STM JOURNALS

Trends in
Mechanical Engineering & Technology

https://journals.stmjournals.com/tmet

ISSN: 2231-1793 (Online)
ISSN: 2347-9965 (Print)
Volume 15, Issue 1, 2025
January–April
DOI (Journal): 10.37591/TMET

Review TMET

# Silent Submarine Propulsion with High-Efficiency Magnetohydrodynamic Drive

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## Abstract

*Magnetohydrodynamic (MHD) propulsion is an exciting technology that can be easily incorporated into a new submarine or existing one can also be upgraded by replacing the propeller drive with a MHD drive without difficulty. This new technology would provide many advantages like a stealth operation, no cavitation, greater maneuverability, increased payload, addition of an emergency drive system, etc. The design of an MHD motor is very simple and consists of superconducting magnetic coils made of NbTi wire with copper cores wound in the shape of a saddle and mounted on a hollow duct fixed to the hull of the watercraft. The superconducting magnetic coils can circulate a very large current producing a very strong magnetic field. After the current in the superconducting coils is established the power supply can be theoretically cut off when the current circulates indefinitely because resistance is nil. The coils are to be submerged in liquid helium to cool the same to -269°C, a few degrees above absolute zero enabling the coils to have superconducting properties. The MHD motor suspended from the hull of the submarine applies a very strong external electromagnetic field to the conducting seawater present in the hollow MHD duct and simultaneously a strong electric field is applied causing a very high current to flow through the conducting fluid generating Lorentz force. The excited Lorentz force applied on the conducting seawater pushes the seawater from the inlet duct to the outlet nozzle and propels the marine vessel by reaction. Key performance factors that affect the power output and efficiency of MHD drive are mainly the generation of magnetic field and electrical conductivity of seawater. The conductivity can be increased locally by the seeding process by the addition of alkali or acid to seawater that reduces the ohmic loss but at the cost of pollution to the marine environment.*

**Keywords:** Magnetohydrodynamic, superconductor, seeding, ReBCO, tesla, Reynolds number

## INTRODUCTION

The idea of using magnetohydrodynamic (MHD) propulsion for ships and submarines has been investigated by many researchers since 1960 and has been found to have many advantages and merits. However, the implementation of this concept is dependent on the development of magnets with a high magnetic flux density, which in recent years can be made economically because of the discovery of high-temperature superconductors. MHD propulsion can be used to propel a ship or submarine by ionizing fluid, such as salty seawater, and intelligently controlling its characteristics with magnetic and electric fields. The system is guided by the principle of the Lorentz force, which propels the vehicle forward.

The potential benefits of this radical technology are mainly noise reduction, as no propeller is required to support conventional propulsion, which is a major source of noise and can be easily detected by using active and passive sonar, which can be operated at higher speeds because an MHD thruster, unlike a propeller, is not cavitation-limited and has enhanced maneuverability through the use of

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Received Date: February 26, 2025
Accepted Date: April 11, 2025
Published Date: April 28, 2025

**Citation:** Rathindra Nath Biswas. Silent Submarine Propulsion with High Efficiency Magnetohydrodynamic Drive. Trends in Mechanical Engineering & Technology. 2025; 15(1): 41–55p.

vectored thrust. The USA, Russia, and China have developed quieter and harder-to-detect submarines with magnetic propulsion systems. The U.S. Navy June 2022 has been reported to have fitted the MHD drive to a Virginia Class Submarine, USS Montana (SSN 794), as shown in Figure 1, which may make this vessel virtually undetectable by passive sonar, as there are no moving parts, such as the propeller [1–3]. Hence, the only way to increase the efficiency of the MHD drive is to enhance the magnetic field intensity by using improved superconducting coils made from high-temperature superconducting (HTS) coils made from rare-earth barium copper oxide (ReBCO) or other HTS materials developed recently. The use of these materials would reduce the weight of the magnet by 43% and increase the magnetic field to 20 T (Tesla). Furthermore, as HTS coils can be operated at a much higher temperature, liquid nitrogen can be used instead of liquid helium, which is a much more cost-effective cryogenic medium. It is to be noted that for operating a marine vessel in practical application required magnetic flux density should be higher than 5T(Tesla). In the near future, watercrafts using HTS superconductors in MHD propulsion systems will be used extensively because they are cost-effective and highly efficient.

## BROAD PARAMETERS OF USS MONTANA (SSN-794)

Class and type: Virginia Class submarine, Displacement: 7800 tons, Length: 115 m, Beam: 10.4m, Draft: 9.8 m, Propulsion: Nuclear with 30 MW: S9G reactor, Speed: 25 knots (46 km/h), Endurance: Can remain undersea for 3 months, Test depth: more than 244 m, Manning: 15 officers + 120 enlisted men, Armaments: 12 Vertical Launch System tubes, four torpedo tubes for Mk-48 torpedoes, UGM-109 Tomahawk cruise missile, Construction started in May 2015 and commissioned on June 25, 2022, estimated cost: $4.3 billion. Annual operating cost: $50 million per unit (in 2012 prices). A typical arrangement of a Virginia Class submarine fitted with an MHD drive is shown in Figure 2. The engine room might have been provided with turbines, electric generators, electrical control systems, cryogenic equipment for superconductors, and so on.

### Mechanism of Noise Generation

In conventional submarines, cavitation noise generated by an underwater rotating propeller is generally the main source of signature noise. When a propeller rotates rapidly in the vertical position, bubbly cavitation is formed on the blade tip region. With a further increase in rpm, there is a reduction in pressure, which develops into cloud-type cavitation with violent bursts owing to bubble collapse, as shown in Figure 3, thus generating cavitation pressure pulses in water, which are broad bands in nature. These pulses from the propeller are transmitted to the hull of the submarine via coupling and power transmission systems and excite the vessel and its structure to vibrate. Thus, the excited vibration is transmitted back into the water as an acoustic pressure pulse again as engine noise or propeller noise.

USS Montana (SSN-794), Latest of Block IV Virginia Class
Rolls Out into Drydock

**Figure 1.** Submarine USS Montana.

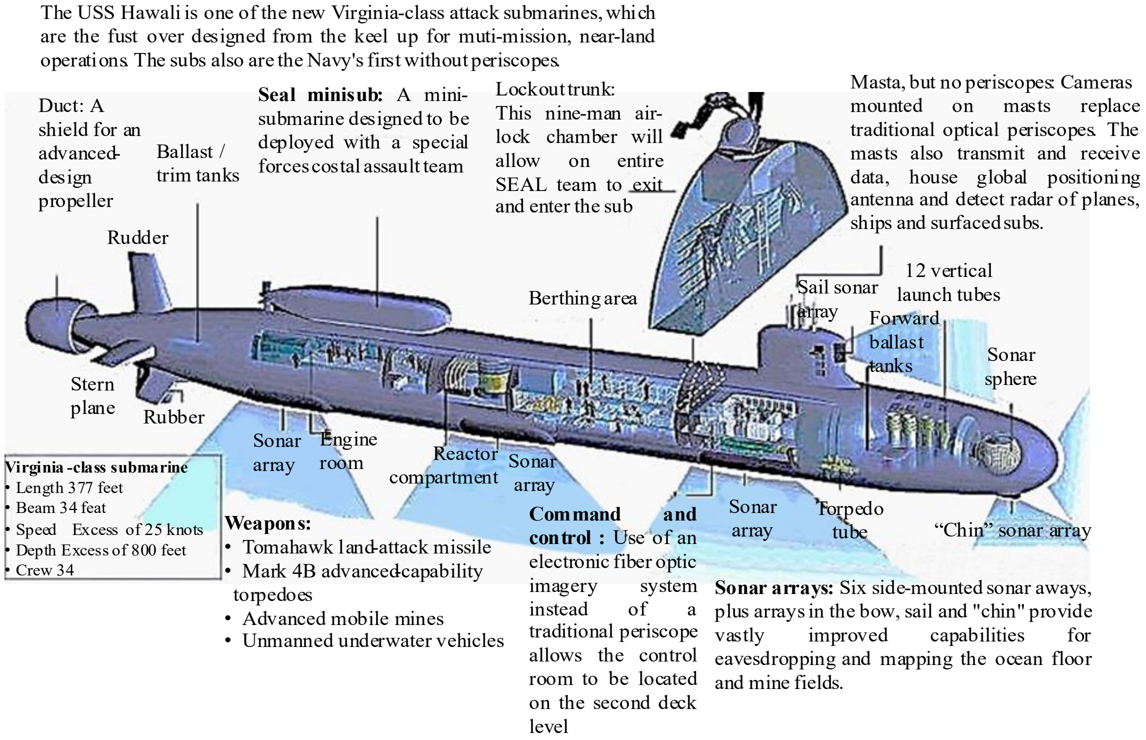

**Figure 2.** Typical arrangement of Virginia Class Submarine fitted with MHD drive.

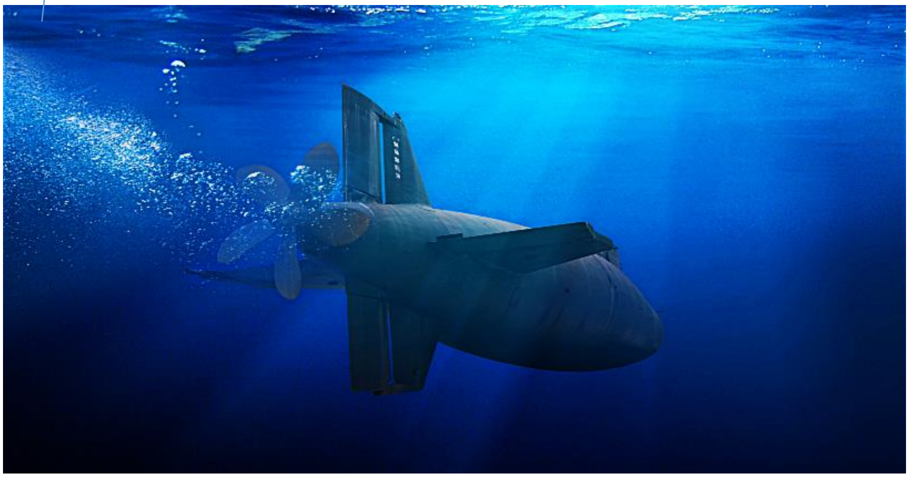

**Figure 3.** Propeller noise due to the formation of cavitation.

Passive sonars provided on a surface ship listen to propeller noise or engine noise and can determine the location and direction of the submarine. Replacing the propeller drive with magnetohydrodynamic propulsion is the only solution to eliminate cavitation noise, which would make the naval vessel stealthy and lethal because there are no moving mechanical parts in the Magnetohydrodynamic (MDH) drive.

## BASIC PRINCIPLE

The MHD drive operates based on a simple principle. Magnetohydrodynamic propulsion thrusters use magnetohydrodynamic forces generated by sending an electric current under the influence of a very strong magnetic field created by superconducting magnets in salty seawater. Superconducting magnets were fixed to the hull of a marine vessel. When an electric current passes through seawater at a right angle to the magnetic field, an electromagnetic force termed the Lorentz force acts on seawater. This force is perpendicular to both the magnetic field and electric current. As a reaction force to this Lorentz force, a propulsion force is generated due to the movement of the conducting fluid, such as seawater.

The fluid moves owing to the Lorentz force without any need for moving components such as a propeller. As the system is fixed to a ship or submarine, the watercraft is free to move in water with minimal resistance to motion. According to Newton’s second law of motion, a vessel recoils and moves in the water. A schematic of a simple MHD thruster is shown in Figure 4. The propulsion unit mainly consists of an inlet nozzle with a flow guide, positive and negative electrodes, superconducting magnets, a flow channel, an outlet duct, and connected electrics, all of which are shielded in an anticorrosive housing attached to the hull.

## MHD Propulsion Process

The MHD propulsion system is a futuristic technology that has caught the attention of scientists since the 60s because it does not require any mechanical components but relies on electromagnetism and fluid dynamics to generate thrust. At the core of marine MHD propulsion is the use of conductive seawater, which can conduct electricity. Next, magnetic fields and electric currents play their roles. The core principle is that when a magnetic field interacts with a conductive fluid, such as seawater, through which electric current is passing, a force is generated, known as the Lorentz force, which is the key driver of MHD propulsion. According to the right-hand rule of electromagnetism, the generated force is perpendicular to both the direction of the electric current and the magnetic field. The perpendicular force created the thrust necessary to propel the vessel. Figure 4 illustrates the operating principle. Under the influence of strong magnetic field **B** generated by superconducting magnets**,** seawater through which electric current is passed from the electrodes experiences Lorentz force **F** which is generated by the interaction of the magnetic field and electric field, both of which are at right angles. Under the influence of the Lorentz force, seawater ejects from the rear of the marine vessel, which, according to Newton’s Third Law, generates an equal and opposite force that moves the vessel forward. A ship or submarine may be provided with one or more MHD propulsion systems, while the latter provides better maneuverability [4].

Generally, the magnet constitutes 20% of the thruster mass, and the remaining mass comprises structural bracings to fix the thruster to the hull such that the thruster does not fly apart. A field strength of approximately 10 Tesla may be required, which can be achieved by using modern HTS. The basic principle of operation of an MHD propulsion system is shown in Figure 5.

## Configuration of Thruster Drive

Three magnetic coil configurations are generally considered: saddle-type, racetrack toroid, and solenoid types. The weight, efficiency, and leakage characteristics of the superconducting magnet must be carefully analyzed to design the optimal magnetic coil configuration of the MHD thruster. Because the conductivity of seawater is not high, a large current and strong magnetic field are required to obtain a larger driving force.

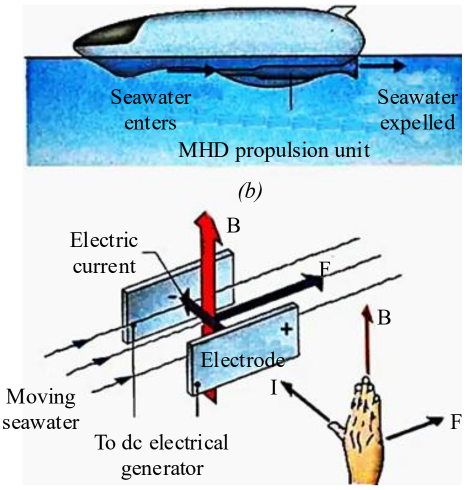

**Figure 4.** Scheme showing the working of MHD drive.

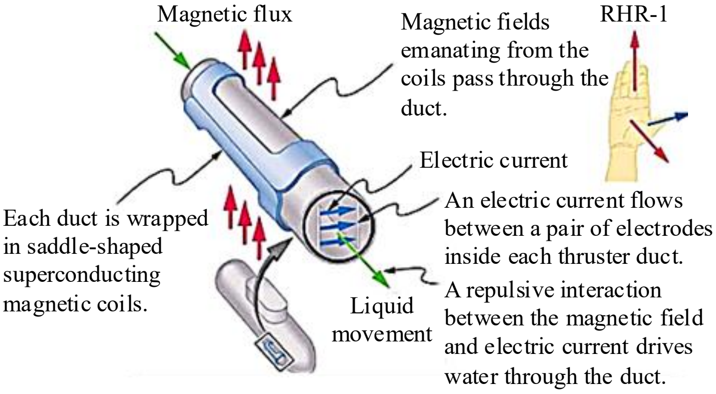

**Figure 5.** Basic principle of working of MHD propulsion.

According to theoretical calculations, a practical submarine requires a magnetic flux density above 5 Tesla. An ordinary electromagnet is saturated at approximately 1.5T and therefore, it is unsuitable. Superconducting magnets must be used to obtain such a high magnetic flux density. A superconducting magnet is a superconducting hollow coil without an iron core, and it is made of a high-temperature superconductor wire. The ideal superconductor resistance is zero, so the coil can circulate a large current producing a super-strong magnetic field. Once the current in the superconducting coil is established and, thereafter, if the power supply is cut off, the flow of current in the coil will circulate indefinitely because there is no resistance in the circuit, and the magnetic field generated would also remain eternal.

## Saddle-Shaped Straight-Tube MHD Thruster

One popular configuration is a straight-tube saddle-shaped superconducting MHD, as shown in Figure 6, which consists of a straight pipe through which seawater ejects out, and two saddle-shaped coils above and below the pipe to generate a super-strong magnetic field in the pipe. There were electrode plates on the face walls on both sides of the pipe, and the electrode plates were connected to the external power supply through the bus bar. Figure 7 shows the cross-section of the saddle-type MHD thruster, in which the azimuth layout of the coil magnetic field and electrodes are represents [5].

Because the superconducting coil must operate at a very low temperature, the coil is soaked in liquid nitrogen. The superconducting coil is wrapped in an outer cover with excellent thermal insulation. There is also a magnetic shield in the outer cover to reduce the leakage of the magnetic fields.

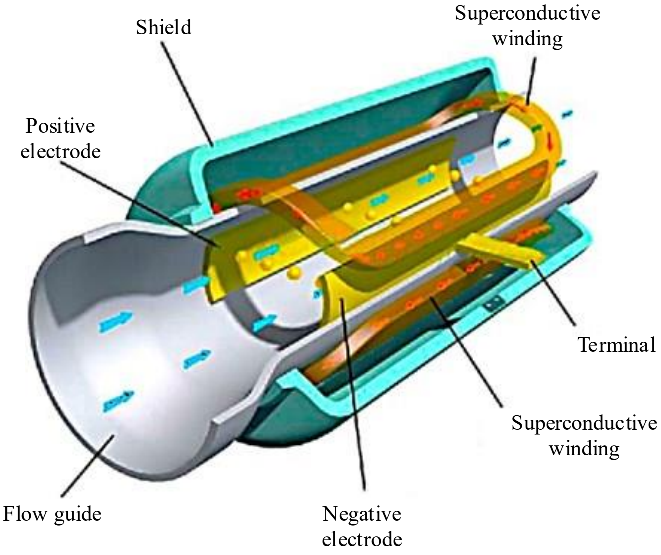

**Figure 6.** Saddle-type thruster.

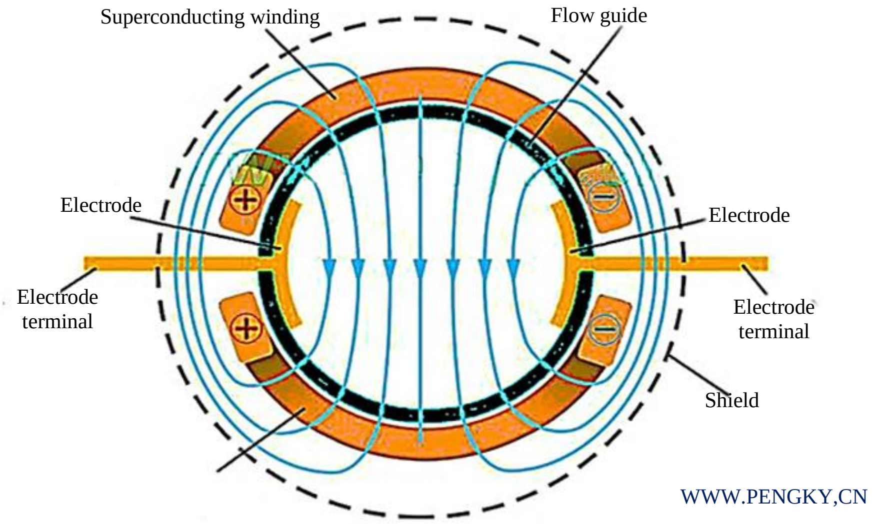

**Figure 7.** Cross-section of saddle-shaped straight-tube MHD thruster.

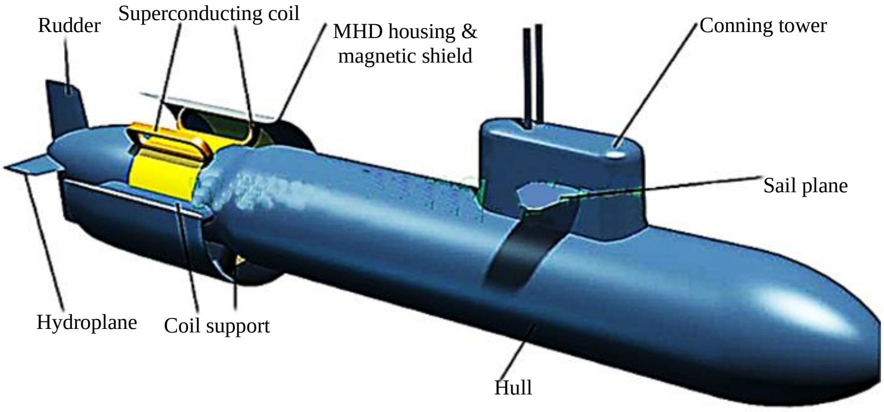

**Figure 8.** Submarine propelled by straight-tube toroidal MDH drive.

## Straight-Tube Toroidal MHD Thruster

Figure 8 shows a schematic diagram of a submarine propelled by a straight-tube toroidal superconducting MHD thruster that pushes seawater backward, and the forward reaction moves the vehicle forward. The magnet coils are runway-shaped superconducting coils and, in a typical submarine, six coils with cryogenic cooling arrangements may be provided. Six coils are installed on the outer circumferential surface of the submarine hull in the form of a ring, as shown in Figure 9. The inner electrode plate, which is connected to the positive terminal of the power supply, is fitted to the inner side of the ring formed by the superconducting coil on the top of the hull of the vessel. All six individual coils, including the cooling arrangement, were housed on a robust protection cover, and the positive and negative electrodes of the thruster were provided with a containment cover (cowl).

The superconducting coils installed inside the coil housing were filled with liquid nitrogen, enabling it to remain at a very low temperature. The coil housing was robust and attached to the thruster cowl to act as structural support. When a magnetic field is applied, seawater flows through the annular space between the submarine hull and thruster cowl under the action of Lorentz force and propels the watercraft.

Figure 10 shows the scheme of an MHD thruster in which when the superconducting coil starts to run, a magnetic field (light blue annular line) is generated in six coils. This diagram also shows the direction of the flow of current (red) and the resulting water flow (green) due to the Lorentz force [6, 7].

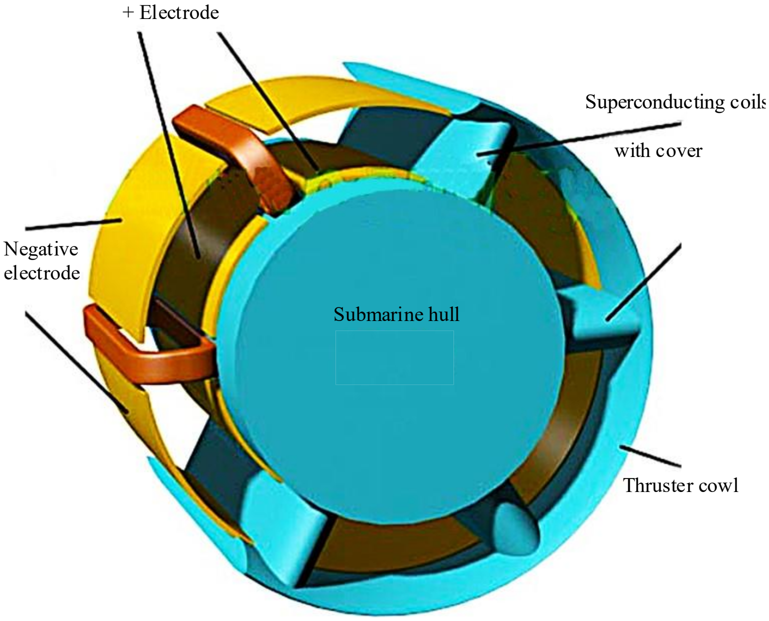

**Figure 9.** The general arrangement of toroidal superconducting MHD thruster.

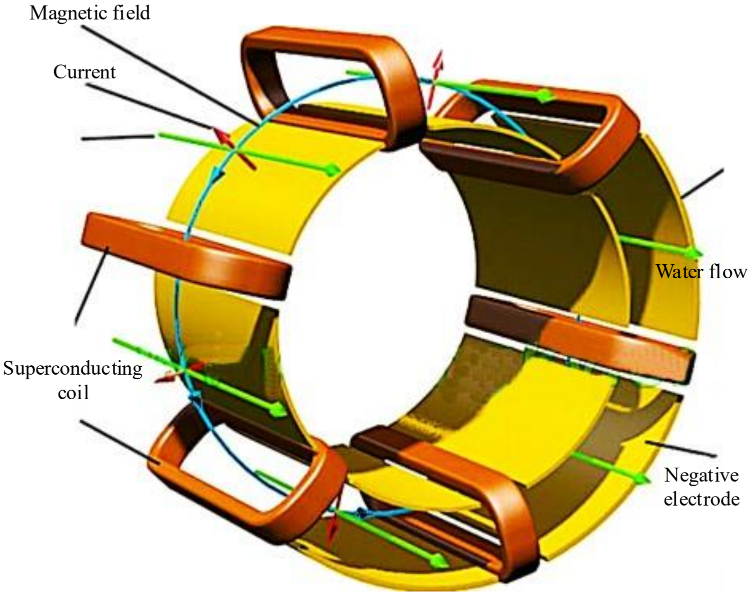

**Figure 10.** The diagram shows the magnetic field, current, and water flow in the MHD drive.

## Helical Type MHD Drive

In addition, to linear channels, helical channels can also be used in MHD thrusters. The helical channel system utilizes a helical channel and solenoid superconducting magnet. A solenoid magnet can realize a high-field and high-temperature hole size. The helical channel improves the effective length of the electromagnetic force and thrust density. The helical MHD comprises axial inlet and outlet insulating walls, cylindrical inner and outer electrodes, an inlet flow guide, helical blades, and rectifiers, as shown in Figure 11. The inlet flow guide changes the axial flow into a helical flow, and the rectifiers change the helical flow into an axial flow; thus, these are designed with precision. If the inlet flow guide has a deficiency in the conversion of axial flow into the spiral flow and the outlet rectifier flow guide is unable to convert spiral flow into axial flow effectively, then there will be significant hydraulic loss that would jeopardize thrust generation and the overall efficiency of the system. The solenoid superconducting magnet generates an axial magnetic field and current along the radial direction and generates an electromagnetic force in the circular direction that forces water to flow along the helical blade, as shown in Figure 12. The superconducting magnet also produces large magnetic leakage in the axial direction, which is a cause for concern [8].

**Superconducting Magnet and Power Supply**

For practical applications, an increased propulsion efficiency should be attained. There are mainly two routes to increase efficiency, either by increasing the conductivity of the medium or by increasing the magnetic field strength. Seawater conductivity can be enhanced using a seeding procedure. However, this is undesirable, as seeding materials are to be stored, which would considerably increase the weight and consume a lot of valuable space. Furthermore, it pollutes the environment. It also leaves a trail of highly conductive fluid. Therefore, the only course of action to increase propulsion efficiency is to increase the magnetic field strength. Research work and field trials have shown that the propulsive efficiency of a vessel operating at 10 knots using a 0.6 Tesla magnet is only 8%. However, the same vessel using 10 T would have a 60% efficiency at 10 knots. The Japanese ship Yamato-I, with an MHD drive with a displacement of 185 tons and a design speed of 8 knots with 4 Tesla low-temperature superconducting magnets, managed to reach a speed of 6.6 knots at 30% propulsive efficiency. MHD drives used for marine propulsion generally use niobium-titanium fibers in an aluminum or copper matrix and are made in the form of wires for superconducting magnets. Its critical temperature is approximately 10 Kelvin when it starts superconducting and can generate strong magnetic fields up to 10 Tesla.

Another option is to use niobium-tin superconductors alloyed with hafnium or zirconium, which increases the maximum current density in a magnetic field and may be used for the fabrication of supermagnets for generating magnetic fields up to 16 Tesla. Its critical temperature is 18.3 Kelvin. However, they are brittle and difficult to manufacture. To overcome this problem, composite wires containing Nb in a copper-tin bronze matrix were drawn and heat-treated.

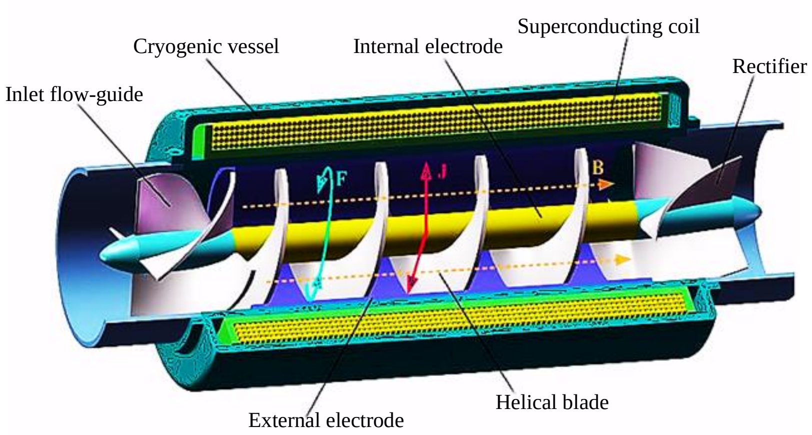

**Figure 11.** Cutaway view of helical MHD thruster.

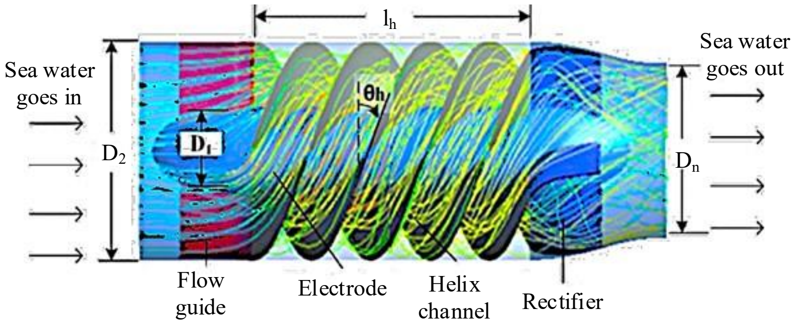

**Figure 12.** Water flows in a helical MHD thruster.

Most superconductors must be cooled down to temperatures of only a few Kelvin above absolute zero to make them superconducting. However, cooling with liquid helium is a costly and complicated process that limits the practical use of this technology. In recent decades, tremendous research has been conducted to produce materials that become superconductors at transition temperatures as high as 138 K, which is much higher than the boiling point of liquid nitrogen. The economic potential of this new class of materials, known as high-temperature superconductors (HTS), is immense. Liquid helium is used to cool conventional superconductors and has a boiling point of 4 K. It costs about $20/l. Liquid nitrogen can be used to cool HTS. It boils at 77K and only costs about $0.20/L. The storage and production of liquid nitrogen on board of a submarine is quite simple and can be operated economically. In recent years, HTS made from ReBCO materials have been developed. The most remarkable member of this class of materials is yttrium barium copper oxide (YBCO), a superconductor with a critical temperature of 93 K, which is higher than the boiling point of liquid nitrogen (77 K). Therefore, cryogenic equipment to cool superconductors would be much simpler and economical, as no helium is necessary and liquid nitrogen can be used. These magnets can generate very high magnetic fields of up to 32 Tesla in the laboratory under ideal conditions. Superconductors exhibit no dissipation loss at constant currents or magnetic fields. However, during operation, transients in the current and magnetic fields dissipate as heat. Considering these losses, the MHD drive with YBCO superconductors may be able to generate a magnetic field of 20 Tesla; such an MHD drive can easily be operated at 90% efficiency. ReBCO superconductors are brittle. However, since 2010, a new technique has been developed to manufacture bendable tapes of ReBCO that do not break easily. It has four main layers: the substrate, buffer layer, superconducting layer of ReBCO, and silver cap. These superconductors are generally termed quasi-two-dimensional materials. All that is needed for a material to be termed quasi-2D when one of its dimensions becomes thin enough to cause quantum confinement of its charge carriers (electrons and holes). The specific thickness required to confine the charge carriers depends on the materials used, and such confinement occurs at 40 atomic layers. Their superconducting properties are determined by electrons moving within the weakly coupled copper oxide layers. Ions, such as barium and strontium, populate the neighboring atomic layers to stabilize the structure and dope electrons or holes onto the copper oxide layer. YBCO superconductors are likely to be deployed in the near future in applications such as watercraft, maglev trains, particle accelerators, and MRI machines. While YBCO has impressive benefits over traditional materials, its utilization in widespread applications is still under development, largely due to the challenges associated with its synthesis and integration with devices. Other promising HTS cuprates are BiSrCaCuO with a critical temperature of 133 K and HgBaCaCuO with a $T_C$ of 133 K.

## Advantages

As there are no moving parts in the MHD device, it experiences minimal wear and tear, leading to a long life and minimal maintenance. Traditional propellers can be noisy because of the generation of bubbles and their mechanical components. The MHD operates silently and efficiently. Hence, they can be used for the propulsion of marine vessels, making them stealthy. This has potential military applications, particularly for submarines.

## Disadvantages

MHD drives using conventional superconductors for the generation of strong magnetic fields are cooled at a very low temperature with liquid helium to reach the critical temperature, which is costly. However, this problem can be addressed using HTS.

Superconductors are difficult to shape because they are brittle. In the presence of a magnetic field within a certain range, superconductors lose their properties and require optimization. This can be achieved by operating the drive at the optimum current level, avoiding transients, controlling eddy currents, Hall effects, resistivity contributions from the induced electric field, maintaining constancy of the magnetic field, etc. However, these steps are technologically challenging and energy-intensive. When current flows through the saltwater in an MHD, hydrogen, oxygen, chlorine, and other gases are formed as bubbles on the electrode surface due to electrolysis. Chlorine corrodes the electrode surface and flow channel. These bubbles impair the efficiency of the system and should be addressed. Bubble generation is a serious issue because bubbles formed on the electrode surface can isolate the electrodes from the conductive solution, which may result in total failure. To address this problem, microscopic, engineered defects or pits may be formed on the electrode surface far from the active surface. During electrolysis, bubbles preferentially form on these engineered defect areas away from the active surface, enabling an unobstructed flow of current for propulsion. The loss mechanisms affecting the performance of the MHD seawater thruster system were identified. These are mainly jet and nozzle losses, Joule heating losses, surface potential and electrochemical losses, frictional losses, and electrical-end losses. At high magnetic Reynolds numbers, MHD-driven flows can experience instabilities. These instabilities must be managed crucially for efficient operation [9].

## The Yamato-I

In 1990, Mitsubishi Heavy Industries, Kobe, Japan built a ship called Yamato-1, which uses an MHD drive driven by liquid-helium-cooled superconductors. It was the first working prototype of her kind, with two magnetohydrodynamic thrusters hanging on the two sides of the vessel, which have no moving parts and were successfully operated in 1992. To keep the superconducting electromagnets cold, they were vacuum-sealed in a chamber filled with liquid helium. Each MHD thruster was provided with six identical tubes, 250 mm in diameter, placed circumferentially like the drum of the revolver. Each tube was wrapped by a superconducting coil of niobium-titanium filament wire alloy with a copper core and envelope, and the coils were placed inside stainless steel containers filled with liquid helium to cool the coils at -269°C to bring it to the superconducting state. The prototype is 30 m long, has a beam of 10.39 meters, a draft of 1.5 meters, a displacement of 185 tons, a capacity of 10 people, and can travel at 15 km/h (8 knots) max. The superconductors used in this prototype vessel used helium to cool it could generate a magnetic field of 4 T, and was quite heavy, which imposed a constraint to reach a higher speed. A higher magnetic field could not be generated because HTC was not discovered at that time. The schematic arrangement of Yamato-I is shown in Figure 13.

## DESIGN CRITERIA OF MHD

It has been found by researchers during investigation in the laboratory that out of three types of MHD thruster configurations, namely the inner ducting type (Figure 6), the annular type (Figure 9), and the pod mount type (as used in Yamato-I ship), the inner ducting type shows the highest propulsive efficiency because in this case a larger amount of electromagnetic field can be induced and because the amount of frictional surface area per unit volume of fluid in the channel is less. The annular ducting type exhibits the lowest efficiency owing to the space limitation of the superconducting magnets. However, this arrangement, as shown in Figure 9, with separate flow channels, provides the ability to steer and maneuver the watercraft by individually controlling the thrust of the channel. The pod-mounted type exhibits a slightly lower propulsive efficiency than the inner ducting type because it has a short hydraulic duct, which means lower drag, but it also causes a reduction in the amount of electromagnetic field, and consequently, the electrical efficiency becomes lower [10].

The electrical conductivity of seawater varied from 4 to 5.1 S/m. Hence, when an electric current is passed between the electrodes of the MHD thruster, it heats the seawater, and there is considerable power loss. Electrical efficiency $\eta_e = P_w/P_e$, where $P_w$ is the mechanical power imparted to the seawater, and $P_e$ is the electrical power supplied to the MHD thruster. When $P_w$ is optimized, $\eta_e$ is equal to 0.5, which means that 50% of the electrical power is lost as heat by ohmic loss. While designing a thruster, this should always be considered.

The velocity and efficiency performance of marine vehicles using such propulsion technology depends linearly on the electrical conductivity of the seawater and the square of the magnetic field strength (B). As the electrical conductivity of the medium has many constraints, such as space limitations and environmental hazards, it is the only option to increase the magnetic field. The new generation HTS can potentially achieve magnetic fields of approximately 20 Tesla operating at 125 K, which is well above the boiling point of liquid nitrogen at 77 K. The cryogenic cooling of HTS with liquid nitrogen has many advantages, such as being much cheaper, can be manufactured on board, and commercial insulation can be used. The cryogenic equipment for nitrogen is smaller, lighter, and more efficient than that required for liquid helium. This simplifies the logistics of operation and maintenance [6]. Test results by simulation by the software COMSOL on a rectangular thruster model 1750 mm long, with a cross-section 340 × 340 mm, current density 2.2 kA/m$^2$, 17T, and consuming 226.4 kW input power for magnetic field generation in seawater can produce 44 kW of thruster power and can generate about 10.6 m/s flow, which means about 20% efficiency.

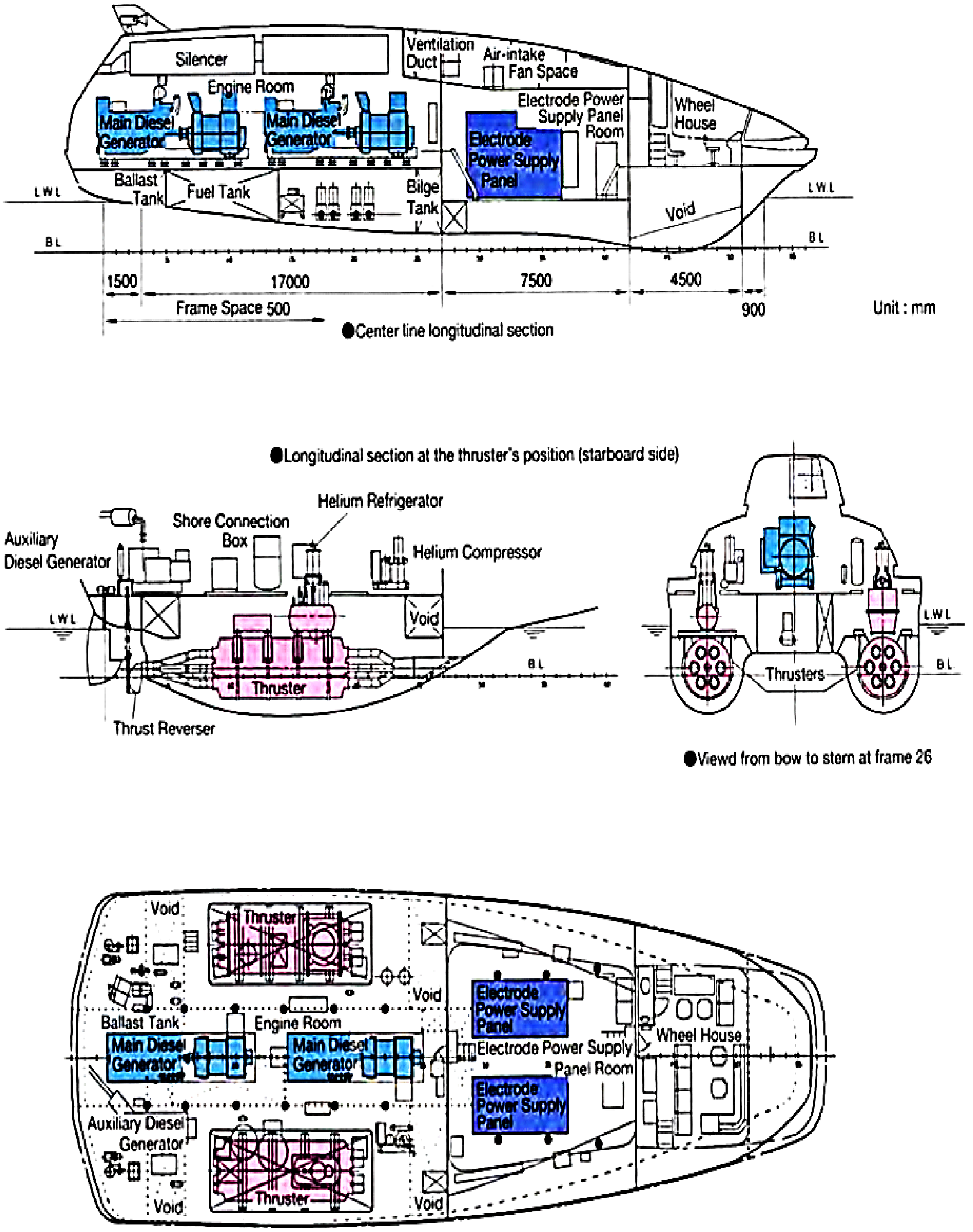

**Figure 13.** Schematic arrangement of Yamato-I.

In another investigation conducted through a 3D simulation using COMSOL software in a research establishment in Teheran to assess the performance of a marine MHD thruster, it was shown that only a magnet with a very large magnetic field using a superconducting electromagnet can increase the efficiency of propulsion to an acceptable limit. The geometry of the thruster model is shown in Figure 14, with a length of 1750 mm, a square cross-section of 340 × 340 mm, and an electrode length of 1250 mm. One electrode was grounded, and the other electrode potential was varied from 0 to 500 V. Seawater with conductivity of 4–5 S/m was used.

Figure 15 shows a graphical representation of the relationship between thruster efficiency, magnetic flux density, and electrical conductivity of seawater at a velocity of 6 m/s. It can be seen from the graph that the thruster efficiency increases with increasing magnetic flux density and electrical conductivity of seawater up to a certain limiting point, after which the thruster efficiency becomes saturated.

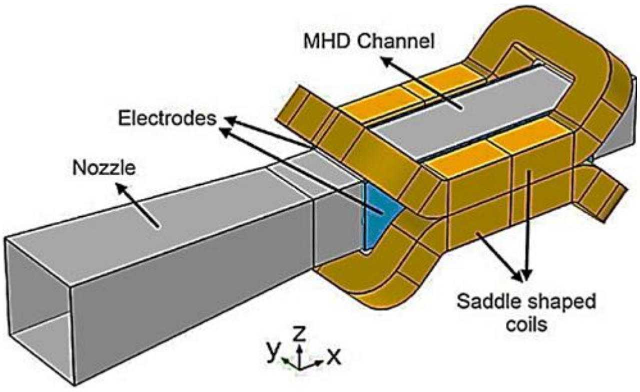

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**Figure 14.** Geometry of MHD thruster model.

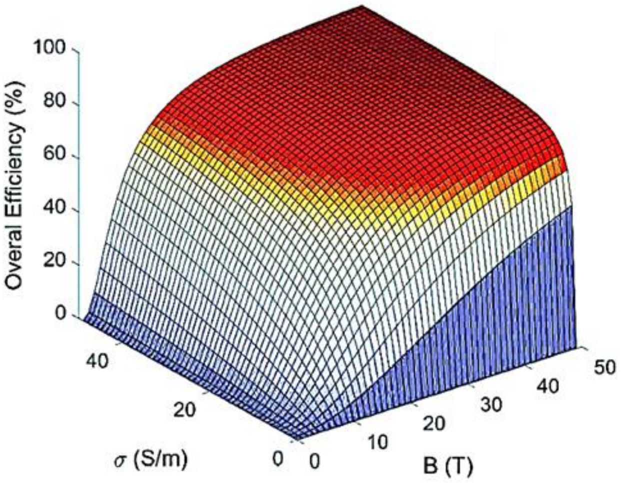

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**Figure 15.** Thruster efficiency as a function of magnetic flux density and seawater conductivity.

The performance of the model of the MHD with respect to different magnetic fields ‘B’ is shown in Figure 16. When the voltage was increased, the magnetic field was enhanced, thereby increasing the magnetic flux density and fluid velocity in the MHD channel, as shown in Figure 16(a). Figure 16(b) shows how the overall efficiency of the thruster increases significantly with the enhancement of the magnetic flux density. Figure 16(c) represents the net force of the MHD thruster as a function of the total electric current of the electrodes for different magnetic flux densities. According to this graph, the net force of the MHD thruster increases with an increase in the magnetic flux density. Figure 16(d) shows the various components of the thruster power at different flux densities and a fluid velocity of 6 m/s. The curve shows that the electrochemical and ohmic losses were inversely proportional to B and $B^2$ respectively. Furthermore, the electric current density decreases with the magnetic flux density, which leads to a reduction in the end losses [11].

## Design Features for Optimization

To achieve higher efficiency, high-speed MHD thrusters are operated under optimum conditions by controlling the design parameters.

While fixing the operating parameters the following points are to be kept in mind:

Increasing the magnetic flux density increases the electrical efficiency. However, higher magnetic forces on the windings that are proportional to $B^2$ require a robust structure to support the coil, which increases the weight and drag of the thruster assembly. To obtain the same efficiency as conventional propellers, the MHD thrusters of a small commercial vessel may require compact and light generators of approximately 10 T, which is possible to manufacture, although difficult.

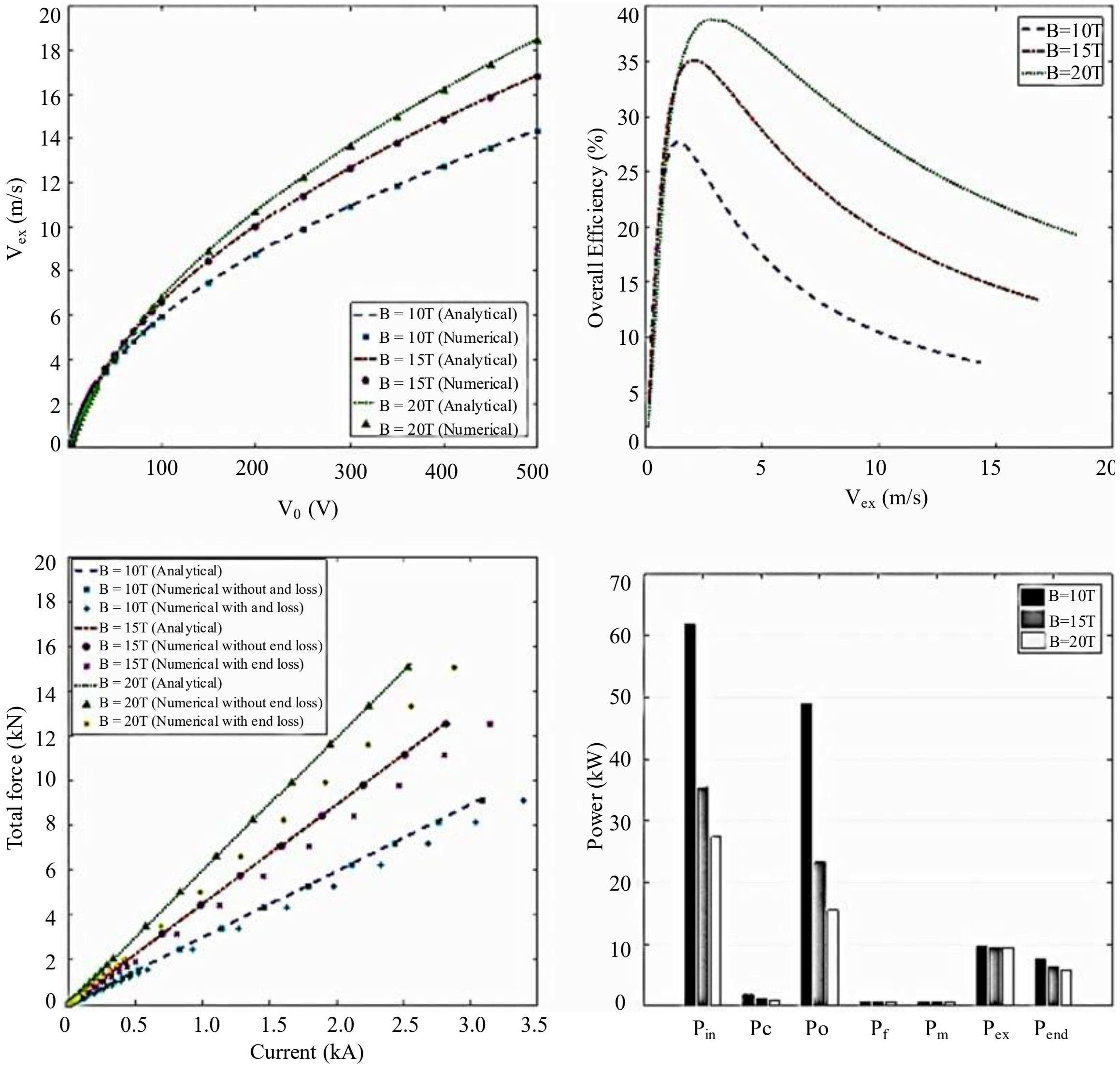

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**Figure 16.** Performance of MHD thruster at different magnetic flux densities.

*$P_{in}$ – Input electric power to the thruster, $P_c$: Electrochemical loss, $P_o$ – Ohmic loss, $P_f$: Friction loss, $P_m$: Minor loss due to gradual contraction of the nozzle, $P_{ex}$: Power to MHD channel, $P_{end}$: Net power that is converted to useful work.*

The drag and frictional skin losses of a submarine decrease thrust energy. When the total thrust force equals the total drag on the submarine, the speed of the submarine becomes steady. Increasing the thruster size increases the thrust power generated in the thruster. Instead of a cluster of thrusters, one large thruster is preferable because it delivers more thrust power. The thrust power generation depends on the power input and efficiency of the MHD duct. The electrical power to the propulsion unit should be maintained at the optimum level; beyond the optimum level, there would be diminishing performance. Increasing the salinity of the seawater and the voltage applied to the electrodes would increase the speed of the vessel. However, the voltage applied to the electrodes should not exceed 1 kV/m, otherwise, there would be excessive electrolysis of seawater causing energy drain, bubble formation, and corrosion, and hence, less thrust power. A higher efficiency of the MHD thruster can be achieved by increasing the electrode size. Larger electrodes provide lower values of induced current on the electrodes in the thruster channel, which increases efficiency. Experimental results in the laboratory showed that if the magnetic field and velocity of seawater in the active portion of the fluid duct increase, the performance of the thruster increases. The geometry of the MHD duct should be carefully designed considering that the ratio of outlet to inlet velocity of seawater inside the MHD duct if increased, would decrease the electrical efficiency.

## RESEARCH WORK AT MIT

A simplified schematic arrangement of the electrics of a submarine with MHD propulsion, as conceived by MIT, USA in their Naval Architecture Department research laboratory, is shown in Figure 17. The research submarine was modeled in line with the Los Angeles submarine. Computer-aided research was carried out in 1989–1990 in the MIT lab to design a submarine with an MHD drive, length of 111m, beam of 10.1m with a speed of 30 knots, and powered by a 100 MWt nuclear reactor.

The design parameters and performance summary, as evaluated during the said research work of the MHD submarine, are given as designed to be powered by a pressurized water nuclear reactor and steam turbine, Top speed – 28.5 knots, Reactor power – 110 MWt, and thermal efficiency of PWR range from to 20–30%. The electrical component characteristics are briefly given as follows: generator: 15 MW, 298 V, 50 kA, 3600 rpm, Alternator: Synchronous, 15 phases, round rotor, oil-cooled, 2m long and 1.3m diameter, weighing about 5.6 tons and provided with rectifier. Because the external thruster is designed to be neutrally buoyant, there would be a weight reduction of approximately 200 tons. Furthermore, as the entire propulsion train to drive the propeller would be eliminated, it would be possible to increase the payload by approximately 265 tons. Thus, a total of 465 tons of arms, ammunition, and other equipment can be additionally loaded in the submarine owing to a reduction in weight.

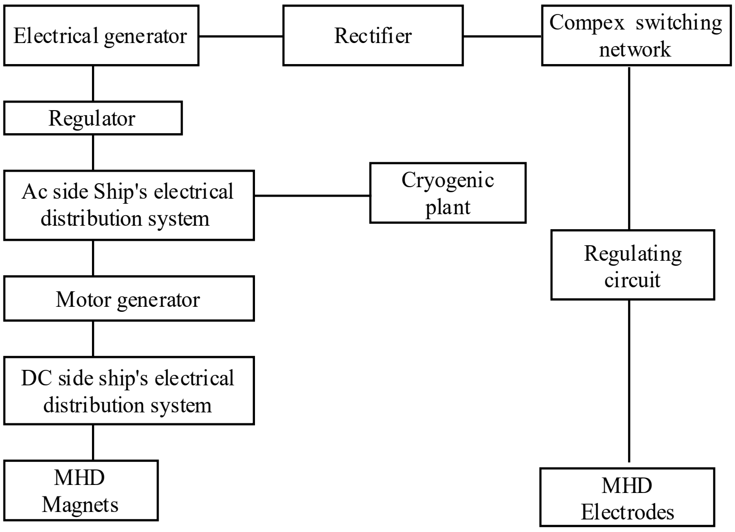

**Figure 17.** Electrical scheme of a submarine with MHD drive.

This is a significant improvement. Because the MHD thruster can be reversed, it is not necessary to provide additional equipment and astern stages to move in the reverse direction, unlike in conventional submarines. The power requirement of the cryogenic plant was estimated to be 200 kW. A magnetic flux density of approximately 8–10 T resulted in optimum propulsion efficiency. Liquid He at 4.2 K, 1 atm. was used during testing to cool the superconducting coils made of niobium-titanium alloys. The MHD propulsion magnets and electrical leads required approximately 20 l/hr. at 5kA and 40 l/hr. of liquid He at 10 kA load. Two cryogenic plants of 30 l/hr. each with two liquefiers were used. However, with the invention of HTS, liquid nitrogen can be used in the future, and cryogenic plants would be much simpler and more cost-effective. This would result in a further weight reduction.

## CONCLUSION

Magnetohydrodynamic propulsion is a very exciting technology that can provide an environmentally sustainable and efficient alternative to traditional marine propulsion systems. The absence of any moving parts and the generation of thrust due to electromagnetic fields reduce noise pollution, which is crucial for naval applications, and this route eliminates harmful exhaust emissions. However, its implementation in commercial vessels faces several challenges such as increased energy demand, high installation and maintenance costs, and corrosion problems. Research on cost-effective high-temperature superconductive magnets and mass production techniques will play a pivotal role in the cost reduction of MHD propulsion. At present, no ships or submarines operate commercially using an MHD drive. Several important modeling simulations have been performed by various countries that experimentally validate the predictions that this innovative technology is technically and commercially feasible.

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