

Article

Study of Helix Angle Parameters of Helical-Channel Magnetohydrodynamic Thrusters

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Abstract

The helical-channel magnetohydrodynamic (MHD) thruster is a silent underwater propulsion device free of rotating mechanical components, which fundamentally eliminates the inherent mechanical noise induced by blades and shaft systems in conventional propeller-driven thrusters. Taking a 10 T-class superconducting helical-channel MHD thruster as the research object, this work establishes a three-dimensional numerical simulation model with bidirectional electromagnetic-fluid coupling via Maxwell–Fluent, filling the research gap of systematic optimization of helical pitch angles in existing low-magnetic-field numerical investigations. A composite magnetic circuit configuration consisting of main coils and compensation coils is adopted, achieving a magnetic field uniformity of 90.13% within the effective working section and markedly alleviating magnetic field attenuation at both ends of the flow channel. Three schemes with helical pitch angles of 23.00°, 17.66°, and 14.29° are quantitatively compared to analyze the effects of helical pitch angle on current density, static pressure, total pressure, radial/axial flow velocities and three-dimensional helical streamlines. Under the rated design mass flow rate of 15.5 kg/s, the scheme with the small pitch angle of 14.29° delivers a thrust of 262.56 N and an electromagnetic efficiency of 7.23%; compared with the large pitch angle scheme of 23.00°, its thrust is improved by 28% and electromagnetic efficiency rises by 53%. Reducing the helical pitch angle extends the effective coupling distance between seawater and the electromagnetic field, optimizes the uniformity of radial current distribution, suppresses eddy currents and Joule heat loss, converts more electromagnetic energy into fluid pressure energy, and thus greatly improves the energy utilization efficiency of the propulsion system. This study provides quantitative design references for the structural optimization and engineering prototype development of low-noise superconducting underwater propulsion equipment, and supports the engineering application of helical-channel magnetohydrodynamic thrusters.

Keywords: magnetohydrodynamic propulsion; helical channel; helix angle; numerical simulation; multi-field coupling



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1. Introduction

Low-noise marine propulsion constitutes an essential core requirement for stealth submarines and deep-sea special transportation platforms. Conventional propeller and pump-jet propulsion systems realize power conversion through gears, transmission shafts

and rotating blades. Continuous mechanical contact induces intense vibration and hydrodynamic noise, severely undermining underwater navigation concealment. Furthermore, long-term operation brings about blade abrasion, bearing wear and transmission power losses, which fail to satisfy the comprehensive design requirements of modern high-end underwater equipment featuring low noise, high reliability and low energy consumption.

As a disruptive direct electromagnetic propulsion technology, magnetohydrodynamic (MHD) [1–4] propulsion requires no moving mechanical components. Its fundamental working principle lies in that conductive seawater is subjected to the Lorentz force within orthogonal electromagnetic fields, whereby electromagnetic energy is directly converted into fluid kinetic energy; the reaction force generated by fluid ejection consequently propels the vehicle forward. This technology fundamentally eradicates mechanical noise sources and possesses prominent merits, including an ultra-low acoustic signature, freedom from mechanical abrasion, compact structural layout and controllable thrust, rendering it a popular research frontier in underwater quiet propulsion and special power systems.

The helical flow channel represents the prevailing optimized configuration for contemporary MHD propulsion. Compared with straight-channel MHD setups [5], helical baffles substantially lengthen the interaction path between seawater and electromagnetic fields under identical magnetic field intensity and electrode voltage boundary conditions, curtail end current leakage and mitigate energy dissipation, thereby achieving markedly superior energy conversion efficiency, a trend validated by abundant existing literature. Nevertheless, when benchmarked against traditional propeller propulsion systems, all existing helical-channel MHD prototypes suffer from relatively low absolute efficiency. The early low-magnetic-field prototype of Japan's Yamato-1 [6,7] achieved an efficiency of merely 3–5%, while the U.S. Defense Advanced Research Projects Agency (DARPA) [8] set breaking through an efficiency threshold of 8% as a core technical target for its military-oriented 10 T superconducting MHD project. Such efficiency deficiency acts as a critical bottleneck restricting practical engineering deployment of this technology. Multiple factors contribute to low operational efficiency, and mismatched helical pitch angles serve as one influential factor, which motivates the present optimization study centering on helical pitch angle as the pivotal variable.

The theoretical exploration and engineering breakthroughs of MHD propulsion have undergone distinct developmental phases worldwide. In the 1960s, the United States pioneered this field by completing fundamental mathematical modeling and principle verification of MHD propulsion under DARPA-sponsored programs. Japan developed Yamato-1, the world's first full-scale superconducting MHD test vessel, in 1992 and accomplished practical prototype implementation. Subsequent low-field experiments focused on adjusting helix pitch and baffle quantity, yet systematic optimization of the helical pitch angle under a high magnetic field of 10 T was not conducted. Russia and Germany have concentrated on theoretical derivations of fundamental electromagnetic coupling and proposed magnetic field homogenization schemes employing compensation coils; these works solely aimed to optimize magnetic field distribution without comparative evaluation of propulsion performance across different channel topologies.

A comparative assessment of various MHD thruster channel configurations verifies the topological superiority of the helical baffle channel. Straight channels feature simple structures yet suffer from short coupling lengths, severe end current leakage and unsatisfactory overall thrust efficiency. Segmented electrode layouts involve complicated wiring arrangements and readily trigger uneven axial Lorentz force distribution accompanied by poor flow stability. By contrast, helical baffle channels form continuous spiral flow passages, drastically extending the interaction length between electromagnetic fields and the working fluid while generating both circumferential and axial Lorentz force compo-

nents simultaneously. Such configurations deliver improved radial current uniformity and exhibit optimal geometric compatibility with cylindrical superconducting magnets, making them the optimal topological scheme for 10 T high-field MHD propulsion.

A comprehensive review of the published literature, technical reports and experimental data identifies three prominent research gaps that this study intends to address [1–3,5,9–12]:

- (1) Most existing parametric analyses are carried out on prototypes operating below 5 T low magnetic fields; systematic optimization of the helical pitch angle under 10 T high-strength superconducting conditions remains absent, and the strong electromagnetic coupling characteristics at high field strengths are insufficiently understood.
- (2) Previous numerical simulations decouple electromagnetic and flow field computations, failing to quantitatively elaborate the complete transmission chain whereby helical pitch angle modulates the spatial distribution of electric current, pressure and flow velocity; the intrinsic coupling mechanism has not been fully clarified.
- (3) Early numerical investigations commonly adopt one-dimensional or quasi-two-dimensional simplified models, which are incapable of capturing crucial loss sources such as electric field distortion near channel ends and radial pressure imbalance, thus offering limited guidance for practical prototype design.

To fill the above research gaps, this paper takes a 10 T-class superconducting helical-channel MHD thruster as the research object and establishes a three-dimensional bidirectional electromagnetic-fluid coupled numerical simulation framework based on Maxwell and Fluent solvers. A combined magnetic homogenization structure composed of main coils and compensation coils is adopted to improve magnetic field uniformity inside the flow channel. Controlled-variable simulations are performed at three representative helical pitch angles of 23.00°, 17.66° and 14.29° to quantitatively reveal how pitch angle affects full-domain multi-physics distributions and overall propulsion performance.

The organizational structure of this thesis is outlined as follows. Section 2 elaborates the fundamental theories of MHD propulsion and numerical models, and demonstrates the suitability of the Realizable $k-\epsilon$ turbulence model for strong swirling helical flows through comparative analysis. Section 3 introduces the numerical simulation framework and detailed settings, including computational configurations and initial boundary conditions. Section 4 evaluates the magnetic homogenization performance of the composite coil assembly, quantitatively analyzes the evolution of current fields, pressure fields, velocity fields and three-dimensional streamlines under the three pitch angle cases, and further discusses corresponding engineering design strategies derived from the simulation results. Section 5 summarizes key quantitative conclusions, specifies the limitations of the present steady-state simulation without thermal field coupling, and proposes future research directions covering prototype fabrication and multi-parameter collaborative optimization. Section 6 acknowledges financial support from relevant research funding projects. An independent nomenclature table is appended after the main conclusions to standardize physical quantities, geometric parameters and technical abbreviations throughout the manuscript for enhanced readability.

2. Theoretical Fundamentals and Numerical Model

2.1. Fundamentals of Magnetohydrodynamic Propulsion

Magnetohydrodynamic (MHD) propulsion essentially relies on electromagnetic force to directly drive conductive fluid without any moving mechanical components. When conductive fluid (seawater) flows through mutually orthogonal magnetic and electric fields, free charges within the fluid are subjected to Lorentz force. This generates an axial thrust acting on the fluid inside the channel and propels the fluid rearward. According to the

law of conservation of momentum, the vehicle acquires a forward reaction force, thereby realizing propulsion.

In a Cartesian coordinate system, the Lorentz force density is expressed as:

$$\mathbf{f} = \mathbf{J} \times \mathbf{B} \quad (1)$$

where $\mathbf{f}$ denotes the body force density, in N/m^3 ; $\mathbf{J}$ is the current density vector, in A/m^2 ; $\mathbf{B}$ represents the magnetic flux density vector, in T.

For helical-channel MHD thrusters, the magnetic field is distributed radially or axially, and electric current passes radially through the seawater layer. The Lorentz force generates circumferential and axial components. The circumferential component drives the seawater to perform helical motion, while the axial component provides net thrust. The rational design of the helix angle, electrode spacing and magnetic field distribution can maximize the axial thrust and minimize energy loss [13].

2.2. Governing Equations of Electromagnetic Field

This study adopts the assumption of a steady-state low-frequency electromagnetic field, where the displacement current can be neglected. The Maxwell equations are simplified as follows:

$$\begin{cases} \nabla \times \mathbf{E} = 0 \\ \nabla \times \mathbf{B} = \mu_0 \mathbf{J} \\ \nabla \cdot \mathbf{B} = 0 \\ \mathbf{J} = \sigma(\mathbf{E} + \mathbf{u} \times \mathbf{B}) \end{cases} \quad (2)$$

where $\mathbf{E}$ is the electric field intensity, unit: V/m ; μ_0 denotes the vacuum permeability, unit: H/m ; σ represents the electrical conductivity of fluid, unit: S/m ; $\mathbf{u}$ is the fluid velocity, unit: m/s .

Introducing the electric potential φ which satisfies $\mathbf{E} = -\nabla\varphi$, and substituting it into the current density equation, yields:

$$\mathbf{J} = -\sigma\nabla\varphi + \sigma(\mathbf{u} \times \mathbf{B}) \quad (3)$$

According to the current continuity equation $\nabla \cdot \mathbf{J} = 0$, the governing equation for electric potential can be derived as:

$$\nabla \cdot (\sigma\nabla\varphi) = \nabla \cdot [\sigma(\mathbf{u} \times \mathbf{B})] \quad (4)$$

This elliptic partial differential equation serves as the core equation solved by the electric potential method in the Fluent MHD module.

2.3. Governing Equations of Flow Field

Seawater is treated as an incompressible viscous conductive fluid. The continuity equation and momentum equation for steady flow are expressed as:

$$\nabla \cdot \mathbf{u} = 0 \quad (5)$$

$$\rho(\mathbf{u} \cdot \nabla)\mathbf{u} = -\nabla p + \nabla \cdot (\mu\nabla\mathbf{u}) + \mathbf{J} \times \mathbf{B} \quad (6)$$

where ρ is the fluid density, kg/m^3 ; p denotes the static pressure, Pa; μ represents the dynamic viscosity, $\text{kg/(m}\cdot\text{s)}$. The term $\mathbf{J} \times \mathbf{B}$ on the right-hand side refers to the electromagnetic body force, which is incorporated into the flow field equations as a momentum source term [14].

2.4. Solution Method for Multi-Field Coupling

In this work, co-simulation combining Maxwell and Fluent-MHD is adopted to realize the bidirectional coupling between the electromagnetic field and flow field.

a. Magnetic field calculation (Maxwell)

A model of superconducting coils and compensation coils is established to calculate the magnetic field distribution of the 10 T class, and the spatial magnetic flux density $B(x,y,z)$ is exported.

b. Flow field and electric field calculation (Fluent-MHD)

The imported magnetic field distribution is used to solve the electric potential equation and obtain the current density J . The electromagnetic force $J \times B$ is calculated and incorporated into the momentum equation as a source term for the iterative solution of the velocity field and pressure field.

c. Coupled iteration

After the flow velocity is updated, the current density and electromagnetic force are corrected. The above procedures are iterated repeatedly until both the electromagnetic field and flow field reach convergence.

2.5. k - ϵ Turbulence Model

In numerical turbulence simulation, the k - ϵ model is the most widely adopted two-equation Reynolds-Averaged Navier–Stokes (RANS) turbulence model. This model closes the Reynolds-averaged Navier–Stokes equations by solving the transport equations for turbulent kinetic energy k and its dissipation rate ϵ , thereby characterizing the transport and dissipation behaviors of turbulent flows.

Three variants of the k - ϵ model are available in Fluent: the Standard k - ϵ model, the RNG k - ϵ model, and the Realizable k - ϵ model. Neither the Standard nor the RNG k - ϵ model incorporates correction terms for rotational curvature into the turbulent viscosity formulation. When applied to the persistent strong swirling flow field inside a helical channel, these two models overpredict flow uniformity within the channel and fail to accurately resolve radial velocity stratification between the inner and outer electrodes, as well as near-wall vortices adjacent to the helical baffles. The RNG model only delivers mild corrections for mean shear effects and yields notable discrepancies in predicting turbulent dissipation for highly curved helical streamlines; furthermore, it suffers poor numerical convergence when coupled with intense Lorentz forces, rendering it unsuitable for the multi-physics coupled helical flow calculations in this work. Accordingly, the Realizable k - ϵ model is selected for turbulence closure in the present study.

On the basis of the standard k - ϵ model, the Realizable k - ϵ model revises the turbulent viscosity formulation with terms accounting for flow curvature and rotation, and substantially reconstructs the dissipation rate transport equation to physically represent energy transfer more reasonably. The two governing equations for incompressible fluids are presented as follows:

$$\frac{\partial(\rho k)}{\partial t} + \frac{\partial(\rho k u_i)}{\partial x_i} = \frac{\partial}{\partial x_j} \left[\left(\mu_1 + \frac{\rho k^2 C_\mu}{k \sigma_k} \right) \frac{\partial k}{\partial x_j} \right] + G_k - \rho \epsilon \quad (7)$$

$$\frac{\partial(\rho \epsilon)}{\partial t} + \frac{\partial(\rho \epsilon u_i)}{\partial x_i} = \frac{\partial}{\partial x_j} \left[\left(\mu_1 + \frac{\rho \epsilon^2 C_\mu}{k \sigma_k} \right) \frac{\partial \epsilon}{\partial x_j} \right] + \rho C_{1\epsilon} S_\epsilon - C_{2\epsilon} \rho \frac{\epsilon^2}{k + \sqrt{\nu \epsilon}} \quad (8)$$

where $C_{1\epsilon} = \max\left(0.43, \frac{\eta}{\eta+5}\right)$. The other model constants are specified as: $C_{2\epsilon} = 1.9$, $\sigma_k = 1.0$, $\sigma_\epsilon = 1.3$.

3. Numerical Simulation Framework and Setup

3.1. Geometric Model and Main Parameters

As shown in Figure 1. The helix angle is defined as the angle between the tangent to the helix and the plane perpendicular to the central axis, which is generally calculated at the pitch diameter. The calculation formula for the helix angle is expressed as:

$$\lambda = \arctan\left(\frac{p}{\pi d}\right) \quad (9)$$

where:

p —lead, namely the axial distance between two adjacent crests of the helix;

d —diameter, which refers to the pitch diameter in general.

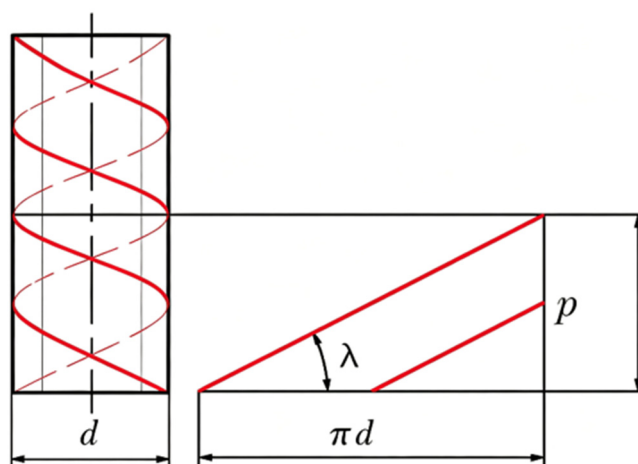


Figure 1. Schematic diagram of helix angle.

Calculation results show that for the effective section of a helical vane channel with an axial length of 600 mm, for 3, 4 and 5 complete helical turns, the corresponding helix angles are listed in Table 1.

Table 1. Helix angles under different numbers of helical turns.

Number of Helical Turns	3	4	5
$p(\text{mm})$	200	150	120
$d(\text{mm})$	150	150	150
$\lambda(^{\circ})$	23	17.66	14.29

The helical-channel MHD thruster consists of an inlet section, flow guide section, effective section, rectifying section and outlet section [15]. The effective section adopts helical vane channels with an axial length of 600 mm. The origin of the Cartesian coordinate system is set at the center of the helical channel in the effective section, and the computational domain ranges from -650 mm to $+750$ mm. The three-dimensional physical model of the helical-channel MHD thruster is presented in Figure 2.

The main parameters of the magnetic field generated by the solenoidal superconducting magnet are listed in Table 2.

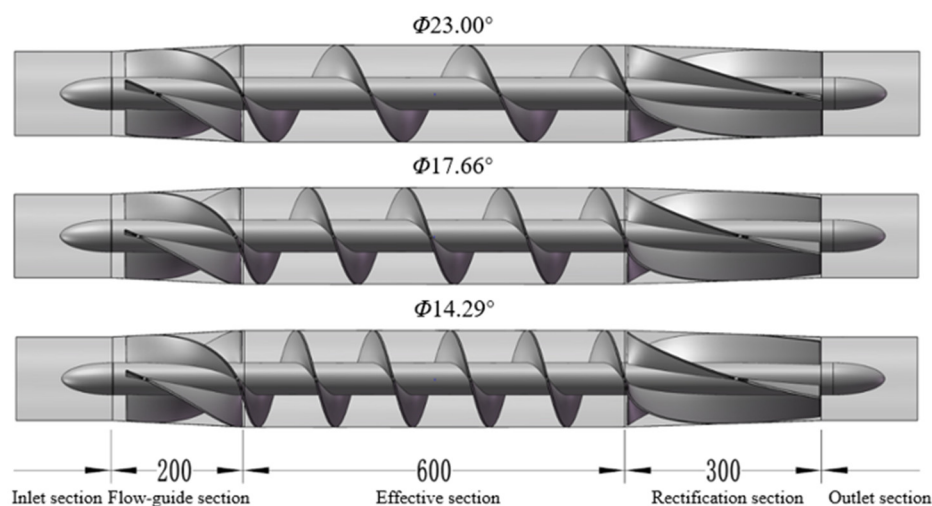


Figure 2. Computational models with different helix angles.

Table 2. Magnetic field parameters of the solenoidal superconducting magnet.

Parameters	Value
Central magnetic field strength	10.073 T
Warm bore diameter	160 mm
Coil length	600 mm

The basic parameters of the effective cross-section of the helical-channel MHD thruster are presented in Table 3.

Table 3. Basic parameters of the helical-channel MHD thruster.

Parameters	Value
Helix angle $\Phi 1$	23.00°
Helix angle $\Phi 2$	17.66°
Helix angle $\Phi 3$	14.29°
Axial length of helical vane (L)	600 mm
Outer electrode diameter (Dout)	150 mm
Inner electrode diameter (Din)	50 mm
Vane thickness (t)	3 mm
Diameter ratio of inner to outer electrode (Di/D0)	0.33
Number of guide vanes (n1)	4
Aspect ratio of guide device ($\lambda 1$)	0.28
Number of rectifier vanes (n2)	4
Aspect ratio of rectifier ($\lambda 2$)	0.17

3.2. Setting of Boundary Conditions and Solution Methods

a. Material Properties

The working fluid is seawater with density $\rho = 1025 \text{ kg/m}^3$, electrical conductivity $\sigma = 5 \text{ S/m}$, vacuum permeability $\mu_0 = 1.257 \times 10^{-6} \text{ H/m}$, and dynamic viscosity $0.001003 \text{ kg/(m}\cdot\text{s)}$. Aluminum is selected as the electrode material. The inner and outer electrodes are defined to simulate the electrode voltage applied in seawater.

b. Boundary Conditions

The flow inlet adopts total temperature and total pressure boundary conditions (298.15 K, 101,325 Pa), with the flow direction perpendicular to the inlet plane. Static

pressure is specified at the outlet, and a no-slip condition is applied to all solid walls. The reference pressure is set to 0 Pa at the coordinate origin.

The electric potential method in the Fluent-MHD module is used to solve the electromagnetic field equations. The inner and outer electrodes are defined as conductive walls: the inner electrode (positive pole) is arranged on the hub, and the outer electrode (negative pole) is mounted on the casing, with an applied voltage of 25 V. All other walls are set as electrically insulated boundaries.

3.3. Mesh Generation and Mesh Independence Verification

The entire flow passage of the helical-channel MHD thruster is discretized by meshing. Boundary layer mesh refinement is performed on fluid–solid interfaces, and local mesh densification is applied around helical vanes, electrode walls, and inlet and outlet regions to fully resolve complex geometric features and near-wall flow characteristics.

Three mesh schemes with 1.8, 3.5 and 6.0 million cells are established for mesh independence verification. The average static pressure and average axial velocity at the outlet of the effective section are taken as monitoring parameters for comparative analysis. The results show that the relative deviation between the solutions of the 3.5-million-cell and 6.0-million-cell meshes is less than 0.5%, whereas the deviation between the 1.8-million-cell and 3.5-million-cell meshes reaches approximately 2.1%. This proves that the 3.5-million-cell mesh can meet the requirements of computational accuracy. Considering computational resources and efficiency comprehensively, the mesh scheme containing about 3.5 million cells is adopted for numerical simulations of all subsequent operating conditions.

4. Analysis of Electromagnetic Field Distribution Characteristics

4.1. Distribution Characteristics of Magnetic Field Contours

The helical-channel MHD thruster adopts a combined configuration consisting of a main superconducting coil and compensation coils arranged on both sides, presenting an overall axisymmetric cylindrical structure. The main coil generates a strong central magnetic field at the 10 T level, while the compensation coils suppress the rapid attenuation of magnetic field at both ends of the channel and improve the magnetic field uniformity in the effective section. The key parameters of the magnet are listed in Table 2 above, and the compensation coils are symmetrically arranged on two sides of the main coil.

Figure 3 shows the overall magnetic field contour of the 10 T solenoidal superconducting magnet. It can be observed that the magnetic field is symmetrically distributed along the axial direction, with a higher strength at the center and lower strength at both ends. The magnetic flux density reaches the maximum value of 10.0085 T in the central region of the main coil. The magnetic field gradually attenuates along the axial direction towards both sides. Benefiting from the compensation coils, the decreasing rate of magnetic field at the two ends of the channel is greatly reduced, and the magnetic field distribution becomes more uniform.

In the effective section ranging from -300 mm to $+300$ mm, the magnetic field exhibits excellent uniformity, and the magnetic flux density remains above 9.0308 T. The magnetic field uniformity of the effective section is 90.13% ($@ \varnothing 150$ mm $\times$ 600 mm), which satisfies the requirement of a strong magnetic field for electromagnetic coupling in the helical vane channel. The magnetic field attenuates rapidly in the flow guide section and rectifying section where the axial distance exceeds 300 mm. The distorted region of the magnetic field at the ends is limited, which effectively suppresses the Joule heat loss at the end parts.

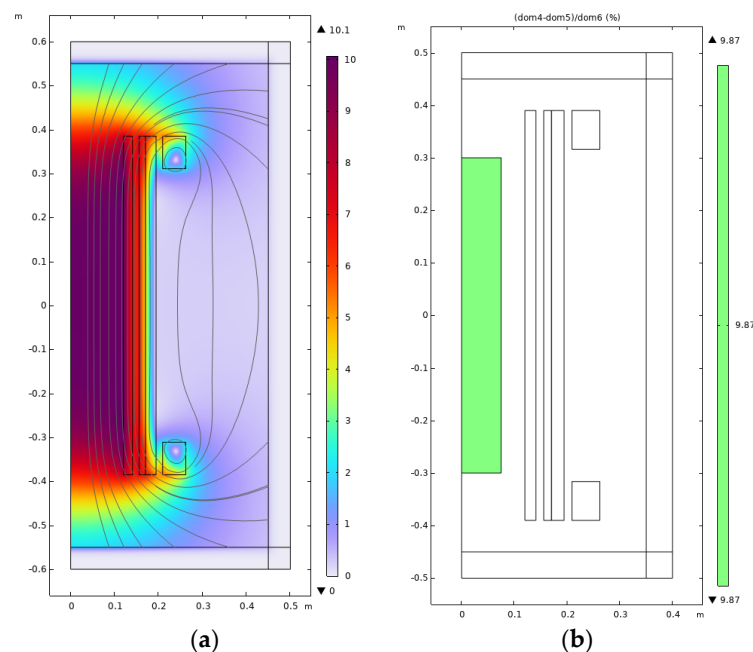


Figure 3. Electromagnetic design of 10 T solenoidal superconducting magnet: (a) magnetic field contour of solenoidal magnet; (b) uniformity.

4.2. Axial Distribution Law of Magnetic Field

Figure 4 presents the axial distribution curve of magnetic flux density along the central axis of the solenoidal magnet. The horizontal axis represents the axial distance (the origin is located at the center of the effective section), and the vertical axis denotes the magnetic flux density B (T).

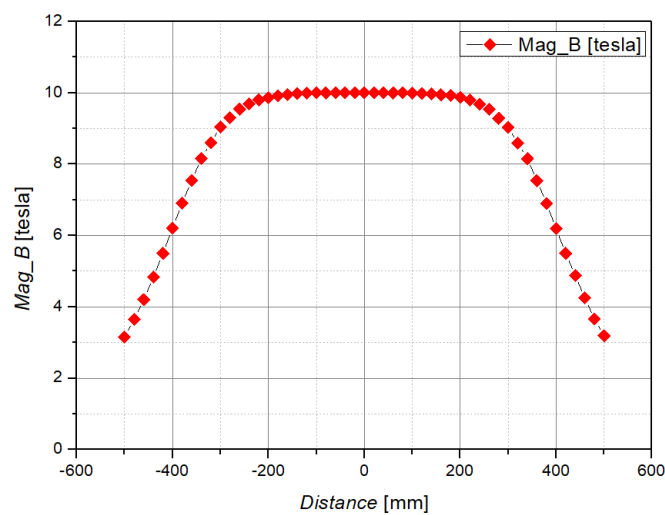


Figure 4. Axial distribution of central magnetic field of solenoidal magnet.

It can be seen from the curve that within the effective section ranging from -300 mm to $+300$ mm, the magnetic field is highly uniform. The magnetic flux density remains stable between 9.0308 T and 10.0085 T, with a fluctuation less than 3%, which guarantees the uniform distribution of electromagnetic force inside the helical channel.

When the axial distance exceeds ± 300 mm, the magnetic field attenuates rapidly and drops to approximately 3.0 T at ± 500 mm.

5. Effects of Helix Angle on Multi-Field Coupling Characteristics of Helical-Channel MHD Thruster

5.1. Flow Rate-Pressure Difference Characteristics

Figure 5 presents the flow rate–pressure difference ($\Delta P - Q$) curves of MHD thrusters with three different helix angles. Numerical calculations are conducted by adjusting the outlet back pressure for models with helix angles of $\Phi 23.00^\circ$, $\Phi 17.66^\circ$ and $\Phi 14.29^\circ$, and the corresponding curves are obtained.

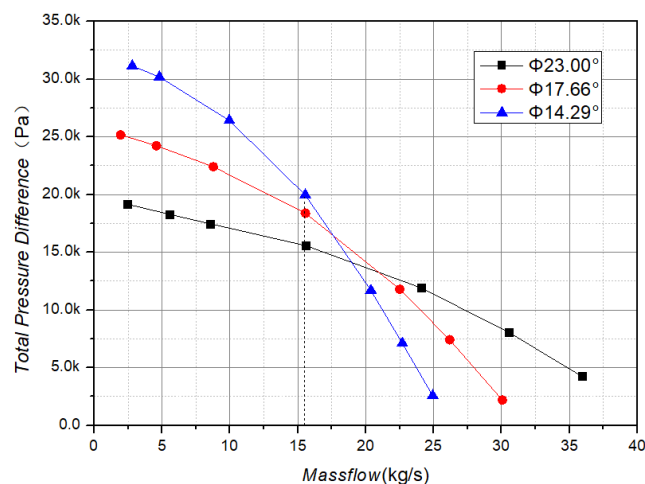


Figure 5. $\Delta P - Q$ curves of MHD thrusters with three helix angles.

Overall, the three models follow a consistent variation trend: the pressure difference between inlet and outlet decreases as the mass flow rate increases. Under low flow rate conditions, the inlet–outlet pressure difference rises with the reduction in helix angle. By contrast, under high flow rate conditions, the pressure difference declines as the helix angle decreases.

The design operating point is set at a mass flow rate of 15.5 kg/s, as shown by the dashed line in Figure 5. A comparative analysis of the three MHD thrusters is carried out at this operating point.

Table 4 lists the inlet–outlet pressure difference, thrust and electromagnetic efficiency of MHD thrusters with helix angles of $\Phi 23.00^\circ$, $\Phi 17.66^\circ$ and $\Phi 14.29^\circ$ under the design operating condition. At this operating point, the inlet–outlet pressure difference, thrust and electromagnetic efficiency all increase as the helix angle decreases.

Table 4. Inlet–outlet pressure difference, thrust and electromagnetic efficiency of MHD thrusters with three helix angles.

	Total Pressure Difference ΔP (kPa)	Propulsion Force T (N)	Electromagnetic Efficiency η_m
$\Phi 23.00^\circ$	15.56	204.83	4.72%
$\Phi 17.66^\circ$	18.37	241.80	5.01%
$\Phi 14.29^\circ$	19.95	262.56	7.23%

The total pressure difference ΔP is calculated by $\Delta P = P_{out}^* - P_{in}^*$, where P_{out}^* denotes the total pressure at the outlet of the MHD channel and P_{in}^* is the total pressure at the channel inlet.

The electromagnetic efficiency is defined as the ratio of electromagnetic power P_m to net input power P , expressed as:

$$\eta_m = \frac{P_m}{P} \quad (10)$$

Under ideal conditions, the electromagnetic efficiency can be written as:

$$\eta_m = \frac{1}{K} \quad (11)$$

where K denotes the load factor, defined as the ratio of electrode voltage to induced electromotive force:

$$K = \frac{U}{BbV_{MHD}} = \frac{E}{BV_{MHD}} \quad (12)$$

The electric field strength E satisfies:

$$E = \frac{U}{b} = \frac{J}{\sigma} + BV_{MHD} \quad (13)$$

Substituting the electric field expression yields the electromagnetic efficiency:

$$\eta_m = \frac{BV_{MHD}}{\frac{J}{\sigma} + BV_{MHD}} = \frac{1}{\frac{J}{\sigma BV_{MHD}} + 1} \quad (14)$$

This equation indicates that for a fixed current, higher magnetic flux density leads to greater electromagnetic efficiency.

5.2. Effect of Helix Angle on Current Density Distribution

Current Density Contours on Axial Cross-Sections

Figure 6 presents the contours of current density J on axial cross-sections of MHD thrusters with helix angles of $\Phi 23.00^\circ$, $\Phi 17.66^\circ$ and $\Phi 14.29^\circ$. The three models exhibit identical distribution patterns of current density. A smaller helix angle makes the current path closer to the radial direction and yields a more uniform current density distribution.

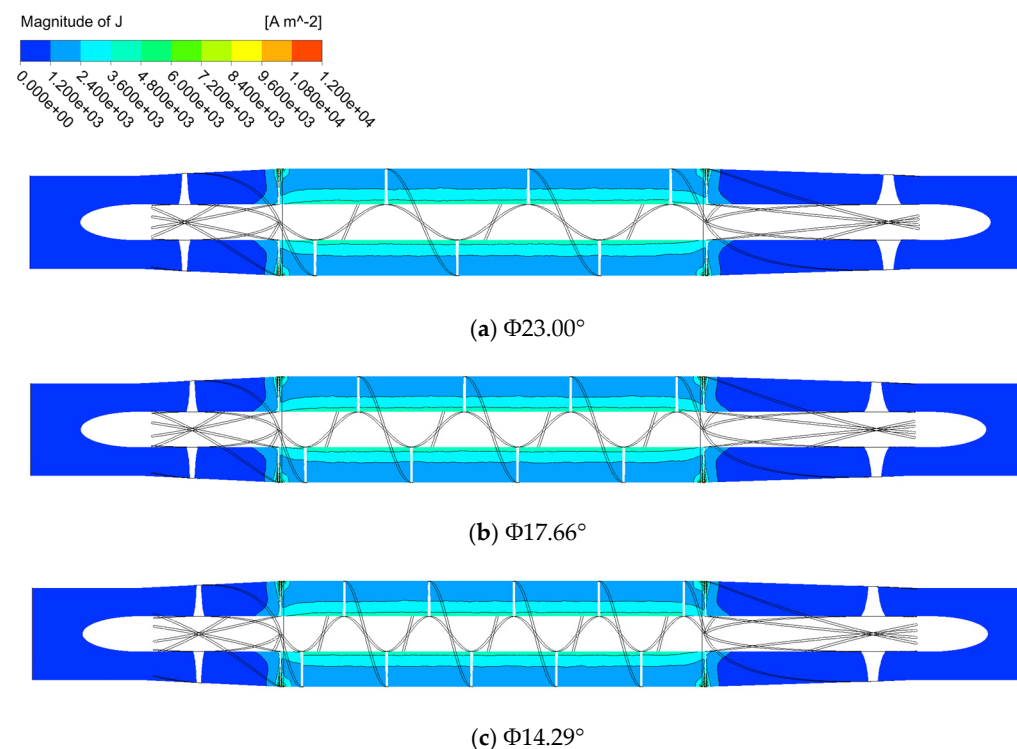


Figure 6. Contours of current density J on axial cross-sections.

Radially, the current density gradually decreases from the inner electrode to the outer electrode. In the middle part of the effective section, the radial gradient of current density

distributes uniformly. At both ends of the electrodes, an obvious axial component of the current density gradient appears. The end current weakens the radial component of current density in the effective section and causes Joule heat loss, which reduces the overall efficiency of the thruster.

5.3. Effect of Helix Angle on Pressure Field Distribution

5.3.1. Static Pressure Distribution Characteristics

Figure 7 shows the static pressure contours on axial cross-sections of MHD thrusters with helix angles of $\Phi 23.00^\circ$, $\Phi 17.66^\circ$ and $\Phi 14.29^\circ$. It can be seen that the static pressure distribution presents distinct staged features along the axial direction. The static pressure remains uniform in the inlet and flow guide sections, rises continuously in the effective section under the action of Lorentz force, and tends to be stable in the rectifying and outlet sections.

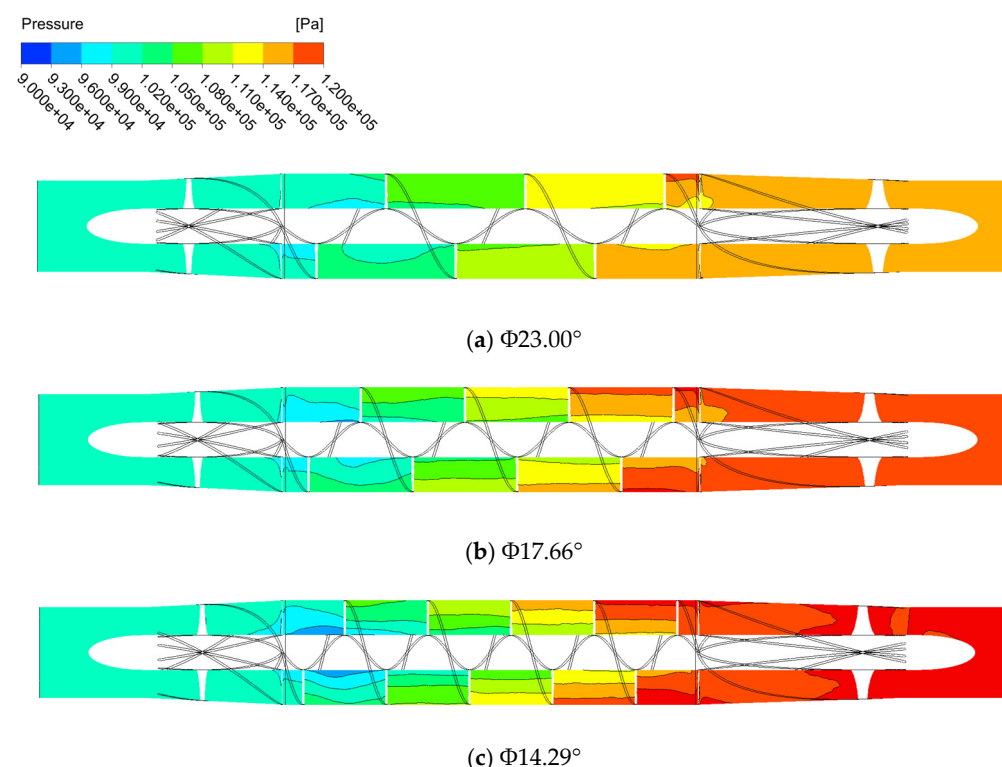


Figure 7. Static pressure contours on axial cross-sections.

As the helix angle decreases, the radial static pressure gradient in the effective section increases remarkably, and the axial pressure rise becomes greater. The pressure rise in the effective section is approximately 12 kPa at 23.00° , 15 kPa at 17.66° and 18 kPa at 14.29° . A smaller helix angle leads to a stronger constraint on the fluid inside the helical channel, higher work efficiency of the Lorentz force and a more notable increase in static pressure.

Figure 8 illustrates the axial static pressure distribution of MHD thrusters with helix angles of $\Phi 23.00^\circ$, $\Phi 17.66^\circ$ and $\Phi 14.29^\circ$. Data are extracted along the line at $x = 50$ mm. In the inlet section, the static pressure curve is nearly flat with negligible variation, indicating low flow loss. A slight drop of static pressure occurs in the guide vane section. On one hand, the guide vanes induce fluid pre-rotation and increase flow kinetic energy. On the other hand, the enlarged wetted area brings additional boundary layer loss.

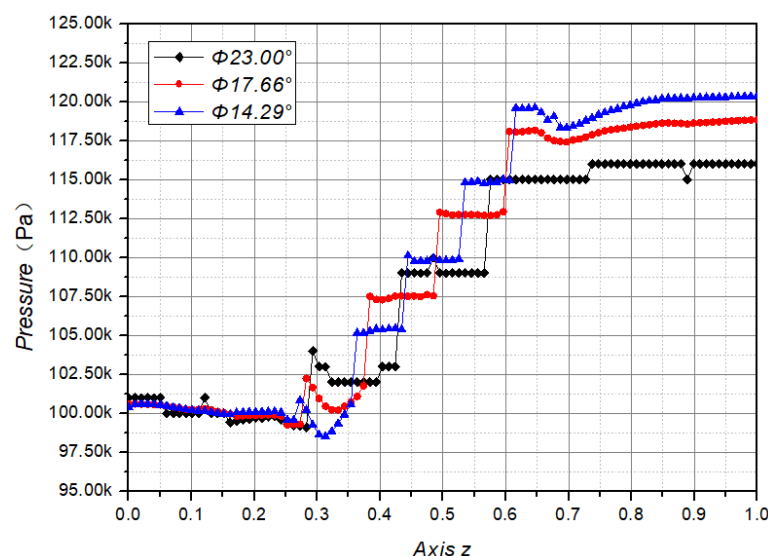


Figure 8. Axial static pressure distribution of MHD thrusters with three helix angles.

In the effective section, the static pressure of seawater rises continuously under the Lorentz force. Since the data extraction line passes through the helical vanes, the static pressure increases in a stepped pattern in the figure. Afterwards, the static pressure rises slightly in the rectifier vane section. The rotating kinetic energy of the fluid is converted into static pressure by the rectifier vanes, and this energy gain exceeds the loss caused by the increased wetted area. Finally, the static pressure changes slightly in the outlet section with minor flow loss.

5.3.2. Total Pressure Distribution Characteristics

Figure 9 shows the total pressure contours on axial cross-sections of MHD thrusters with helix angles of $\Phi 23.00^\circ$, $\Phi 17.66^\circ$ and $\Phi 14.29^\circ$. The total pressure distributes uniformly with no obvious gradient from the inlet section and guide vane section to the front part of the effective section. In the effective acceleration section, the Lorentz force generated by the interaction of electric and magnetic fields drives the seawater to do work. Accordingly, the total pressure rises gradually and reaches its peak at the end of the effective section. It is notable that the radial total pressure gradient in the effective section increases significantly as the helix angle decreases sequentially from 23.00° to 17.66° and 14.29° .

Figure 10 presents the axial total pressure distribution of MHD thrusters with helix angles of $\Phi 23.00^\circ$, $\Phi 17.66^\circ$ and $\Phi 14.29^\circ$. The total pressure curve remains flat in the inlet section with little variation, which indicates low flow loss. A slight drop of total pressure appears in the guide vane section. The guide vanes induce fluid pre-rotation and raise kinetic energy, while the increased wetted area also causes certain boundary layer loss.

In the effective section, the total pressure of seawater rises steadily under the Lorentz force. Since the data extraction line passes through the helical vanes, the total pressure increases in a stepped manner in the figure. Afterwards, slight fluctuations of total pressure are observed in the rectifier vane section, and the total pressure stays nearly constant in the outlet section. The model with a helix angle of 14.29° achieves the highest outlet total pressure, which is approximately 15% higher than that of the 23.00° model and features the minimum flow energy loss.

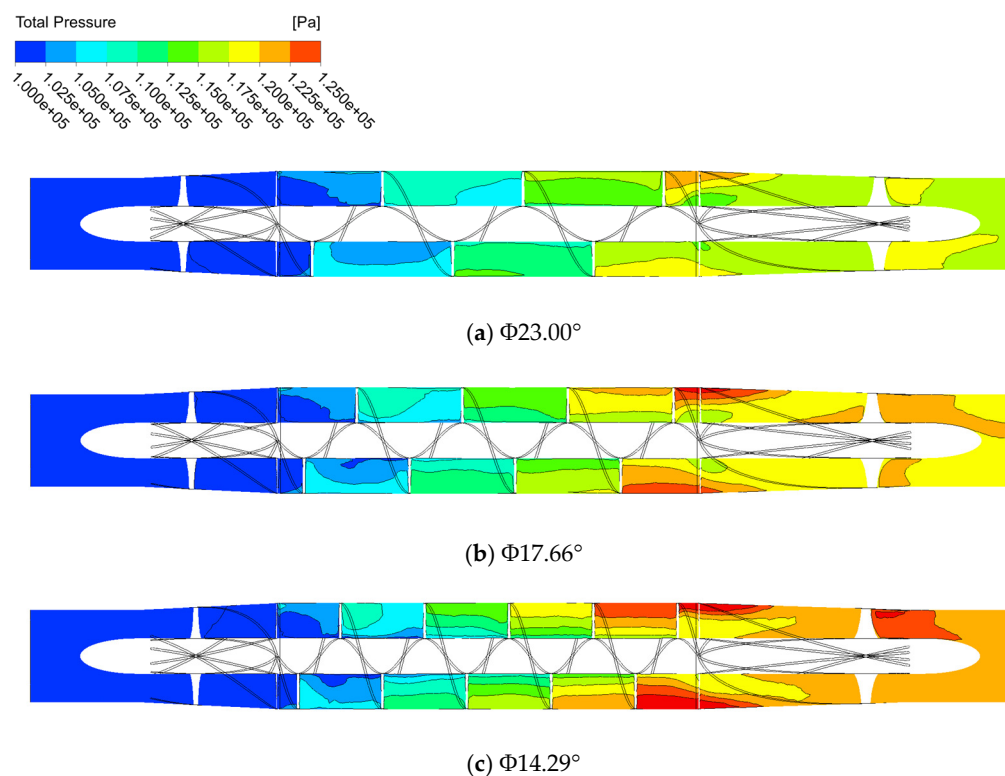


Figure 9. Total pressure contours on axial cross-sections.

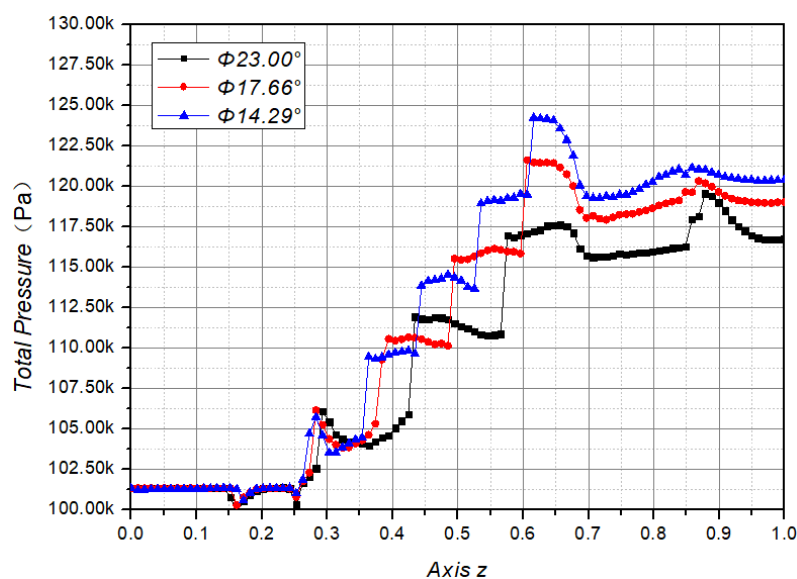


Figure 10. Axial total pressure distribution of MHD thrusters with three helix angles.

5.4. Effect of Helix Angle on Velocity Field Distribution

5.4.1. Cross-Section Velocity Distribution

Figure 11 shows the velocity contours on the vertical cross-section at the axial position of 300 mm for MHD thrusters with helix angles of $\Phi 23.00^\circ$, $\Phi 17.66^\circ$ and $\Phi 14.29^\circ$. The three cases share similar velocity distribution patterns on this cross-section. The flow velocity is low near the inner electrode and high near the outer electrode, and increases gradually along the radial direction.

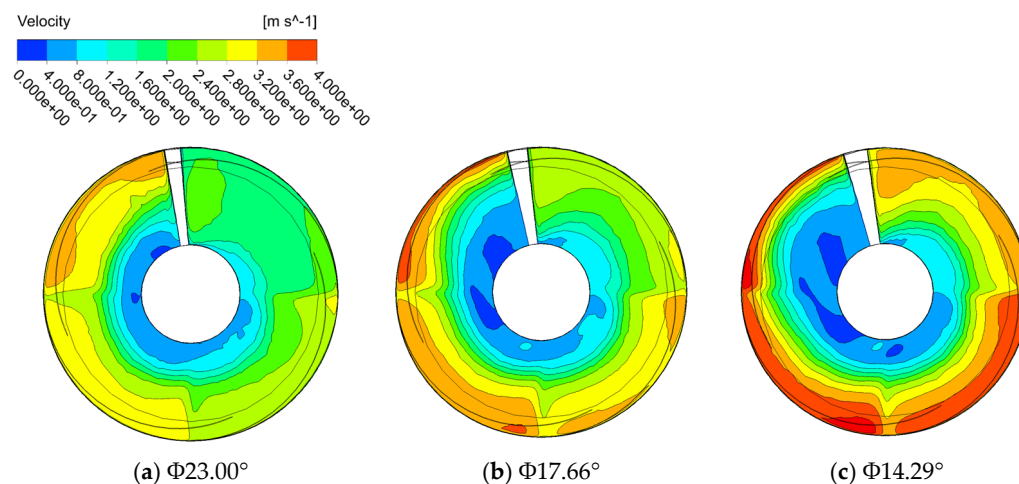


Figure 11. Velocity contours on vertical cross-section at axial position of 300 mm.

For the thruster with a helix angle of 14.29° , the high-velocity region near the casing and the low-velocity region near the hub both expand significantly. Comparative analysis indicates that the cross-section velocity at this position rises as the helix angle decreases.

Figure 12 shows the radial velocity at the 270° direction on the vertical cross-section at the axial position of 300 mm for MHD thrusters with helix angles of $\Phi 23.00^\circ$, $\Phi 17.66^\circ$ and $\Phi 14.29^\circ$. This plot quantitatively reflects the velocity distribution characteristics of the corresponding line in the aforementioned velocity contour.

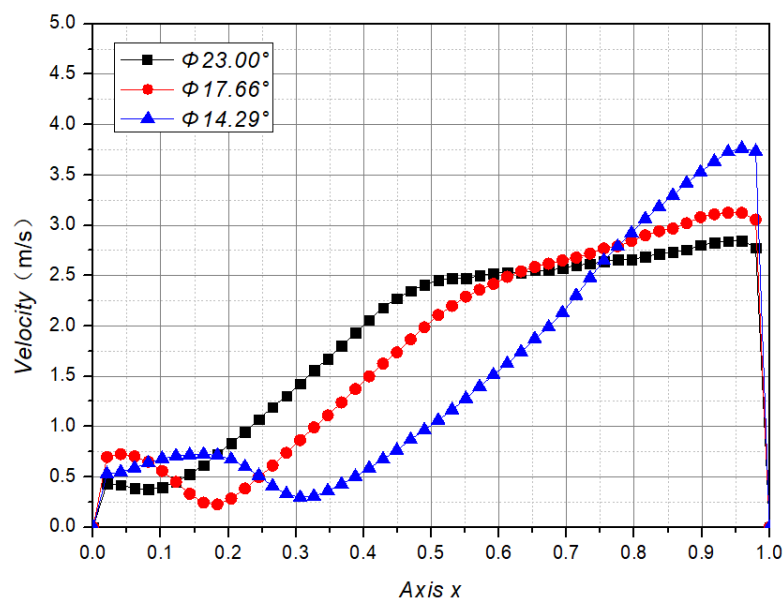


Figure 12. Radial velocity at 270° on vertical cross-section at axial position of 300 mm.

A smaller helix angle corresponds to a wider high-velocity zone near the outer electrode and a more prominent low-velocity zone near the inner electrode. For the case of 14.29° , the maximum velocity near the casing reaches 4.0 m/s, an increase of about 25% compared with the 23.00° case. The expanded low-velocity region near the hub helps reduce wall friction loss.

5.4.2. Axial Velocity Distribution

Figure 13 presents the velocity contours on axial cross-sections of MHD thrusters with helix angles of $\Phi 23.00^\circ$, $\Phi 17.66^\circ$ and $\Phi 14.29^\circ$. The flow velocity is relatively uniform in the inlet section. Fluid pre-rotation occurs in the guide vane section under the action

of guide vanes. Obvious velocity fluctuations and radial inhomogeneity appear at the entrance of the effective section. In the subsequent rectifier vane section, the main flow is dominated by axial motion. In the outlet section, residual velocity circulation leads to distinct velocity gradients.

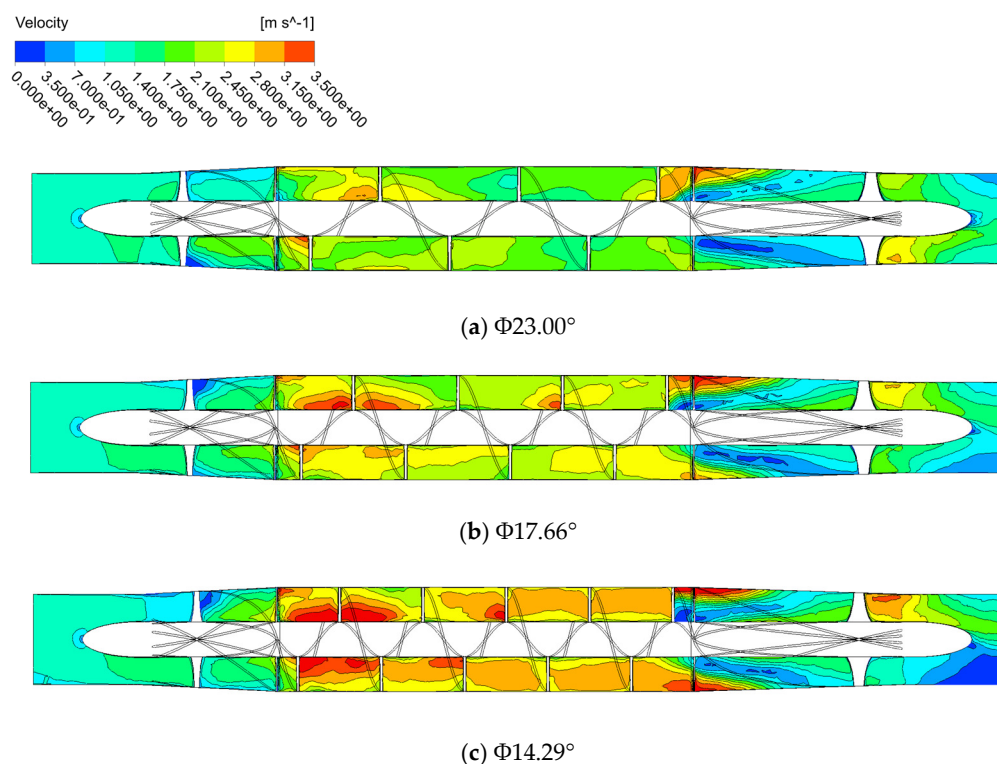


Figure 13. Velocity contours on axial cross-sections.

Figure 14 shows the axial velocity distribution of MHD thrusters with helix angles of $\Phi 23.00^\circ$, $\Phi 17.66^\circ$ and $\Phi 14.29^\circ$. Since the data extraction line passes through the helical vanes, the velocity periodically drops to zero at these positions. As illustrated, the flow velocity is the highest under the $\Phi 14.29^\circ$ condition and the lowest under the $\Phi 23.00^\circ$ condition within the effective section. The opposite trend is observed in the outlet section, where the $\Phi 14.29^\circ$ case has the minimum outlet velocity. This indicates that more electromagnetic energy is converted into fluid pressure energy rather than kinetic energy, leading to higher propulsion efficiency.

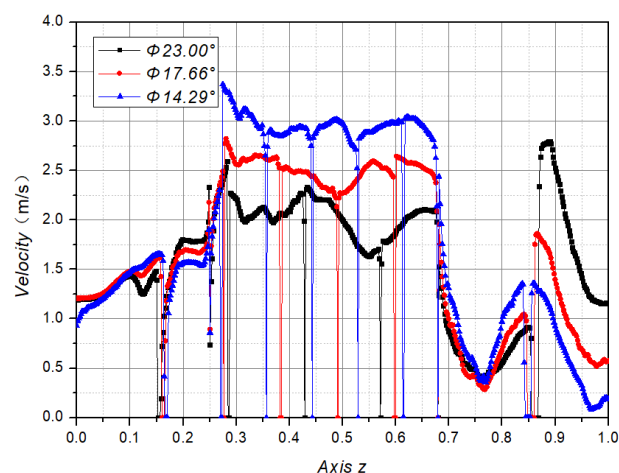


Figure 14. Axial velocity distribution of MHD thrusters with three helix angles.

5.4.3. Characteristics of 3D Streamlines

Figure 15 displays the three-dimensional streamline distribution and static pressure contours on vane surfaces of MHD thrusters with helix angles of $\Phi 23.00^\circ$, $\Phi 17.66^\circ$ and $\Phi 14.29^\circ$. The axial incoming flow passes through the guide device, whose wall exerts a torque to generate pre-rotation. Certain flow inhomogeneity and turbulence emerge before the flow enters the effective section. Continuous spiral flow is observed in the effective pressurization section. Afterwards, the rectifier acts to suppress the circumferential velocity of seawater, and the main flow gradually turns into axial flow with a small residual circulation. Comparative results show that the mainstream velocity in the effective section rises obviously as the helix angle changes.

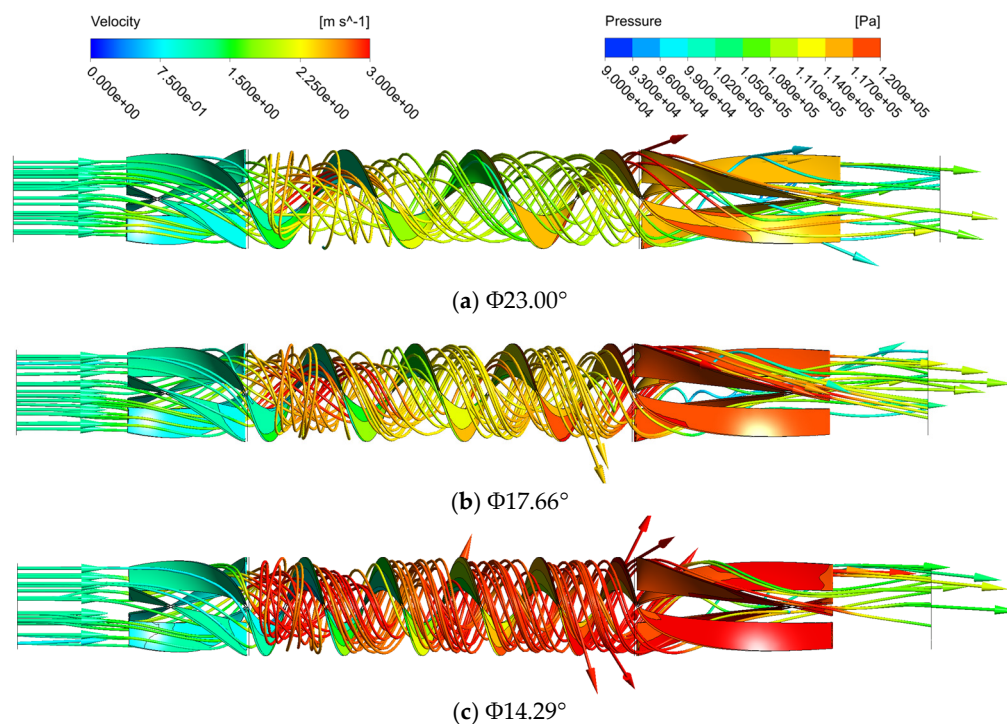


Figure 15. 3D streamline distribution and static pressure contours on vane surfaces.

According to the static pressure contours on vane surfaces, the static pressure drops slightly from the channel inlet to the front of the effective section due to frictional loss. In the effective section, the Lorentz force does work and gradually increases the static pressure on vane surfaces, which reaches the maximum at the outlet of this section. Affected by centrifugal force, the static pressure rises along the vane span. In the rectifier section, the static pressure on vane surfaces remains basically stable with a slight decline. It is found that the static pressure on vane surfaces increases as the helix angle decreases.

A smaller helix angle corresponds to a smaller spiral angle of streamlines and longer axial extension in the effective section. This prolongs the interaction time between the fluid and electromagnetic field and achieves more sufficient energy exchange. The maximum static pressure on vane surfaces reaches 1.2×10^5 Pa under the $\Phi 14.29^\circ$ condition, indicating a higher load-bearing capacity.

5.5. Comprehensive Analysis of Influence Mechanism

Reducing the helix angle can optimize the propulsion performance. A smaller helix angle makes the current path more radial, delivers a more uniform current density distribution, increases the proportion of the axial component of electromagnetic force, and strengthens the electromagnetic-fluid coupling effect. Meanwhile, a gentler helix angle

suppresses flow separation and vortex formation, reduces boundary layer losses, and improves the uniformity of the pressure and velocity fields inside the effective section. Furthermore, a smaller helix angle extends the axial interaction distance between the fluid and electromagnetic field for sufficient energy exchange. More electromagnetic energy is converted into fluid pressure energy instead of kinetic energy, thereby achieving significant simultaneous improvements in thrust and electromagnetic efficiency.

6. Conclusions

In this paper, a bidirectional electromagnetic-fluid coupled numerical model is constructed for a 10 T-class superconducting helical-channel magnetohydrodynamic (MHD) thruster. The electromagnetic field distribution inside the helical channel and the influences of three helical pitch angles (23.00° , 17.66° , and 14.29°) on multi-physics coupling characteristics and propulsion performance are systematically investigated.

The simulation results indicate that the combined configuration of main coils and compensation coils achieves a magnetic field uniformity of 90.13% within the effective working section and effectively suppresses magnetic field attenuation at both channel ends. As the helical pitch angle decreases, the radial static pressure and total pressure rise inside the effective section increase remarkably; the high-velocity region near the outer electrode expands while the outlet flow velocity declines. Meanwhile, the interaction path between seawater and the electromagnetic field is extended, leading to more sufficient energy conversion. Under the rated design condition with a mass flow rate of 15.5 kg/s, the thruster delivers a thrust of 262.56 N and an electromagnetic efficiency of 7.23% at the helical pitch angle of 14.29° , representing approximately 28% higher thrust and 53% higher efficiency compared with the case of 23.00° . Comprehensive evaluation confirms that the 14.29° scheme yields the optimal performance among the three working conditions.

6.1. Limitations of the Present Study

Nevertheless, several limitations exist in the present study. All numerical simulations adopt the steady-state assumption, without considering transient navigation conditions such as variable flow rates, applied voltages and sailing speeds. Accordingly, the transient loss characteristics including instantaneous Joule heat generation and abrupt flow separation during startup, speed regulation and low-flow cruising cannot be captured, which introduces discrepancies between numerical predictions and practical underwater maneuvering conditions. Furthermore, the numerical model excludes thermal field coupling effects and fails to account for variations in seawater electrical conductivity and fluid viscosity induced by Joule heating. Heat accumulation during long-duration continuous operation or low-flow conditions disturbs the matching relationship of multi-physics coupling, making it impossible to quantitatively evaluate the adverse degradation of propulsion efficiency caused by thermal effects.

6.2. Engineering Design Guidelines for Superconducting Helical-Channel MHD Thrusters

Based on the results of three-dimensional bidirectional electromagnetic-fluid coupled numerical simulations in this work, quantitative design criteria that can directly guide the development of engineering prototypes are summarized for the 10 T-class superconducting helical-channel MHD thruster as follows:

(1) Design criterion for helical pitch angle

For the 10 T-class superconducting helical MHD thruster with a pitch circle diameter of 150 mm and an effective channel length of 600 mm, a helical pitch angle of 14.29° (corresponding to five full helical turns) is recommended under the rated design mass flow rate of 15.5 kg/s. This configuration delivers a thrust of 262.56 N and an electromagnetic

efficiency of 7.23%, exhibiting the best overall performance. If the small pitch angle cannot be adopted due to constraints from channel machining technology or structural space, 17.66° (four full helical turns) can be selected as a compromise solution. This angle retains relatively high thrust while lowering the machining difficulty and manufacturing cost of the helical baffles.

(2) Matching criterion for magnetic circuit configuration

The superconducting magnet system shall adopt a composite magnetic circuit consisting of main coils paired with bilateral compensation coils. This arrangement guarantees a magnetic field uniformity no less than 90% within the effective axial region (± 300 mm), and effectively mitigates magnetic field attenuation at the inlet and outlet ends of the flow channel.

(3) Recommendations for energy loss control of prototypes

Adopting a relatively small helical pitch angle (e.g., 14.29°) extends the axial interaction length of electromagnetic-fluid coupling, converting more electromagnetic energy into fluid static pressure energy rather than outlet kinetic energy, thereby cutting down outlet flow loss. This optimization strategy is particularly vital for low-noise and high-efficiency underwater propulsion prototypes. Under low-speed high-thrust operating conditions, a small pitch angle remarkably reduces jet velocity at the channel outlet, weakens wake noise radiation, and improves overall energy utilization efficiency simultaneously.

The above design criteria are derived from steady-state simulation results in this study. During subsequent prototype fabrication, these parameters need to be verified and adjusted according to practical machining processes, cooling schemes, and the voltage withstand level of insulating materials. It is suggested that parameter sensitivity analysis and experimental validation be carried out to finalize the optimal combination of engineering design parameters.

This study provides theoretical support for structural optimization and practical engineering application of helical-channel MHD thrusters. Follow-up work can be extended to transient condition analysis, multi-parameter collaborative optimization via orthogonal experimental design, and experimental verification based on physical prototypes.

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Nomenclature

Nomenclature of main symbols used in this paper:

Symbol	Definition
B	Magnetic flux density (T)
J	Current density (A/m ²)
u	Velocity vector of seawater flow (m/s)
p	Static pressure of fluid (Pa)
σ	Electrical conductivity of seawater (S/m)
μ	Dynamic viscosity of fluid (Pa·s)
E	Electric field intensity (V/m)
φ	Electric potential (V)
T	Output thrust of the thruster (N)
ΔP	Total pressure difference between inlet and outlet of the flow channel (Pa)
η_m	Electromagnetic energy conversion efficiency
k	Turbulent kinetic energy (adopted in the Realizable k- ϵ turbulence model) (m ² /s ²)
ϵ	Turbulent dissipation rate (m ² /s ³)
λ	Helical pitch angle (Helix angle)
μ_0	Vacuum permeability
$C_{1\epsilon}$	Empirical coefficient for the dissipation rate equation in the Realizable k- ϵ model
$C_{2\epsilon}$	Empirical constant for the dissipation rate equation in the Realizable k- ϵ model
σ_k	Turbulent Prandtl number corresponding to turbulent kinetic energy k
σ_ϵ	Turbulent Prandtl number corresponding to turbulent dissipation rate ϵ

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