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EXPERIMENTAL DETERMINATION OF MAGNETOHYDRODYNAMIC SEAWATER THRUSTER PERFORMANCE IN A TWO TESLA TEST FACILITY

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ABSTRACT

A two Tesla test facility was designed, built, and operated to investigate the performance of magnetohydrodynamic (MHD) seawater thrusters. The results of this investigation are used to validate MHD thruster performance computer models.

The facility test loop, its components, and their design are presented in detail. Additionally, the test matrix and its rationale are discussed. Finally, representative experimental results of the test program are presented, and are compared to pretest computer model predictions.

Good agreement between predicted and measured data has served to validate the thruster performance computer models.

INTRODUCTION

The idea of using MHD seawater propulsion for surface ships and submarines has been examined in the past by many investigators.^[1-5] However, it has been demonstrated that the attractiveness of this propulsion concept is dependent on the development of high magnetic flux density superconducting magnets.^[6]

Recent advances in superconductors have renewed

interest in using this propulsion concept. The potential benefits of this forward-thinking propulsion system include reduced noise (from the elimination of rotating machinery required to support conventional propulsion) and potential for operating at higher speeds because an MHD thruster, unlike a propeller, is not cavitation limited. Moreover, the arrangement of components needed for MHD propulsion does not require a fixed stack-up, thus allowing greater architectural flexibility for the shipbuilder. To explore these potential benefits, conceptual designs of surface ships and submarines are being pursued.^[7] Crucial to this process are validated design tools that address the performance characteristics of MHD thrusters as a function of their geometry and operating parameters.

A collaborative effort between Newport News Shipbuilding (NNS) and Argonne National Laboratory (ANL) was established to demonstrate the feasibility of MHD seawater propulsion through development of computer models of thruster performance and experiments to validate adequacy of the developed models. The first phase of this multiyear/multiphase program, the development of a design oriented, lumped parameter, systems code that predicts the performance of an MHD thruster, was completed in 1990.

The focus of the second phase is experimental validation of the thruster performance code and

identification through testing of any phenomena which may limit the theoretically predicted thruster performance thereby impacting the attractiveness of this propulsion system for shipboard applications. To accomplish this in a cost-effective manner, a test facility has been built at ANL using an existing 2 Tesla conventional electromagnet.

TEST FACILITY LAYOUT

The test facility, Figure 1, consists of a 2 Tesla conventional electromagnet, a test section, gas separator, a loop pump, polyvinylchloride (PVC) piping, and related fittings. Additional systems support both loop operation and data acquisition.

Figure 1: Test Facility Layout

The purpose of the test loop is to circulate the working fluid through the test section, located in the two Tesla magnetic field. The test loop also provides for the removal of the electrolytically generated hydrogen bubbles from the working fluid.

WORKING FLUID - Aqueous solution of sodium chloride (NaCl) was selected as the working medium in lieu of Instant OceanTM because the NaCl solution does not contain additional dissolved salts whose precipitates (e.g. calcium hydroxide - $\text{Ca}[\text{OH}]_2$ and magnesium hydroxide - $\text{Mg}[\text{OH}]_2$) might foul the loop during operation. Increased NaCl concentrations beyond values characteristic of seawater are used to enhance electrical conductivity and thus achieve test operating conditions closer to prototypic than would have been possible with conductivities representative of seawater alone.

All loop components were selected to be compatible with both the working fluid and the products of electrolysis such as: hydrogen gas (H_2), sodium hypochlorite (NaClO), and hypochlorous acid (HClO).^[8]

MAGNET - An existing 2 Tesla, iron core, conventional electromagnet with a uniform magnetic field volume of 8" x 30" x 50" is used in the test setup. This 67 ton water-cooled electromagnet was selected because the magnetic field can be oriented either vertically or horizontally to observe the effect of gravity on bubble

evolution and MHD thruster performance.

TEST SECTION - Sheets of optically-clear polycarbonate resin were solvent welded with methylene chloride (CH_2Cl_2), strengthened with brass screws, and sealed with a silicone rubber adhesive to form the 6" x 6" x 12' test section. This material was selected to enable visual observation/measurement of the electrolytically-generated hydrogen bubbles at the cathode. Seven pressure taps were installed along the 50" active length of the test section (that portion of the test section where the electrodes are located) to measure the internal pressure distribution. Each electrode was segmented into five parts enabling specific measurement of both applied current and voltage to better ascertain the impact of fringing current on thruster performance. The anode segments are a mixed-oxide coating (ruthenium) on a 1/4" thick titanium substrate and the cathode segments are titanium plates of the same thickness. A removable lid was installed to allow for electrode maintenance. The non-active portion of the test section was included in the design, along with an inlet flow straightener, to provide a well developed velocity profile for the active section of the thruster.

BUBBLE SEPARATOR - A bubble separator was included in the loop to assist in the separation of hydrogen bubbles from the working fluid. The separator tank design is based on a cyclone principle commonly used to separate solids and liquids from gas streams. In this application, the centrifugal field moves the hydrogen bubbles to the center where they rise, enter the standpipe gas space, are diluted by nitrogen gas below the flammability limit, and are exhausted to the atmosphere. The tank is 30" in diameter and 74 1/2" tall. Inlet and outlet connections were installed off-axis to generate the centrifugal field required for separation. A flanged lid was provided to facilitate coating the interior of the tank with a synthetic rubber corrosion preventative. Elliptical heads were installed to facilitate gas removal and loop drainage.

A 33" tall, 4" diameter, 3/8" thick acrylic pipe is installed, via adapter, at the top of the separator to enable loop operators to monitor the working fluid level in the loop, facilitate the injection of nitrogen into the system, and to provide an expansion volume. Loop pressurization, hydrogen dilution, and venting is accomplished through appropriate standpipe penetrations.

LOOP PUMP - The loop pump is a 30 kw (40 hp) horizontal end-suction 12" x 10" centrifugal pump whose motor is driven by a variable frequency speed controller. This controller enables testing at fluid velocities in the range of 2-8 m/s independently of current applied to the electrodes.

PIPING - Schedule 40 PVC piping was used in the test loop. Pipe sizes were established by the pump discharge (10"), the flowmeter (8"), and the pump suction (12"). Fiberglass reinforced piping transitions (10" round to 6" square) were installed to reduce flow losses into/out of the test section. An 8" flexible connection was installed between the two fixed points in the system, the loop pump and the separator tank, to accommodate changes in pipe length due to variations in temperature, to reduce vibration in the loop from the pump, and to accommodate any

misalignment of loop components.

INSTRUMENTATION

Two types of instrumentation were used in the test program. The first type includes the instrumentation that supplies the data necessary to satisfy the primary objective of the test program, i.e. the determination of thruster performance. The second type includes all instrumentation necessary to monitor loop performance and carry out the various operations during preparation for loop start-up, testing, and post-test loop shutdown. The instruments in the former group include:

- An 8" electromagnetic flowmeter to measure flowrate (and thus, flow velocity) in the thruster.
- A working fluid conductivity analyzer.
- Two differential pressure transducers/transmitters along with an appropriate valving system, to measure the pressure distribution in the test section.
- Ten current shunts for the measurement of the individual electrical currents supplied to the five anode segments and the corresponding currents collected from the five cathode segments.
- A multichannel integrating digital voltmeter to sample the potential difference across the five anode/cathode pairs to ensure that they are driven by the same differential voltage.
- A thermocouple to measure fluid temperature.

All signals from these instruments, as well as others that provide pressure distribution along the loop are sampled, on demand, by a minicomputer-driven data acquisition system (DAS) and recorded in memory. In addition to measurement of electrical and mechanical thruster parameters, the fully transparent test article provided a unique opportunity for visual observation of the bubbles and optical measurement of their characteristics via high speed video recording. Visual observation was done over a length of 47" downstream of the electrodes whereas optical measurements were carried out 33" downstream of the electrode edge.

PRE-TEST ANALYSIS

A pre-test analysis was performed to support the design of the loop and provide guidance in establishing a test matrix, using the system code developed in Phase I. The MHD propulsion system code includes computer models for different components of the propulsion system. Among those components are models of the MHD thruster, nozzle, diffuser, pipe, and drag for submarines and surface ships.

The MHD thruster model couples a one-

dimensional hydrodynamic flow model to a two-dimensional electrical model. The equations used in the hydrodynamic model are the usual one-dimensional equations for conservation of mass:

$$\dot{m} = \rho A u$$

and conservation of momentum.

$$\rho u \frac{du}{dx} = - \frac{dp}{dx} + J_x B - \frac{f \rho u^2}{2d}$$

The two-dimensional electrical model solves Maxwell's equation for the electrical field potential in conjunction with Ohm's law which for an MHD thruster can be written:

$$J = \sigma (E - uB)$$

The resulting modified Laplace equation for the electrical potential given by:

$$\frac{\partial^2 \phi}{\partial x^2} + \frac{\partial^2 \phi}{\partial y^2} = 0$$

is solved using an overrelaxation procedure. This two-dimensional electrical model is used to predict the current in the fringing region of the magnet near the ends of the electrodes and to determine the electrical end losses in that region. Details of the MHD thruster model are given in reference [6]. The MHD system code, including the thruster model, has been used to design loop components, define optimum operating conditions, assist in the selection of instrumentation for the individual components, and predict the overall characteristics of the test loop.

A parametric sweep was performed using the following variables:

- Separator loss coefficient $\lambda = 0 - 1.25$
- Working fluid conductivity $\sigma = 4.5 - 22.5$ S/m
- Test section velocity $u = 2 - 8$ m/s
- Load factor $K = 1.1 - 30$

Output values include voltage, current, working fluid, loop component velocity and pressure drop, and pressure loss/recovery in the test section. The actual magnetic flux distribution of the 2 Tesla magnet was used in the facility model.

TEST MATRIX

The test program consisted of the following measurements:

1. Measurement of pressure distribution in the test section with zero magnetic field over a velocity range of 2-8 m/s to determine the baseline frictional losses.
2. Measurement of pressure distribution in the test section at 2 Tesla with no current supplied to the thruster

over a velocity range of 2-8 m/s to determine the modification of the pressure distribution by the magnetic field alone.

3. Measurement of the volt-ampere characteristics of the thruster at zero magnetic field to determine the total electrochemical potential, confirm the conductivity of the working fluid, and obtain preliminary evidence on the effect of bubbles on the electrical performance of the thruster. Data were obtained at two different fluid velocities and current densities in the range of 67-780 A/m². This current density range spans the expected current density range of a full-size marine MHD thruster.

4. Measurements of the thruster performance at a magnetic field of 2 Tesla over a velocity range of 2-8 m/s and a current density range of 70-820 A/m².

Measurements 1 through 4 were obtained at two fluid conductivities, 4.5 and 22.5 S/m, with a horizontal magnetic field, and one conductivity, 22.5 S/m, with a vertical magnetic field. The test matrices included more than 400 data scans for different operating conditions and pressure differentials.

RESULTS AND DISCUSSION

The measured Volt-Ampere (V-I) characteristics of the center pair of thruster electrodes (30" in length) are shown in Figure 2 for different conductivities, flow velocities, and magnetic field orientations. The straight line character of the V-I characteristics indicates that, for thruster-relevant current densities, the generation of hydrogen bubbles at the cathode has a negligible effect on the current transport across the working fluid and that the single electrode potentials (SEP's) are independent of the current density. The fact that the V-I characteristics are independent of both the velocity and the magnetic field orientation provides further support to the first conclusion. The fluid conductivity calculated from the slope of the V-I characteristics is in excellent agreement with the value measured by the conductivity probe. Finally, the sum of the SEP's at the anode and cathode, given by the y-intercept of the V-I characteristic (2.6 V for 4.5 S/m and 2.5 V for 22.5 S/m), is in excellent agreement with the sum of the single electrode potentials provided by Eltech, the electrode manufacturer. Eltech quoted a measured SEP of 1.1 volts for the anode and an estimated value, based on literature, of 1.5 V for the cathode. These figures are expected to increase slightly with increased current density and decreasing salt concentration. In their totality, the V-I characteristics results demonstrate that for the current densities of interest to MHD seawater propulsion, well established constant values of SEP's and fluid conductivity are the only electrical material properties that enter in the calculation of current transport and thruster performance.

Since the electrodes are segmented, the measurement of individual currents permits the determination of fringing current effects at the electrode ends. Figure 3 shows the measured and calculated average current densities over the five electrode segments. The figure indicates that the fringing current effects are confined to relatively small areas and, as such, they are

Figure 2: V-I Characteristics

expected to have a small effect on the performance of thrusters with moderately large length to width ratios in load factors greater than 1.5.^[9]

Figure 3: Current Distribution Among the Electrode Segments

The measured pressure difference over the 30" center electrode was used to determine the degree to which the performance of the thruster follows theoretical predictions. Specifically, the measured pressure difference during thrust producing operation is reduced by the measured pressure difference at the same velocity and magnetic field, but at zero current. The resultant MHD pressure rise is normalized by the theoretical pressure rise calculated on the basis of the measured current, and plotted as a function of the current density as indicated in Figure 4. As expected, there is good agreement between measured and calculated pressure rise (thrust).

The thruster efficiency, defined as the ratio of the mechanical power generated by the thruster to the electrical power supplied the thruster is given by:

$$\eta = \frac{\Delta p Q}{\Delta V I}$$

where Δp is the pressure rise along the thruster, Q is the volumetric flow rate, ΔV is the potential difference across the electrodes, and I is the electric current.

Figure 4: Comparison of Calculated and Measured Pressure Rise vs. Current Density

In Figure 5, the measured total efficiency for $\sigma=22.5$ S/m and $u=2$ m/s is plotted against the load factor K .

$$K = \frac{\Delta V/d}{uB}$$

where, d is the electrode separation, B is the magnetic flux density, and u is the fluid velocity. As shown in Figure 5, a total efficiency of about 9% was achieved under these conditions. Figure 5 also shows that the total efficiency is given by the ideal thruster efficiency (equal to $1/K$) reduced by frictional drag and SEP losses. Since both the losses and the ideal thruster efficiency are easily calculated, the performance of MHD thruster can be predicted with confidence. The calculation of the effect of end losses on efficiency is more complicated, but such losses are of little practical importance unless thrusters with magnetic flux densities in excess of 10 Tesla and for thrusters operating near load factors $K=1$ are under consideration.^[9]

Figure 5: Thruster Efficiency and Losses vs. Load Factor

The measured ideal thruster efficiency for different operating conditions, calculated from the measured total efficiencies and losses, is plotted against the load factor in Figure 6. As shown in this figure, there is good agreement between the experimentally determined ideal efficiencies

and theoretical dependence of $1/K$.

Figure 6: Measured (Ideal) Efficiency vs. Load Factor

As seen from the above figures, the theoretical predictions are in good agreement with the measured values. Deviations can be attributed to experimental errors, given the fact that differential pressure measurements are as small as a few tenths of a psi for some of the cases. The results presented here are confined to the central portion of the thruster, away from the fringing current areas. Measurements in these end regions are subject to large experimental error because the pressure differentials involved are small. Calculations have indicated that losses associated with such end effects are much smaller than frictional losses for the expected range of parameters of actual seawater thrusters.

As stated earlier, during the course of the test program, both visual observations and optical measurements of the hydrogen bubbles generated at the cathode were made. A detailed discussion of these measurements is beyond the scope of this paper. It is only mentioned that the presence of hydrogen bubbles downstream of the thruster is a function of both fluid velocity and current density. For example, at 500 A/m², bubbles appear only at fluid velocities below 7 m/s, whereas at 250 A/m², bubbles appear only at fluid velocities below 3.5 m/s. Apparently, provided that the hydrogen production rate at the cathode is sufficiently low and the mass transfer rate away from the cathode is sufficiently high, hydrogen goes into solution immediately. If this is indeed the case, hydrogen solubility and the dissolved concentration of hydrogen are important. In our tests the amount of dissolved hydrogen was not monitored. Because the static pressure in the thruster controls the solubility of hydrogen it is important to note that the static pressure was at all times 21.5 ± 0.5 psia.

CONCLUSIONS

1. A one-of-a-kind magnetohydrodynamic test facility has been designed, fabricated, tested, and operated to provide unique data on seawater propulsion.
2. The test loop was modeled with both one and two dimensional models. The results of the tests indicate that the phenomena affecting the performance of marine MHD thrusters are well understood and can be adequately

quantified with relatively straight-forward analytical tools. Good agreement between measured and predicted data served to validate the developed NNS/ANL thruster performance code.

3. The production of hydrogen at the cathode does not appear to have an impact on performance for the current densities relevant to full size thrusters.

4. The performance of the thruster is independent of the orientation of the magnetic field relative to gravity.

5. Bubble formation at the cathode (and presumably related noise) is dependent on both current density and fluid velocity.

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The opinions expressed herein are those of the authors and do not necessarily reflect those of Argonne National Laboratory or Newport News Shipbuilding and Dry Dock Company.

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