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Analytical and Experimental Studies of the Cyclic Magnetohydrodynamic Thruster Designs

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ABSTRACT

This paper describes the results of our analytical and experimental studies of nonintrusive magnetohydrodynamic (MHD) pumping of seawater. The application of this study is in marine vehicle propulsion. Analytical models were developed to predict the performance characteristics of two different MHD thruster configurations in a closed loop environment. These analytical results are compared with experimental data. A significant increase in MHD energy conversion efficiency compared to this group's previous designs is realized. Photographic results of the MHD-induced flows are also presented.

INTRODUCTION

The presence of salts allows seawater to conduct electricity by electrolytic ion exchange. Thus by passing an electric current through seawater in the presence of a magnetic field, a Lorentz ($j \times B$) force will act to move the seawater in the direction normal to both the magnetic field and electric current directions. This is the basis for magnetohydrodynamic (MHD) propulsion. Few mechanical moving parts are required with MHD propulsion. As a result, this type of propulsion can be very quiet. This technology became practical with the advent of multi-Tesla superconducting magnets. With superconducting magnets, the magnetic field can be increased and the magnet's weight and electrical consumption decreased significantly. Recently there has been an increase of research and development activity in this field (Lin, 1992a). An experimental ship utilizing MHD propulsion has recently been built and tested in Japan (Motora et al., 1991). The YAMATO-1 experimental ship, sponsored by Japan's Ship and Ocean Foundation, uses two MHD thrusters, each capable of producing 4,000 N of thrust. Research in the United States includes large-scale thruster experiments at the Argonne National Laboratory (ANL) (Petrick et al., 1991) and the Naval Undersea Warfare Center (NUWC) (Meng et al., 1991). Analytical studies of seawater MHD propulsion (Doss and Roy, 1991; Lin et al., 1991a) and seawater electrolysis, conductivity enhancements and electrode studies (Lin, 1990; Gilbert et al., 1991) have also been conducted. These analytical studies did not consider the effects of the electrolytic bubbles on the performance of the thrusters. Subsequent studies (Lin et al., 1991b) have shown that these effects are significant. The large-scale experiments of ANL and NUWC use 6 and 3.2 Tesla dipole magnets, respectively. These magnets lack optical access of the warm bore, thus the only direct visualization of an MHD-induced flow has been conducted by this group (Lin et al., 1992b).

This paper reports the results of analytical and experiments studies based on MHD thrusters of unique designs. These designs were chosen to more fully take advantage of the cylindrical shape of the solenoid magnet used by this group. In these studies, the magnetic field and electric current are applied axially and radially, respectively. As a result, the MHD flow is induced in the azimuthal direction. Two identical test sections were manufactured with the ability to operate either singly or in tandem. Both strobe-light photography and real-time videography were used to record the complex flows. In addition, the performance characteristics (flowrate, thrust and mechanical efficiency) of the thrusters are measured/calculated with a PC-based data acquisition system.

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KEY WORDS: Magnetohydrodynamics, MHD, two-phase flow, seawater electrolysis, propulsion, Lorentz Force.

ANALYTICAL APPROACH

To optimize the geometry of the test section and to predict the performance of each thruster in a closed loop, analytical models were developed and codified. This code calculates the MHD-induced flowrate by equating the pressure rise in the thruster due to the MHD effect to the sum of all the hydraulic losses around the loop, including the losses in the thruster. According to the Lorentz Law, the force created by the thruster is:

$$\vec{F} = \vec{J} \times \vec{B} \tag{1}$$

where $\vec{F}$ = the resultant Lorentz vector per unit volume, $\vec{J}$ = the electric current density vector and $\vec{B}$ = the magnetic field strength vector.

Therefore, the pressure rise due to the MHD effect in the test section is:

$$\Delta P_{MHD} = \frac{IDB}{A_{flow}} \tag{2}$$

where I = electric current, D = gap distance between electrodes and A_{flow} = the thruster's flow area.

Relationship Between Voltage and Current

In order to use Eq. 2, the relationship between the current, magnetic field, fluid velocity in the test section (U) and overpotential (V_o, the minimum voltage required for electrolysis) must be ascertained. Two phenomena diminish the electric potential: the back electromotive force (EMF), V_B, and overpotential. The magnitude of the back EMF is given by:

$$V_B = BUD \tag{3}$$

For our electrode combination the overpotential is approximately 2.25 volts. Therefore the current can be calculated from: