocity profile is flatter over the insulating wall than that over the electrode wall. This is a result of the MHD JxB forces acting on the flow.

Figure (3) shows the corresponding variation of the current density component Jy across the duct between the insulating walls. For constant electrical potential between the electrode walls, and for the assumed constant seawater electrical conductivity, the current density, $J_y$, is larger in the sidewall boundary layer because of the smaller velocities. This leads to a larger accelerating force ( $J_y$ B) on the flow in the sidewall boundary layers as compared to the main flow. Consequently, the velocity profile is flatter over the sidewall in comparison to that in boundary layers over the electrode wall as shown on Fig. (1).

As a result of such nonuniformities in the flow fields, nonuniform distribution of the skin friction is expected along the thruster walls. Figure (4) illustrates the variation of the friction factor along the electrode wall and the sidewall of the thruster. The skin friction is higher on the sidewall. It has been found that the discrepancies in the boundary layer velocity profiles and the skin friction between the sidewalls and the electrode walls increases as the magnetic field increases. This is expected because of the increase of the MHD interaction with the flow as the magnetic field increases.

### Parametric Study

As the main emphasis of this paper is on the effects of several operating parameters on the thruster electrical efficiency, a definition of this efficiency is in order. In general, the thruster electrical efficiency is defined as

$$\eta_e = \Delta P\, Q / VI$$

where $\Delta P$ is the pressure rise along the thruster, Q is the volumetric flow rate, V and I are the applied external voltage and current. Physically this efficiency represents the net resulting MHD push power (after subtracting losses) divided by the input power. For an ideal situation, where all losses are ignored and for constant area duct and constant fluid properties, one can show that the thruster electrical efficiency is

$$\eta_{e,ideal} = 1/K$$

This means that the maximum electrical efficiency is 100% for a load factor of 1, which corresponds to the case of an open circuit and with no thrust being generated. This simple relationship, however, is included for comparison purposes in all subsequent figures for thruster efficiency.

As frictional losses are included in the analysis, the thruster efficiency is expected to decrease. However, as discussed in reference [5], the frictional losses along the thruster walls, for a constant flow velocity, wall roughness, magnetic field, and thruster diameter, are almost the same regardless of the value of load factor (K). Therefore the deviation of the computed values of the thruster electrical efficiency from the ideal values is expected to get larger as the load factor K decreases, since the generated thrust decreases. As a matter of fact, the curve for the computed electrical efficiency shows an increase as the load factor decreases, reaches a peak and then changes its slope at lower values of K, where the electrical efficiency starts decreasing and can even become negative. This situation will take place whenever the MHD JxB forces become less that the frictional losses, at load factors close to one. This trend applies to all subsequent results of the parametric study.

Figure (5) shows the effect of the magnetic field on the thruster electrical efficiency for different load factors and for a thruster diameter of 1 m with smooth walls and for a flow velocity of 20 m/s. As the magnetic field increases, the thruster efficiency improves. The reason for that is the decrease of the frictional losses in proportion to the generated JxB forces as the magnetic field increases. However, frictional losses still have a significant effect in reducing the thruster electrical efficiency for smaller load factors between 1 and 2.

Figure (6) presents the variation of the frictional losses (in proportion to the generated thrust) with the load factor for the operating conditions corresponding to Fig. (4). This figure illustrates the adverse impact of friction on the thruster performance as the load factor decreases and for lower magnetic fields.

Figure (7) presents the effect of thruster diameter on the thruster efficiency for different load factor and for U = 20 m/s, B = 20 T, $\varepsilon = 0$ m. The thruster efficiency increases as the thruster diameter increases. The reason for that is the decrease of the thruster frictional losses as the diameter increases.

Figure (8) illustrates the effects of the flow velocity on the thruster efficiency for different load factors and for d = 1 m, B = 20 T and for smooth walls. The results indicate that the thruster efficiency decreases with the flow velocity. Once again the role of frictional losses is manifested as the flow velocity increases from 5 to 30 m/s. Higher flow velocities lead to higher frictional losses which in turn reduce the thruster electrical efficiency.

Figure (9) presents the effect of wall roughness on the thruster efficiency for different load factors and for d = 1 m, B = 20 T and U = 10 m/s. As the surface roughness of the thruster walls increases, friction losses increase and the thruster efficiency decreases. The results indicate that the maximum thruster efficiency decreased by 10 percentile points as the size of the average surface roughness increases from o (smooth walls) to 2 mm.

## 5. SUMMARY AND CONCLUSIONS

1. A three-dimensional parametric study has been performed to analyze the performance of continuous electrode seawater thrusters under different operating parameters. Such parameters include the variation of the magnetic field (0-20 T), thruster diameter (1-2 m), flow velocity (5-30 m/s), electric load factor (1-10), and wall roughness (0-2 mm).

2. The results of the three-dimensional analysis indicate that the axial velocity profiles are flatter over the sidewalls in comparison to the velocity profiles over the electrode walls. This phenomena is caused by the stronger JxB forces in the Hartmann layers of the sidewalls in comparison to those in the main flow. This velocity nonuniformities lead to higher skin friction over the sidewalls than over the electrode walls.

3. The results of the parametric study indicate that the frictional losses have a deleterious effect on the thruster electrical efficiency close to a load factor equal to one where the generated MHD thrust is smaller. Furthermore, the results show that the thruster efficiency increases with the strength of the magnetic field and thruster diameter, and decreases with the flow velocity and the surface roughness.

Careful consideration should be given to the analysis and the design of MHD thrusters in order to minimize the frictional losses because of their adverse impact on the thruster efficiency, particularly for load factors between one and two.

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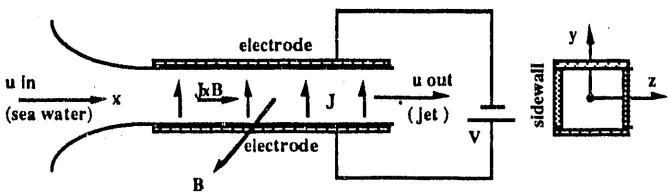



**Figure 1 A Schematic Diagram of an MHD Thruster**

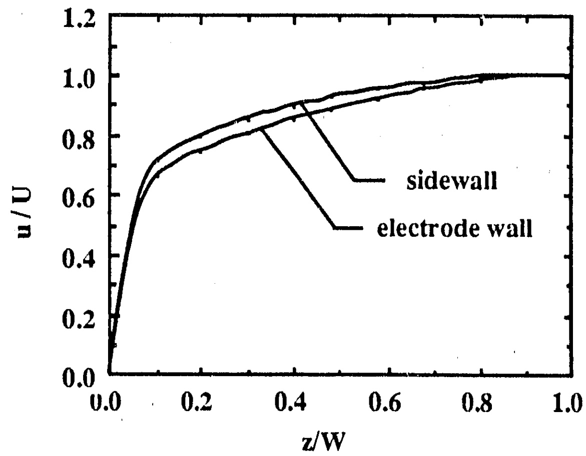
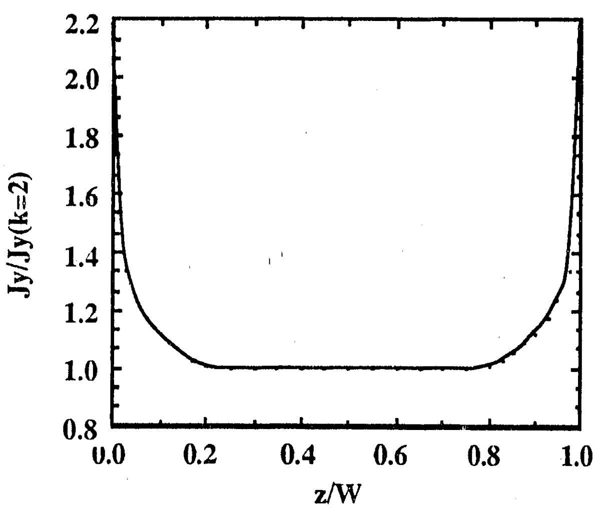



**Figure 2 Normalized Velocity Profiles Along the Thruster Walls ( x = 8m )**




**Figue 3. Normalized Current Density Across the Sidewalls ( x = 8m )**

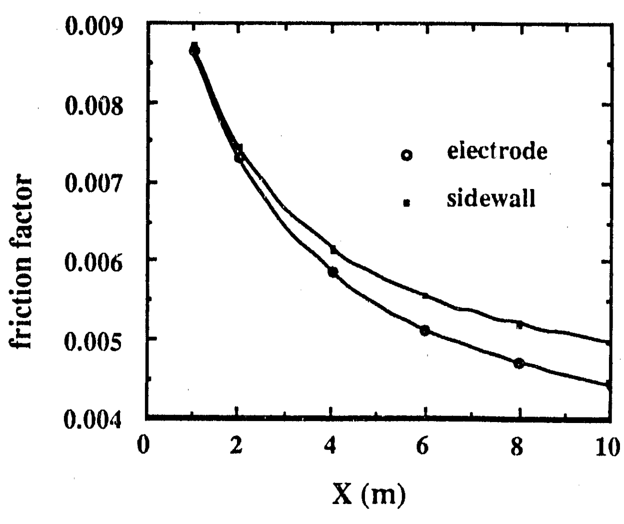



**Figure 4. Variation of the Friction Factor Along the Thruster Walls**

Figure 5. Effect of Magnetic Field on Efficiency (d=1 m, u=20 m/s)

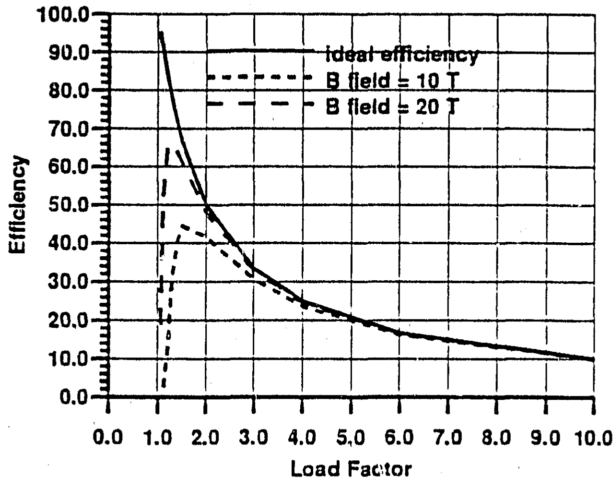



Figure 7. Effect of Thruster Diameter on Efficiency (B=20 T, u=20 m/s)

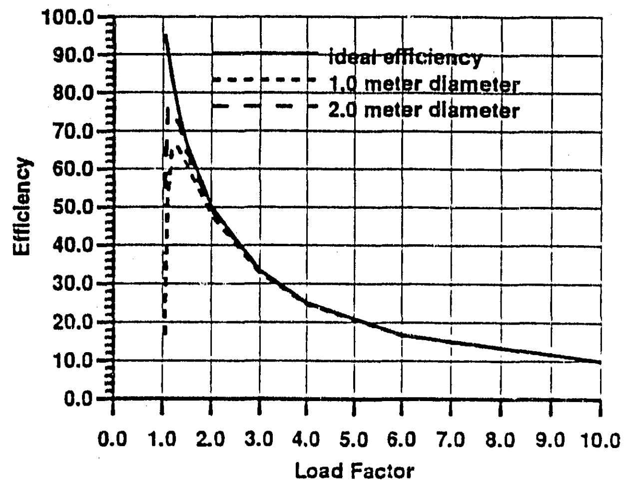



Figure 6. Friction as a Percentage of Thrust (d=1 m, u=20 m/s)

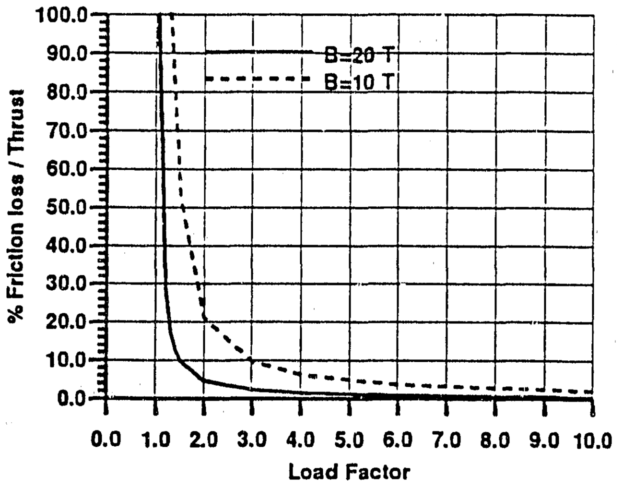



Figure 8. Effect of Flow Velocity on Efficiency, d=1 m, B=20 T

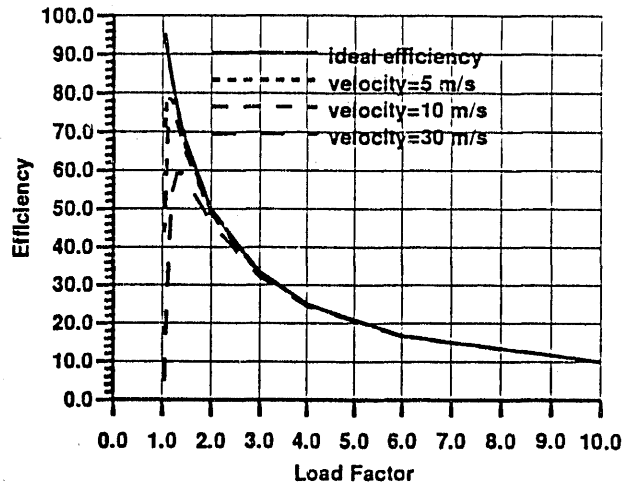
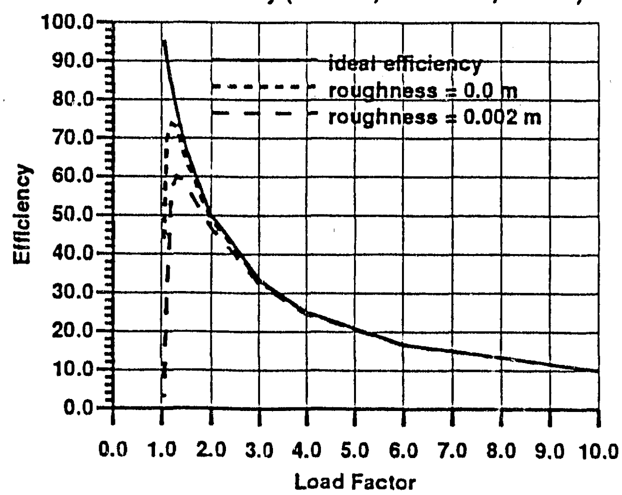



Figure 9. Effect of Wall Roughness on Efficiency (B=20 T, u=10 m/s, d=1 m)



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