한국에너지공학회지(1993), 제2권 제2호
Energy Engg. J (1993), Vol. 2, No. 2 pp. 231~236

An Overview of Magnetohydrodynamic Ship Propulsion with Superconducting Magnets

Yeong Kyung Kong
Agency for Defense Development, Chinhae

Abstract—The feasibility of Magnetohydrodynamic(MHD) Ship Propulsion using Superconduction Magnets is reviewed in light of recent advances in high-temperature superconducting. The propulsion using a screw propeller in the noise reduction has it's own limitation. The epochal noiseless MHD propulsion method which does not have this disadvantage is studying nowadays. The subject of a marine MHD as propulsion has been examined before and was found to be interesting because of relatively low magnetic flux densities. It is demonstrated that the MHD propulsion is technically interesting with high magnetic flux density. The development of large-scale magnets using the high-temperature superconductors now under development could make it practical to construct submersibles for high-speed and silent operation.

1. Introduction

It has long been the dream of the naval engineer to build faster ships, and recently to this has been added the desire to go fast quietly. It has been clear for some time now that these two desires cannot be met simultaneously with the marine propeller. Electro-magnetic propulsion of ships or submarines may be realized by sending an electric current through the sea water in the presence of applied transverse magnetic field.

The concept of MHD Ship propulsion was proposed by W.A. Rice[1] in 1961 as a similar idea of MHD pumps used for liquid metal. During 1960s, investigations into MHD Ship propulsion were conducted mainly in the U.S.A.. Theoretical as well as experimental research works on superconducting electromagnetic propulsion have been done. Owen M. Phillips[2] and R.A. Doragh[3] stuided the feasibility of MHD Ship propulsion in 1960 s. Experimental tests of MHD propulsion were carried out in 1966 by S. Way[4] of Westinghouse using a 10 ft (3 M) model submersible, the EMS -1, which weighed 405 kg with batteries. The dc magnetic fields, generated by conventional wire-wound coils, and dc drive current were external to the hull in a free-field configuration. The model achieved speeds of 1.5 knots in field trials off the California coast of Santa Barbara.

The first field test of MHD propulsion using superconducting magnets was carried out by Saji et al[5] and colleagues in 1976 at the Kobe Unibersity of Mercantile Marine dc operation with free-field current and magentic field distributions external to the hull. The maximum field for the 13-cm-long superconducting coil was 0.6 T at the hull surface. A later model, the ST-500, increased the size of the vessel to 3.6 m in length and 700 kg in weight with a 2.0 T maximum magnetic field at the hull surface[6]. A thrust of 15 N and speed of 0.6 m/s were obtained in a test tank at the Kobe University of Mercantile Marine.

An extensive series of calculations for the propulsive efficiencies of MHD propulsion systems were carried out by G. Hummert[7] of Westinghouse in 1979. The objective of the study was to determine the practicality, at the time, of using MHD propulsion units for small to medium scale submersibles, i.e., with hull diameters of 1~10 m. Hummert adopted a rectangular internal duct, pump-jet configuration for this study.

Kong et al generally announced the papers on the Superconducting Magnetohydrodynamic Ship Propulsion[8-11]. In this study, the author totally reviewed efficiency vs. speed with 10 T magnetic flux densities. That is, the author dealt with 10 T range in parameters that extended in comparision with G. Hummert[7].

2. Modeling and scaling relations

A wire or other electrical conductor placed in a magnetic field experiences a force perpendicular of electrical current. If the electrical current flows through an incompressible fluid, such as seawater, then the

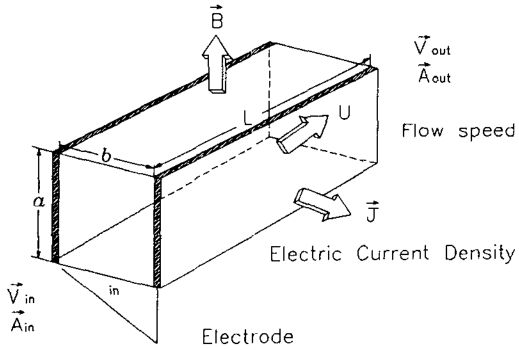

Fig. 1. Schematic diagram for a simple MHD pump-jet.

Lorentz force exerts a pressure on the seawater, which may be used to drive a MHD pump-jet. The force per unit volume acting on the seawater is given by

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

where $\vec{J}$ is the current density and $\vec{B}$ is the magnetic flux denisty.

A simple pump-jet with uniform magnetic fields and current distributions is shown in Fig. 1. The configuration adopted here is a simplified version of the MHD thrusters adopted by Doragh[3] and Hummert[7] for their studies.

The pressure head is given in terms of the volume Lorentz force by Eq. (2). The increase in velocity of the jet exhaust is given by Bernoulli's principle as in Eq. (3). A_{in}=inlet area; A_{out}=outlet area; B=magnetic flux density; J=current density; L=electrode length; $\Delta P\rho$=pressure head; =density of seawater; V_{in}=inlet speed; and V_{out}=outlet speed.

The approximations are made to facilitate the development of simple scaling relations and do not affect the conclusions. For the pump-jet shown in Fig. 1, the pressure difference generated by the Lorentz force is given by

$$\Delta P=\vec{F}\cdot\vec{L} \tag{2}$$

where L is the length of the electrodes. The increase in velocity due to this pressure head can be calculated from the relation for the conservation of energy as expressed by Bernoulli's equation:

$$\Delta P=\frac{\rho}{2}(V_{out}^2-V_{in}^2) \tag{3}$$

where is the density, V_{in} is the inlet speed or speed of the vessel, and V_{out} is the speed of the jet. For incompressible fluids, the speeds of the inlet and outlet also are related by the flow rate Q :

$$Q=A_{in}V_{in}=A_{out}V_{out} \tag{4}$$

or

$$\frac{V_{out}}{V_{in}}=\frac{A_{in}}{A_{out}}=r \tag{5}$$

where A_{in} A_{out} are the inlet and outlet areas, respectively, and r is the ratio. By the conservation of momentum, the thrust T for a pump-jet is given by

$$T=\rho Q(V_{out}-V_{in}) \tag{6a}$$

$$T=\rho Q(r-1)V_{in} \tag{6b}$$

Typical values for the thrust required to drive a 2000 ton submarine are given by Doragh[3] as a function of the speed. For 30 knots, the thrust is 43,065 kg, which corresponds to a power of 8800 HP or 6.5 MW. To generate this thrust with reasonable efficiencies, he finds that fields of the order of 10 T with ducts 1.5~3.0 m in width and 15.2~30.5 m in length are required. The hydraulic efficiency for the pump-jet shown in Fig.1 is given by the mechanical output power divided by the mechanical power input,

$$\eta_H=\frac{TV_{in}}{\Delta PQ} \tag{7}$$

By Eqs. (3), (5) and (6), this simplifies to

$$\eta_H=\frac{2}{r+1} \tag{8}$$

Thus, the hydraulic efficiency is independent of the speed and depends only on the ratio r. The total efficiency η_T is given by the product of hydraulic and electrical efficiencies where the electrical efficiency is given by the rate of conversion of electrical to mechanical power divided by the electrical power input:

$$\eta_E=\frac{\Delta PQ}{IV_o} \tag{9}$$

where I is the total current through the seawater and V_o is the voltage applied to the electrodes by the generator. The net elelctric field in the seawater E is given by

$$\vec{E}=\vec{E}_o\vec{V}_{out}\times\vec{B} \tag{10}$$

where w $|\vec{E}_o|=V_o$ with w representing the width of the duct and the other quantities defined as before. The current density J in the seawater is given by

$$\vec{J}=\sigma\vec{E}=[\vec{E}_o-\vec{V}_o\times\vec{B}] \tag{11}$$

where is the conductivity (normally taken as 4 mho m^{-1}).

Combining equations, the electrical efficiency can be expressed in the form

$$\eta_E=\left[1+\left(\frac{\rho}{\rho B^2}\right)\left(\frac{r^2-1}{r}\right)\frac{V_{in}}{2L}\right]^{-1} \tag{12}$$

Equation(12), as written here, is equivalent to the electrical efficiency calculated by Hummert[7].

According to Eq.(12), the efficiency is optimized for r=1. However, the thrust goes to zero as r=1 and, therefore, the limit is not practical. As will be seen later, r is not an independent parameter, but rather depends on the relative sizes of the vessel and the pump-jet intake. Resonable values for r lie in the range 1.1~1.5. The first set of terms to the right in Eq.(12) includes the conductivity σ, the density ρ, and the agnetic flux density $\vec{B}$. Since the density and the conductivity of seawater are fixed, for all practical purposes, the only free variable is the magnetic flux density. Due to the quadratic dependence, the magnetic field is, in fact, a critical parameter for the design of MHD propulsion systems. The comment often appears that the efficiencies of MHD propulsion units are low due to the small value for the conductivity of seawater. The optimal scale for vessels operating in seawater can be estimated in an order-of-magnitude sense by the scaling arguments developed here. The crudity arises from the nonlocal character of the MHD equations and their sensitivity to boundary conditions. Improved estimates would require solution of the Navier-Stokes equations with the proper boundary conditions. The scaling relation for the conductivity follows from consideration of the magnetic Reynold's number, which is given by Handbook of Fluid Dynamics[12]:

$$R_m=\mu_o\sigma V_oS \tag{13}$$

where μ_o is the permeability and σ is the conductivity *of seawater with* S *a characteristic dimension and* V_o a characteristic speed for the vessel. Comparison with the usual Reynold's number defined as $R=V_oS/\upsilon$,

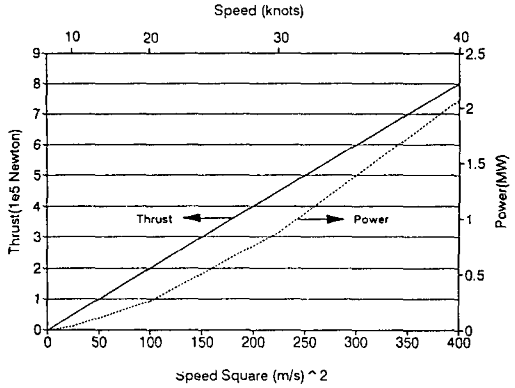

Fig. 2. The values for the drag and equivalent thrust required to maintain constant speed are given as calculated from Eqs.(17)-(19).

where υ is the viscosity, shows that $(\sigma\mu)^{-1}$ plays the role of viscosity in the magnetic Reynold's number. The diffusion length or skin-depth δ is given by

$$\delta=V_D\tau \tag{14}$$

where τ is a characteristic time, here taken to be S/V_o and V_D is the diffusion velocity of the field through seawater. With these relations, the ratio of diffusive velocity to ship velocity, or the ratio of diffusion length to ship length, can be written

$$\frac{\delta}{S}=\frac{V_D}{V_o}=(R_m)^{1/2} \tag{15}$$

For this ratio to be suitably large, say

$$\delta/S\geq 10 \text{ then}$$
$$SV_o\sigma\geq 8\times 10^3 \tag{16}$$

where the terms are expressed in MKS units.

The second terms in Eq.(12) includes only the single prarmeter r, which represents the ratio of inlet to outlet areas for the pump-jet.

The magnitude of the area does not appear. However, if we take the condition that the total thrust generated by the pump-jet equals the drag of the vessel at a constant speed V in, then

$$\rho Q(r-1)V_{in}=K_DV_{in}^2 \tag{17}$$

but since

$$Q=A_{in}V_{in} \tag{18}$$

and since K_D may be approximated by O.M. Phillips[2]

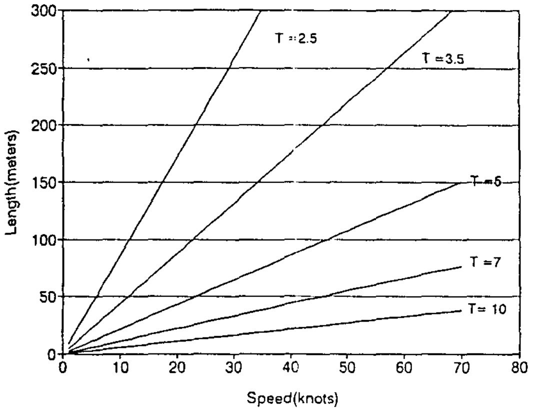

Fig. 3. MHD propulsion length vs. speed for 50% electrical efficiency.
The electrode length L required to achieve an electrical efficiency η_E= 0.5 is plotted as a function of the speed in knots with the magnetic flux density B as a parameter. The efficiency is calculated by Eq.(12) with a jet ratio of 1.5, i.e., the hydraulic efficiency η_H=0.8.

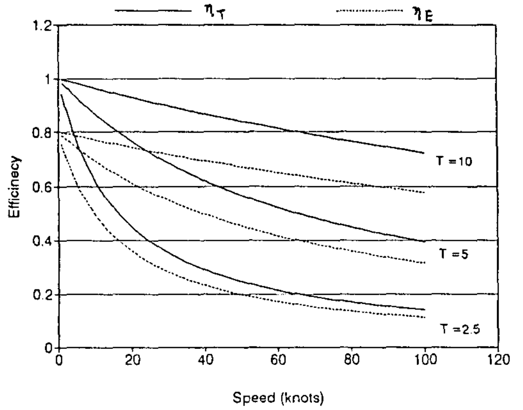

Fig. 5. MHD propulsion efficiency vs. speed. The electrical efficiency η_E and total efficiency η_T are shown as a function of speed in knots for Several values of magnetic flux density B. Values for η_E and η_T were caluclated from Eq.(12) for a model submersible with an electrode length of 140 m and a hydraulic efficiency η_H=0.8 (jet ratio, r=1.5).

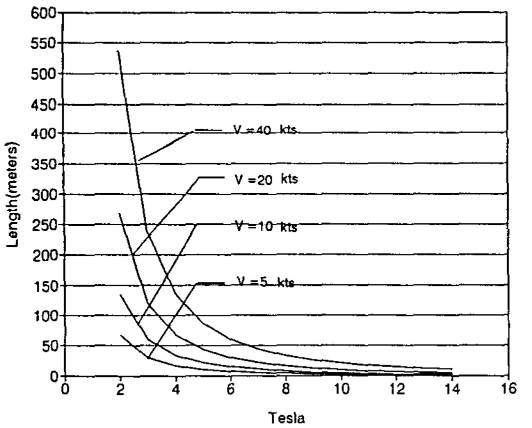

Fig. 4. MHD propulsion length vs. field strength for 50% electrical efficiency. The electrode length L is replotted from Fig. 2. as a function of magnetic flux density B with the speed as a parameter. Note the rapid increase in length at lower values of B.

$$K_D = \frac{1}{2} C_D \rho A_s \tag{19}$$

where C_D is the drag coefficient and As is the total cross sectional area for the vessel, then

$$(r-1) = C_D \frac{A_s}{2A_{in}} \; C_D \Gamma \tag{20}$$

3. Parameters for a model submersible

Values of the drag for a model submersible with a diameter of 10 m and an assumed drag coefficient of 0.05 are plotted in Fig. 2 as a function of the speed in knots (top scale) or the speed squared in meters per second (bottom scale).

The values for the drag and equivalent values for the thrust required to maintain constant speed were calculated from Eqs.(17)-(19).

The drag value calculated by Phillips[2], Doragh[3],and Hummert[7] correspond to values for the drag coefficient C_D of 0.05, 0.05, and 0.13, respectively. We adopt a value of C_D=0.05 for this study following Doragh, who considered a large number of factors in arriving at his estimate. The output power required to drive the model vessel at constant speed also is plotted in Fig. 2 as a function of the speed. The power levels are approximately the same as those given by Doragh[3], but are significantly lower than Hummert's values discussed above.

where $\Gamma = A_s 2A_{in}$

Substituting Eq.(17) in Eq.(12), η_E can be written

$$\eta_E = \left[1 + \frac{\rho}{\sigma B^2}\left(\frac{C_D\Gamma(C_D\Gamma+2)}{(C_D+1)}\right)\frac{V_{in}}{2L}\right]^{-1} \tag{21}$$

The term in parentheses scales as $C_D\Phi$ with a coef-

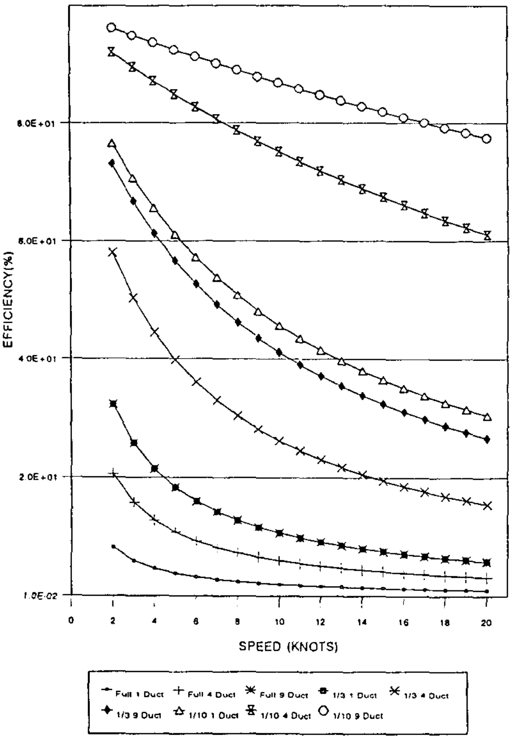

Fig. 6 Ideal efficiency vs. speed with 10 T magnetic flux densities: The importance of developing large-scale magnet systems with field strengths>5 T is illustrated in Fig. 6. The cross-hatched regions represent the range in parameters for magnetic flux density and speed-to -length ratio that were adopted by Doragh[3] and Hummert[7] in their studies. Also shown in Fig. 7 is the curve for an electrical efficiency of 50%, as calculated from Eq.(12), with a jet rato $r=1.5$.

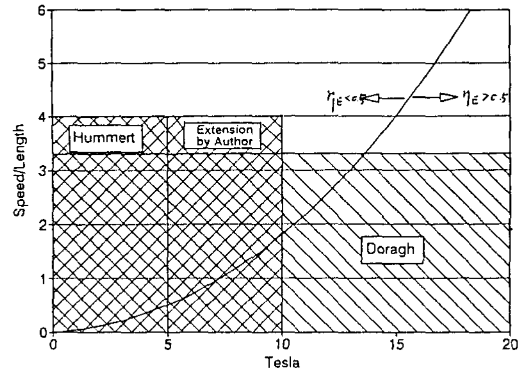

Fig. 7 MHD propulsion parameter ranges for calculated efficiencies.

ficient 2 for $C_D\Phi \ll 1$ and coefficient 1 for $C_D\Gamma \gg 1$. Reasonable values for the drag coeffi ecient C_D lie in the range 0.03-0.1. Therefore, to maintain the hydraulic efficiency at reasonable values, say, $\eta_H>0.8$, requires $\Gamma>10$ for a medium value $C_D \leq 0.05$. This corresponds to a cross-sectional area of the submersible that is about 20 times the pump-jet intake area. This corresponds to 2-m duct for a vessel with a 10 m diameter.

The last term in Eq.(12) or (21) scales as the speed divided by the length of the vessel (more properly, as the electrode length). This, the efficiency improves with increasing size, for any given speed, provided that the pump-jet volumes are increased proportionately. The length of electrode required to achieve an electrical efficiency of 50% is plotted in Fig. 3 as a function of the speed in knots. The electrode lengths are replotted in Fig. 4 as a function of the magnetic flux density B with the speed as a parameter. This figure shows that rather respectable efficiencies are achiveable for large submersibles (lengths > 100 m) for speeds of 40 knots and greater. High speeds require large fields, of the order of 5 T or greater.

Values for the electrical efficiency η_E and the total efficiency η_T for the model vessel described in Fig. 2 are given in Fig. 5 as a function of the speed in knots for several values of the magnetic flux density B. The figure shows that values for the total efficiency in excess of 60% are possible for speeds up to 70 knots, provided that magnetic flux densities of 10 T could be sustained over the required volumes. The corresponding speed for 60% efficiency is 29 knots for a 5 T flux densities. The efficiencies presented in Fig. 5 demonstrate the importance of developing practical magnet systems in the range 5-10 T in order for MHD propulsion to be feasible for vessels on this scale.

The author also confirmed that it will be necessary to adopt Superconducting MHD Propulsion Ship with the magnetic flux densities of 10 T to compete the conventional Propulsion Ship. The necessity of MHD efficiency with the magnetic flux densities of 10 T is illsutrated in Fig. 6. The electrolysis of seawater with consequent generation of hydrogen and chlorine gases was addressed by Phillips[2], Doragh[3], and Hummert[7]. All of the authors concede that the generation of gases and erosion of electrodes ard detrimental side-effects to MHD propulsion, but do not consider either to be a factor limiting feasibility. Magnetic signature may also be a concern, but proper magnet design and shielding could minimize the problem. Higher current densities, of the order $10^9 A/m^2$ or greater, at fields of the order of 10 T, will be required for MHD propulsion to become practical for high-speed vessels.

4. Conclusions

MHD propulsion systems have potential advantages for submarines which could lead to revolutionary advances in marine propulsion. Perhaps the most significant of these features is the potential for quiet and efficient operation at speeds that would not be possible with conventional propeller-driven vessels. The scaling reactions for MHD pump-jets indicate that the efficiency of MHD propulsion units scales inversely with the ratio of speed to pump length; therefore, such units become more efficient for larger vessels. Electrical efficiencies of 80% or more are possible at speeds of the order of 60 knots for pump-jets 100 m in length with the magnetic flux denisities of 10 T.

The actual dependence of the efficiencies on the size, speed, and conductivity is beyond the scope of this study and would require more extensive calculations of the MHD equations for specific geometries with consideration of the finite diffusion velocity of the magnetic field through the conducting medium. In order for MHD propulsion systems to become feasible, it will be necessary to develop practical magnet materials and systems capable of producing fields in the range of 5-10 T over volumes of the order of 100 m^3. The recent discovery of new classes of superconducting materials with critical temperatures well above liquid nitrogen temperatures could lead to revolutionary advances in large-scale electrical machinery and magnet systems.

References

1. W. A. Rice: US patent 2997013 (1961).
2. O. M. Phillips: J. Ship Res., 43 (1962).
3. R. A. Doragh: "Magnetohydrodynamic Ship Propulsion Using Super-conducting Magents", SNAME Annual meeting, New York (1963).
4 S. Way: "Electromagnetic Propulsion for Cargo Submarines", Journal of Hydronautics, **2**(2), 49 (1968).
5. Y. Saji., M. Kitane, and A. Iwata: "Basic study of Super-Conducting Electromagnetic Thrust Device for propulsion in Seawater", Advanced Cryogenic Engineering, **23**, 159 (1969).
6. A. Iwata, Y. Saji, and S. Sato: Proc. ICEC **8**, 775 (1980).
7. G. T. Hummert: "An Evaluation of Direct Current Electromagnetic Propulsion in Seawater", ONR-CR-168-007-1 (1979).
8. Y. K. Kong, Y. S. Kim, and C. J. Noh: "Marine MHD Propulsion System", The Korean Society of Marine Engineers, Spring meeting, 20 (1991).
9. Y. K. Kong, T. I. Choi, Y. S. Kim, and C. J. Noh: "A Study on Mangetohydrodynamic Porpulsion System (I)", The Korean Institute of Electrical Engineers, Summer meeting, 69 (1991).
10. Y. K. Kong, T. I. Choi, Y. S. Kim, and C. J. Noh: "A Study on Magnetohydrodynamic Propulsion System (II)", The Korean Institute of Electrical Engineers, Summer meeting, 114 (1992).
11. Y. K. Kong, T. I. Choi, Y. S. Kim, and C. J. Noh: "Magneto-hydrodynamic Propulsion System with Super Conducting Magnets", The Korean Society for Energy Engineering, Autumn meeting, 35 (1992).
12. V. L. Streeter: "Handbook of Fluid Dynamics", McGraw-Hill, New York (1961).