

Article

A CFD Study of the Hydrodynamic Characteristics of an Autonomous Underwater Helicopter

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Abstract: A new autonomous underwater vehicle (AUV) has high maneuverability near the bottom and a direction turnaround ability, called the autonomous underwater helicopter (AUH). This paper numerically investigates the hydrodynamic performance of the AUH. A Reynolds-Averaged Navier–Stokes (RANS) equation, a computational fluid dynamics (CFD) technique, is applied to analyze the AUH’s behavior. Investigations of the AUH’s hydrodynamic characteristics become more obvious with a service speed in the range of 0.4–1.2 m/s. For the same velocity condition, the resistance of the AUH increases, and the irregular eddy at the rear of the AUH expands with changes in the angles of attack and the length/height ratio. Essential design characteristics including pressure, velocity distribution, and velocity streamlines are shown and analyzed. These insights can be used as a guideline to reduce drag force and optimize the AUH profile for future designs. It has great potential for improving the AUH’s control algorithms.

Keywords: autonomous underwater vehicle; autonomous underwater helicopter; computational fluid dynamics; numerical simulation; hydrodynamic characteristics



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1. Introduction

In recent years, the study of motion stability in autonomous underwater vehicles (AUVs) with a disk-shaped hull has gained increasing importance within deep-sea mobile observation networks [1–3]. Motion stability analysis is crucial for improving the performance of autonomous underwater helicopters in complex underwater tasks, such as pipeline maintenance, mobile observation networks, resource exploration, and environmental sampling for hydrological research [4–6]. The challenging task of AUV control depends on the mass, payload, buoyancy, and working region. Notably, successful tests of disk-shaped AUVs with a new method using passive inverted ultra-short baseline (piUSBL) positioning in the South China Sea have marked advancements in the underwater navigation of AUV technology [7].

To ensure data collection, maintaining stability in horizontal motion and precise hovering in vertical motion is essential. Therefore, a new AUV model, the autonomous underwater helicopter (AUH), is proposed. During the operation of the AUH, it will be influenced by multiple factors: wave dynamics, water ingress, thruster performance,

buoyancy mechanisms, and others. Furthermore, the growing number of pipelines currently transport oil, natural gas, and fiber optic cables around the world. These systems encounter difficulties from the coastal environment, including seawater corrosion and unstable geological formations, which may result in damage, oil leaks, and disruptions to the global network. Zhang et al. [8] compared a multi-beam echo sounder (MBES) with forward-looking sonar (FLS) for the automated inspection of undersea pipelines. The Otsu algorithm is selected to reduce the recalculation time while preserving excellent computational efficiency. Adegboye et al. [9] reviewed numerous studies demonstrating that various factors influence pipeline monitoring and oil leakage detection in marine environments. Consequently, each approach is only appropriate for specific qualities and localities. Calculating energy is vital for AUVs to acquire more information during operational periods. Three critical factors include motion parameters, hydrodynamic coefficients, and control parameters. The aforementioned components denote the first-order sensitivity indices for energy consumption as proposed by Song et al. [10]. Two methodologies employed to assess energy management strategies are fuzzy logic and finite-state machines. [11]. Chen et al. [12] investigated the relationship between the Magnus force and controlling AUHs to characterize the disturbance area. In the literature about the seakeeping study of underwater vehicles, Qi et al. [13] presented research on the effects of forces experienced during the water-entering procedure with actual AUVs. The axial loads of the AUV have the greatest value when the AUV is launched and then become stable after a rapid decline. The radial force depends on the entry angle. The effects coming from the seabed are also carefully examined, focusing on understanding how these impact the overall dynamics and performance of underwater vehicles [14,15]. Wu et al. [16] developed a hybrid dynamic mesh method to simulate the AUH's hydrodynamic behavior. The hydrodynamic interference between the AUH and a cone-shaped dock depend on various docking parameters and ocean conditions. Reducing drag and decreasing power consumption is a critical problem in improving the operation of AUHs. So, Liu et al. [17] used just three vertical thrusters instead of four thrusters following the previous methods. In particular engineering applications, the drag and lift forces are important for operating AUHs. Scientists worldwide continuously find solutions to this problem, so the geometry of the AUH is necessary to produce a smoother and more accurate isogeometric analysis (IGA). Computer-aided design (CAD) methodologies and software tools create the irregular profile of complex shapes. Tanakitkorn et al. [18] based their research on the proportional–integral–derivative (PID) control system, enabling the transition from hover style to flight style. Sener et al. [19] focused on the hydrodynamic performance of a head AUH. It is described through skin friction distribution, wake area, and flow characteristics.

Computational fluid dynamics (CFD) is a crucial tool for analyzing the hydro-aerodynamic properties of fluid motion and has been utilized in applications such as microchannels, sterilizing chambers, torpedo-shaped underwater gliders, and heat transfer inside the gearbox [20–24]. The numerical results solved that heat, mass transport, and multiphase flow [25] issues significantly influence the motion behavior of fluids. Currently, to monitor the necessary seabed, there is very little equipment that can be surveyed here. Mitra et al. [26] applied the Reynolds Stress Model (RMS) to hydrodynamic characteristics with many different changes. CFD examines drag force performance through differences in the length-over-depth ratio (L/D) [27]. Amiri et al. [28] studied the role of the leeward vortical flow structure in the hydrodynamic behavior of underwater vehicles with the Froude number constant, submergence depths, and drift angles. With the increasing demand and more challenging tasks that humans set for underwater exploration, underwater vehicles are continuously being rapidly developed to serve that purpose. Shariati et al. [29] analyzed hydrodynamic characteristics that are caused by appendages such as rudders, hydroplanes, and sails. CFD is used to estimate the hydrodynamic coefficients of the circulating water channel (CWC) side wall for AUVs [30]. In recent years, much hydrodynamic research on AUHs has been conducted, but there is less research on hydrodynamic disturbance to AUHs' motion with various submarine speeds. The CFD technique is intriguing for

analyzing the hydrodynamic characteristics of an AUH, validating experimental results, enhancing control algorithms, and proposing an optimal design for further investigation.

In this study, numerical methods are utilized to investigate the hydrodynamics of the AUH. Governing equations and the Lagrangian–Eulerian (ALE) technique are used to obtain the transient velocity and pressure pattern around the AUH. It is known that the drag and lift force is changed through changes in velocity and pressure fields. The effects of velocity, the angle of attack (AOA), and the length/height ratio are considered. The numerical simulation results are also discussed and compared with previous experimental results.

2. Methodology and Numerical Approach

2.1. Methodology

The AUH operates almost at the seabed, completing tasks and missions that require motion stability, communication, charging, etc. In deep-sea exploration, many factors influence the disk-shaped hull, so we will attempt to achieve high maneuverability. Based on previous studies, the high maneuverability of the AUH is usually obtained by optimizing the geometry and thruster system. The AUH, equipped with two thrusters, experiences challenges in maintaining a steady orientation in the water. Conversely, employing four thrusters enables the AUH to modify and regulate its posture with greater efficacy, hence assuring steady motion. The hovering-type AUV features a symmetrical design and eight thrusters that provide enhanced stability; however, it occupies more space and results in increased energy losses. To increase the installation area for sensors and minimize energy consumption, the AUH is designed with four propellers, comprising two vertical and two horizontal propellers. The disk-shaped hull is defined as a body of revolution, with height and diameter being two critical dimensions for the profile of the AUH's hull. The Non-Uniform Rational B-Splines (NURBSs) include a curved B-spline and Bézier. It is convenient for making the design of curvature. As shown in Figure 1 and detailed in Table 1, the parameters used to model the AUH in ANSYS Fluent are defined. The AUH's parametric profile is sketched with three control points on a quarter of its outline.

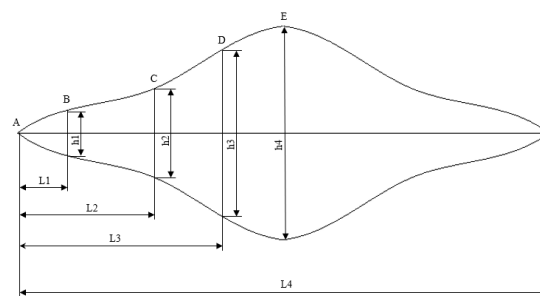


Figure 1. The schematic illustration is employed for calculations.

Table 1. Geometric characteristics of AUH utilized for computation.

Parameter.	Value
h1	100 mm
h2	160 mm
h3	300 mm
h4	400 mm
L1	125 mm
L2	250 mm
L3	375 mm
L4	1000 mm

Reynolds-Averaged Navier–Stokes (RANS) equations offer the most efficient approach for analyzing viscous flow. The k - ϵ or k - ω two-equation turbulence model is a turbulence model utilized in industrial applications. They are to perform a numerical analysis of hydrodynamic coefficients for AUV [31,32]. The governing equations encompass the conservation of mass, momentum, and Reynolds-Averaged Navier–Stokes (RANS) equations, which are employed to analyze the single-phase fluid flow surrounding the autonomous underwater helicopter and are expressed as follows:

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_i} (\rho \cdot u_i) = 0 \quad (1)$$

$$\frac{\partial}{\partial t} (\rho u_i) + \frac{\partial}{\partial x_j} (\rho u_i u_j) = \frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_i} \left[\mu \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} - \frac{2}{3} \delta_{ij} \frac{\partial u_i}{\partial x_i} \right) \right] + \frac{\partial}{\partial x_j} (-\rho \overline{u'_i u'_j}) \quad (2)$$

where u_i and u_j are the mean average flow velocities, u'_i and u'_j are fluctuation velocities, ρ is the density of water, p is the pressure, μ is the fluid dynamic viscosity, δ_{ij} is the Kronecker delta function, and $-\rho \overline{u'_i u'_j}$ is the Reynolds stress tensor, which shows the turbulence effect. The Reynolds stress for incompressible flow is expressed as follows:

$$-\rho \overline{u'_i u'_j} = \mu_t \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) - \frac{2}{3} \left(\rho k + \mu_t \frac{\partial u_i}{\partial x_i} \right) \delta_{ij} \quad (3)$$

$$\mu_t = \rho C_\mu \frac{k^2}{\epsilon} \quad (4)$$

where C_μ is a dimensionless constant.

The RNG k - ϵ turbulence model, which includes the transport equations for turbulent kinetic energy (k) and its dissipation rate (ϵ), can easily capture the symmetric flow field around the AUH hull. Therefore, RNG k - ϵ was adopted in this simulation.

$$\frac{\partial}{\partial t} (\rho k) + \frac{\partial}{\partial x_i} (\rho k u_i) = \frac{\partial}{\partial x_j} \left(\alpha_k \mu_{eff} \frac{\partial k}{\partial x_j} \right) + G_k + G_b - \rho \epsilon - Y_M + S_k \quad (5)$$

$$\frac{\partial}{\partial t} (\rho \epsilon) + \frac{\partial}{\partial x_i} (\rho \epsilon u_i) = \frac{\partial}{\partial x_j} \left(\alpha_\epsilon \mu_{eff} \frac{\partial \epsilon}{\partial x_j} \right) + C_{1\epsilon} \frac{\epsilon}{k} (G_k + C_{3\epsilon} G_b) - C_{2\epsilon} \rho \frac{\epsilon^2}{k} - R_\epsilon + S_\epsilon \quad (6)$$

G_k denotes the generation of turbulent kinetic energy attributed to mean velocity gradients, G_b signifies the generation of turbulent kinetic energy resulting from buoyancy, and Y_M indicates the contribution of fluctuating dilatation in compressible turbulence to the total dissipation rate. α_k and α_ϵ represent the inverse effective Prandtl numbers for k and ϵ , whereas S_k and S_ϵ denote user-defined source terms. The correlation constants are denoted as $C_{1\epsilon}$, $C_{2\epsilon}$, and $C_{3\epsilon}$. The parameters G_k and G_b are specified as follows:

$$G_k = \mu_t \cdot S^2 \quad (7)$$

$$G_b = \beta g_i \frac{\mu_t}{Pr_t} \frac{\partial T}{\partial x_i} \quad (8)$$

where Pr_t is the turbulent Prandtl number for energy, g_i is the component of gravity, β is the coefficient of thermal expansion, and S is the modulus of the mean rate of the strain tensor.

The total pressure p_t is estimated by:

$$p_t = p_s + p_g \quad (9)$$

where p_s is the atmosphere pressure and p_g is the gauge pressure.

The total drag force, including friction force, is caused by the surface shear stress of the AUH and the pressure resistance. Therefore, the total drag coefficient (C_d) and the lift coefficient (C_L) are written as follows:

$$C_d = \frac{F_{df}}{\frac{1}{2}\rho U^2 A_f} + \frac{F_{dp}}{\frac{1}{2}\rho U^2 A_f} \quad (10)$$

$$C_L = \frac{F_L}{\frac{1}{2}\rho U^2 A_f} \quad (11)$$

where F_{df} is the viscous fluid force caused by the surface of the glider, F_{dp} is the pressure fluid force, A_f is the wetted surface of the AUH, and F_L is the hydrodynamic lift force.

ANSYS-FLUENT is useful as the CFD simulation tool. Figures 2 and 3 show a computational zone for the simulation with a length, width, and height of 12 m $\times$ 4 m $\times$ 5 m, which is adopted to achieve the simulation results [33]. The coordinate origin was set as the center of the AUH. The inlet velocity is applied to the flow entering the computation domain. The pressure outlet is used on the side opposite the inlet with a pressure outlet. The hull of the AUH is a non-slip wall, and other components use the free slip wall condition.

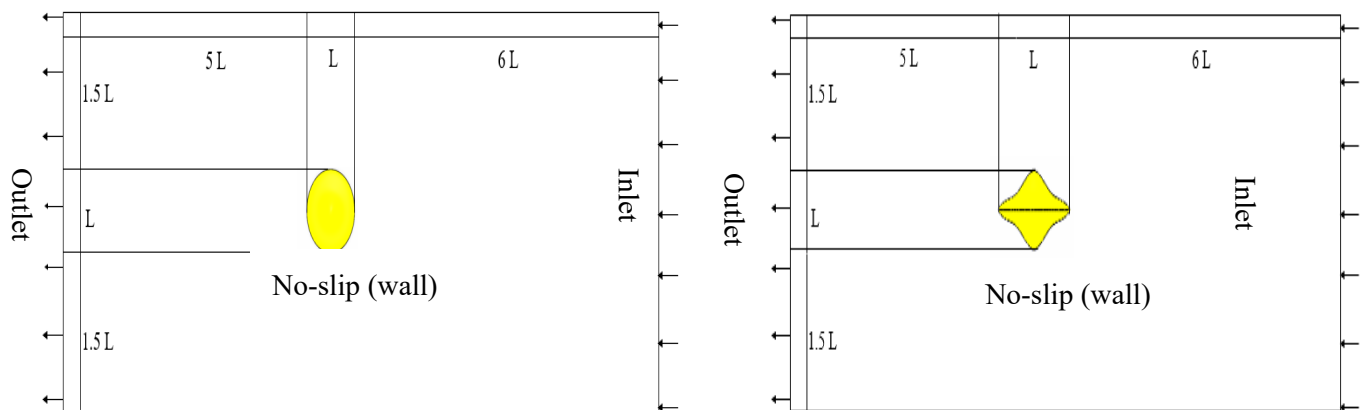


Figure 2. The boundary conditions for translation: superior perspective in the Oxz plane and lateral perspective in the Oxy plane.

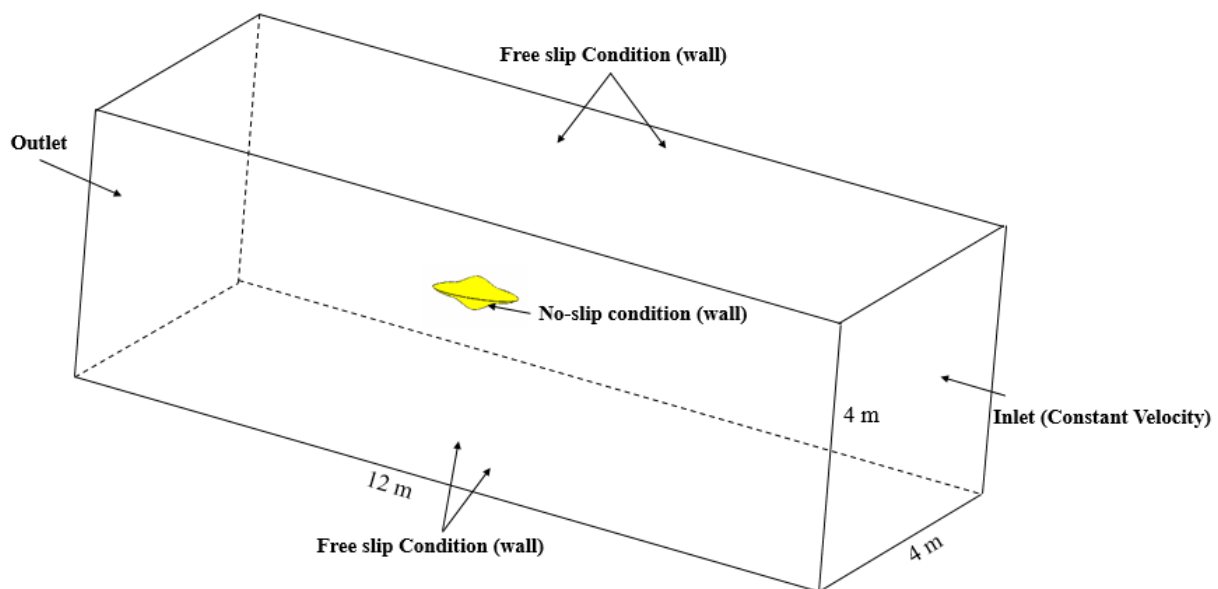


Figure 3. The domain of numerical computation.

2.2. Numerical Approach

To investigate the hydrodynamics of the AUH well, the finite volume method (FVM) is applied to mesh the model. The mesh is divided into two types: structured mesh and unstructured mesh to handle complex geometry [34]. The density of the mesh will be concentrated around the profile of the disk-shaped underwater vehicle, while other areas will have gradually larger mesh sizes. To simulate with the least error compared with the experimental results, the size of the mesh elements is critical. The size of the mesh has a direct impact on the accuracy of CFD results, so we relied on several evaluation criteria such as skewness, orthogonal quality, and Δy^+ . We estimated the appropriate parameters for this simulation the boundary layer thickness.

$$\delta = 0.035L\text{Re}^{-\frac{1}{7}} \quad (12)$$

where L is the diameter of AUH, Re is the Reynolds number defined by $\rho U \nabla^{\frac{1}{3}} / \mu$, and ∇ is the volume of AUH.

To correctly model the first layer, the thickness can be expressed as follows:

$$\Delta y = L\Delta y^+ \sqrt{80\text{Re}}^{-\frac{13}{14}} \quad (13)$$

In this case, the dimensionless wall distance value usually satisfies the simulation of the AUH for $20 < \Delta y^+ < 200$ [14], so the first layer thickness $\Delta y = 0.86$ mm. The total thickness of the boundary layer around the AUH hull was calculated with Equation (12) to be approximately 5.44 mm and the growth rate was 1.2. Figure 4 demonstrates the tetrahedral grid used in this study. The overlapping mesh is employed in the simulation. The computational zone is segmented into a background zone and a dynamic zone.

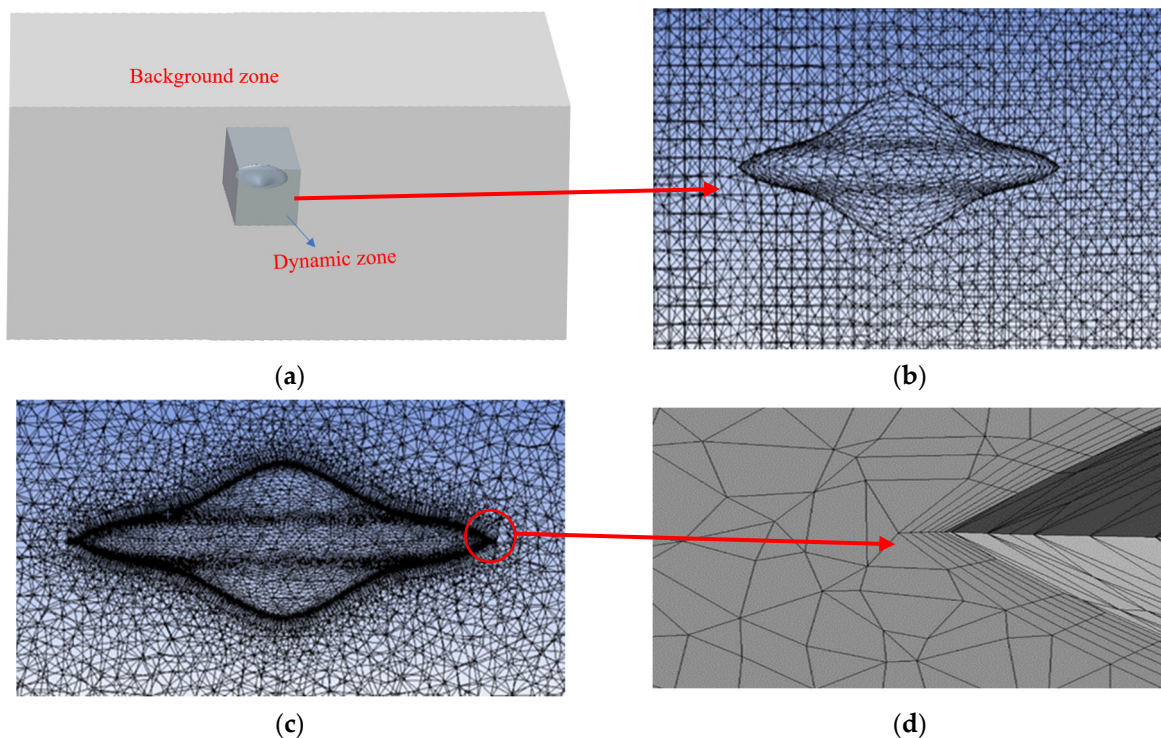


Figure 4. The (a) tetrahedral structured computational domain grid, (b) initial mesh, (c) boundary layer after refining the mesh boundary layer mesh, and (d) boundary layer mesh.

The dependency of the number of elements can lead to errors in the CFD calculation process; thus, the round-off and interval were ignored together with the discretization uncertainty [35]. Likely, the number of inflation layers, mesh size, and assumptions made

in the numerical modeling may not fully capture the complex fluid dynamics around the AUH and similar aspects. Besides CFD factors, surface roughness, small protrusions, temperature changes over time, and other time-varying factors also have an impact on error generation. The number of elements for the dynamic zone is 0.4 million. The grid independence is checked by calculating the drag force along the x -axis (F_x), with the total number of elements, as shown in Table 2. The elements are increased by refining the surface meshes on the AUH. In the numerical domain with 2.8×10^6 elements, the drag force tends to be stable. Therefore, meshes of the same sizes are created. If a higher number of elements are generated, it will lead to longer calculation times without a significant improvement in accuracy.

Table 2. Change of element sizes.

Total Numbers Elements (Millions)	Refined Elements Size of Background Zone (mm)	Drag Force (N)
1.5	100	15.96
2.8	80	15.82
3.8	60	15.78

3. Results and Discussion

In this investigation, the AUH travels horizontally at a velocity of $U = 0.8$ m/s with an angle of attack of zero degrees. Figure 5 depicts the pressure field surrounding the AUH at various time intervals. Initially, the pressure is uniformly distributed across the AUH's profile. As the AUH moves, the pressure distribution intensifies in the bow of the AUH. At the time $t = 2$ s, the pressure distribution equalizes both anteriorly and posteriorly relative to the AUH. During this period, the pressure near the bow of the AUH exhibits modest fluctuations around 200 Pa. This phenomenon directly influences the resistance between the vessel's solid surface and the fluid. The numerical results indicate that the fluid flow greatly affects the tip of the nose. Consequently, in future designs of the AUH, it is essential to focus on the bow where the initial interaction between the AUH and the flow occurs in the direction of movement. Regions of elevated gauge pressure should possess a streamlined configuration to prevent the induction of motion imbalance.

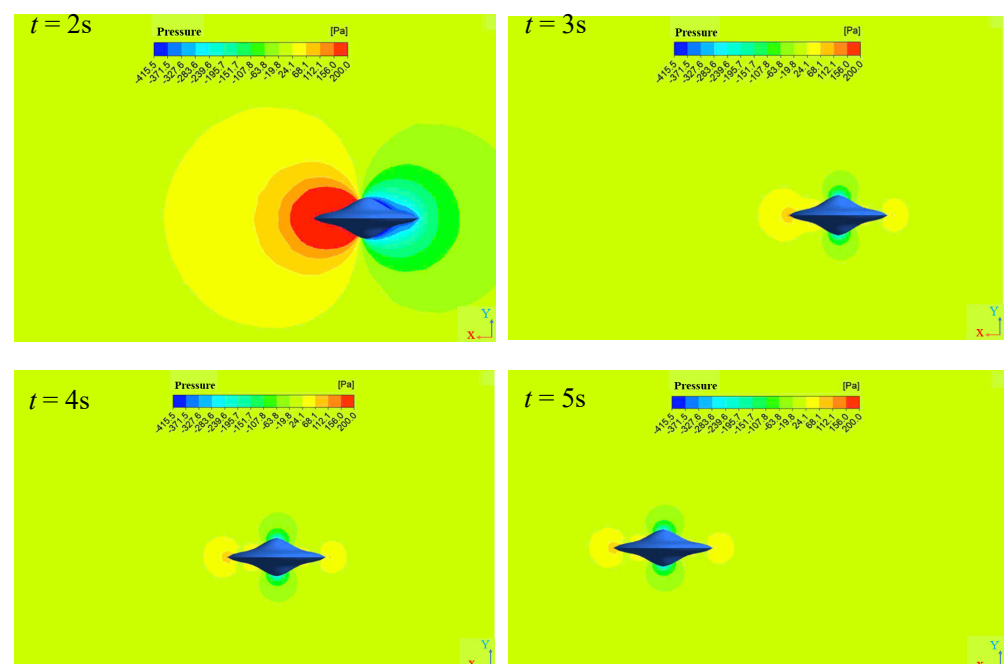


Figure 5. Pressure contour of AUH at different times.

Figure 6 shows the velocity contour representing the effect between the flow and the AUH hull. Based on the Bernoulli equation, pressure and velocity are two quantities that are inversely proportional to each other. When the fluid flow encounters the AUH, it will create a stagnation point, which divides the flow into upper and lower parts. The fluid flow moves closely along the profile of the AUH. The velocity of the fluid flow has the smallest value in front of the AUH, and at the top position of the vehicle, the fluid speed reaches the maximum value. Figure 7 depicts the streamlines around the AUH in the xoy and xoz planes at the selected time. Because the profile of the AUH is a disk-shaped rotating body, the streamlines are also distributed symmetrically through the X-axis. The structure of the AUH creates small vortices near the disk-shaped hull form, but this only creates slight vibrations for the AUH when horizontally moving. Therefore, according to Figure 7c,d, the AUH can deduct the fluctuation in the hydrodynamic force (F_z) as small, ensuring it does not affect the accuracy of the fixed point tracking.

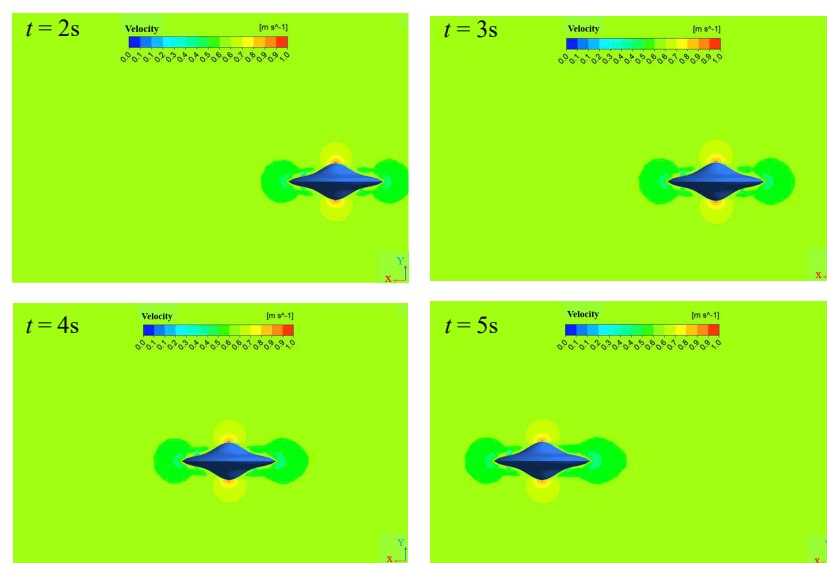


Figure 6. Velocity contours of AUH at different times.

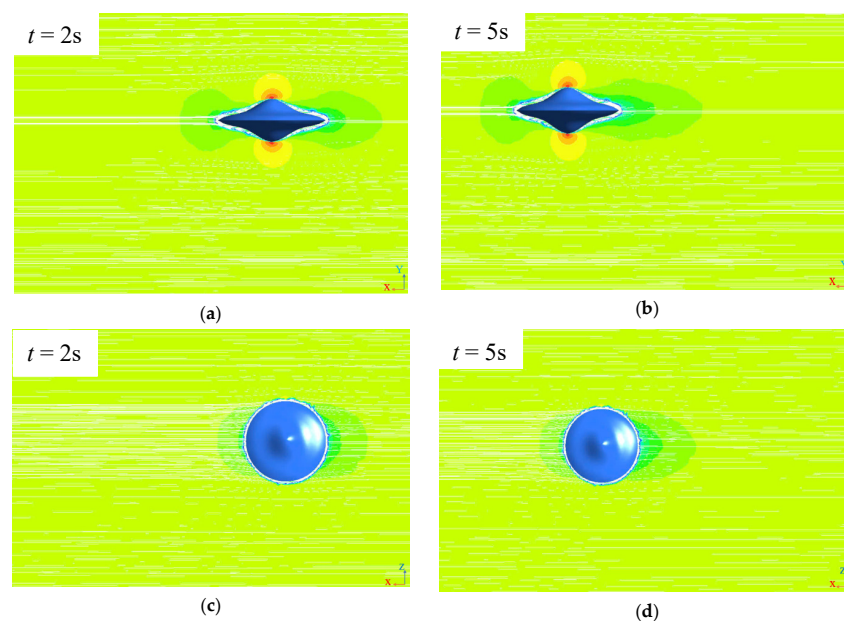


Figure 7. The streamlines around the AUH with the AOA = 0° in the xoy (a,b) and xoz (c,d) planes at different times.

The computational domain around the AUH is water with density $\rho = 1025 \text{ kg/m}^3$ and fluid viscosity $\mu = 0.00125 \text{ Pa}\cdot\text{s}$. Figure 8 indicates the drag force impact on it from 0.1 to 1.2 m/s. The numerical results of the drag force were compared with the experimental observation [36]. The error in simulation results compared to reality ranges from 2% to 14.2%, which verifies the feasibility and accuracy of the model [37].

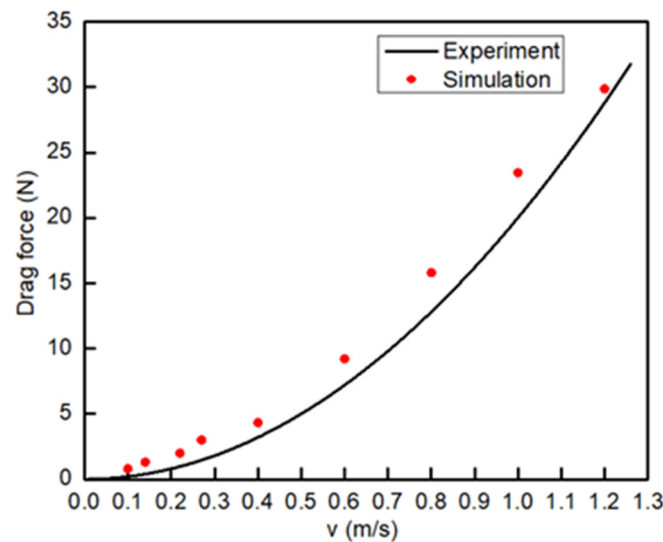


Figure 8. Validation of drag forces.

This study examines the hydrodynamic parameters of the AUH at various velocities ranging from 0.4 to 1.2 m/s. Figure 9 illustrates the drag and lift forces exerted on the AUH body at various velocities over time. Initially, the levels of drag and lift forces significantly diminish, subsequently stabilizing as time progresses. Figure 10 illustrates the top views of the pressure distribution surrounding the glider's circumference at a velocity of $U = 0.8 \text{ m/s}$, corresponding to various angles of attack. As the angle of attack increases, the augmented wet cross-section of AUH alters the hydrodynamic force and the position of boundary layer separation. In the xoz plane, it is clear that the pressure distribution at the top side ($z+$) and bottom side ($z-$) on the AUH's configuration did not alter with the same value of the AOA.

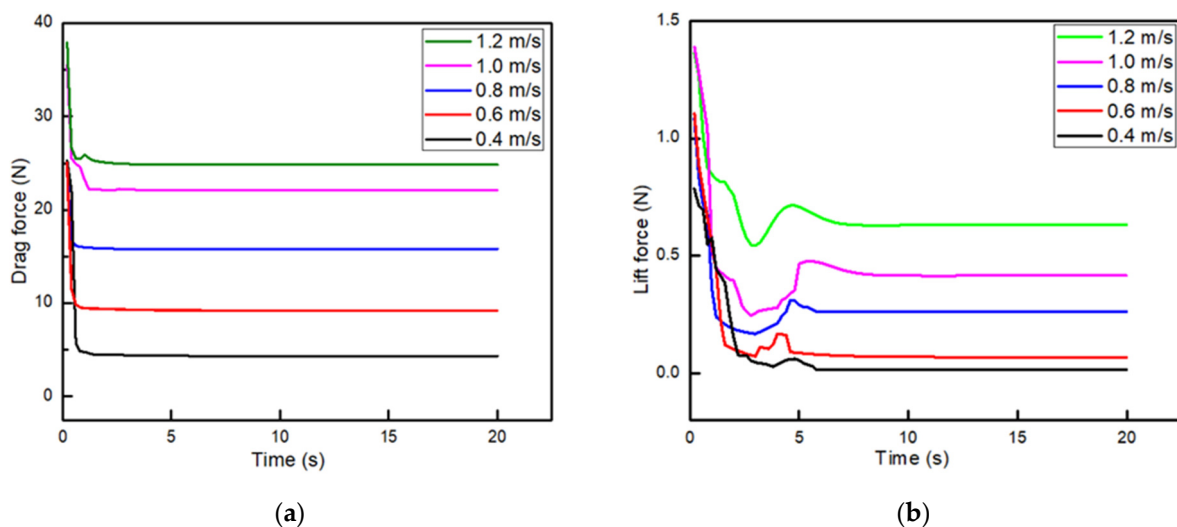


Figure 9. (a) Drag and (b) lift force of AUH at different velocities.

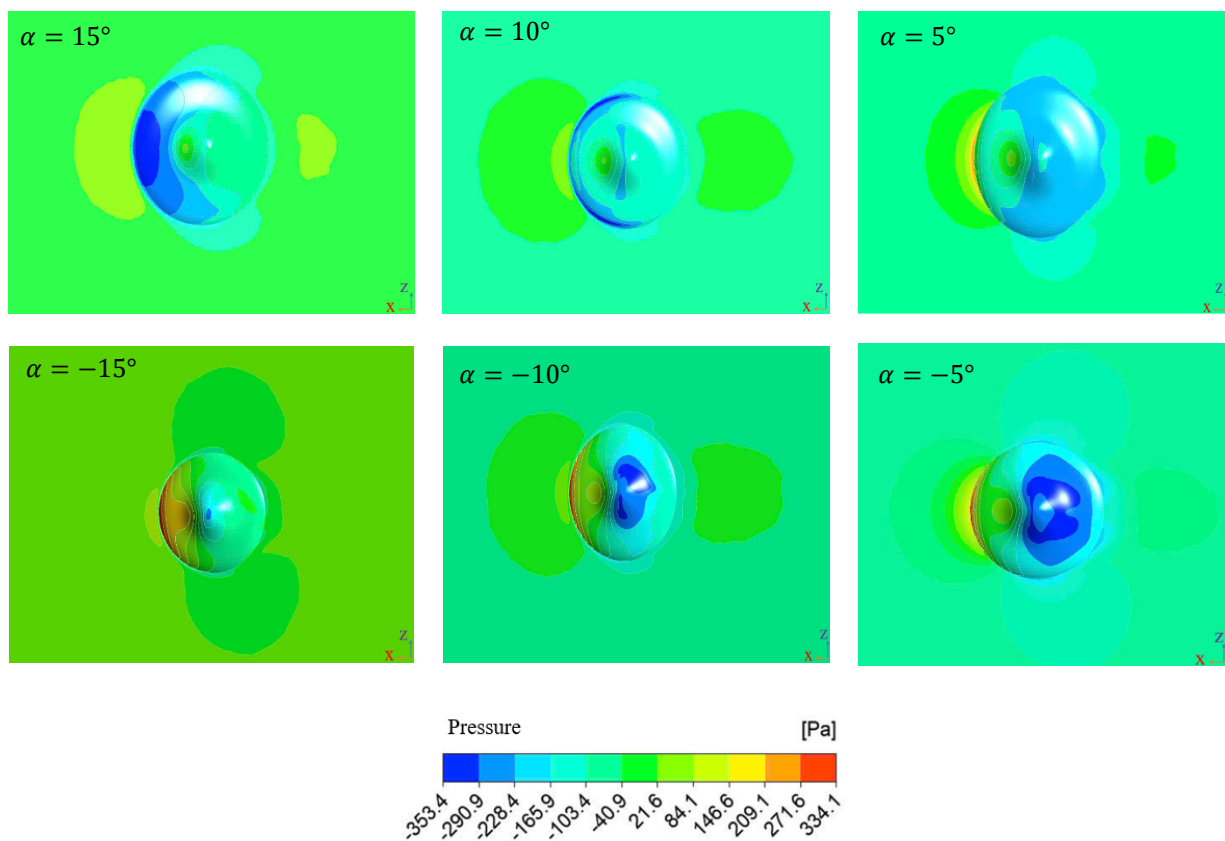


Figure 10. The pressure distribution in the xoz plane (top) of the AUH with different AOAs.

Figure 11 shows the fluid dynamics surrounding the AUH at a velocity of $U = 0.8$ m/s, examining several angles of attack (-15° , -10° , -5° , 0° , 5° , 10° , 15°) in this analysis. The velocity contours around the AUH's body indicate favorable hydrodynamic performance. The current results indicate that the velocity distribution is significantly influenced by the angle of attack. The fluid traverses the surface of AUH, revealing the emergence of a wake zone at the rear of AUH. In the wake region, there is a combination of high pressure and low pressure, so it is easy to promote vortices. The larger the AOA, the larger the vortex area behind the vehicle.

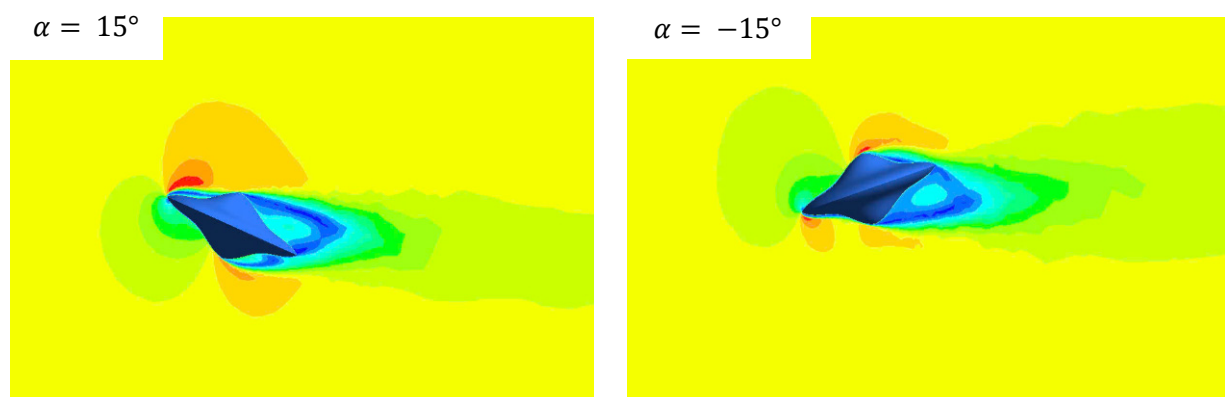


Figure 11. Cont.

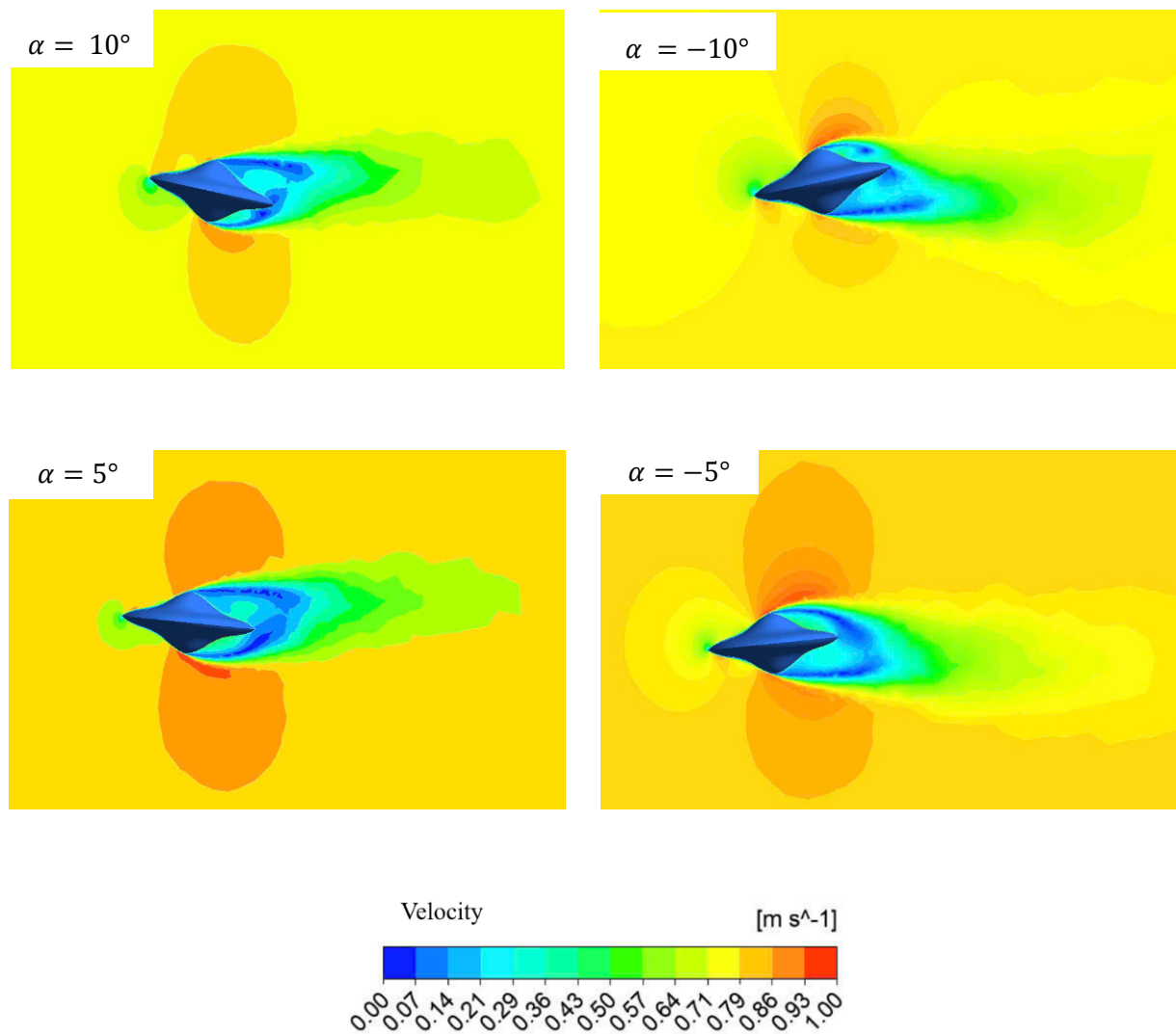


Figure 11. The velocity contours surrounding the AUH with a velocity of $U = 0.8$ m/s at various angles of attack.

Figure 12 shows the relationship between drag and lift forces with angles of attack and varying speeds. The graphic indicates that at an angle of attack of 0° , the drag forces are minimized, which elucidates that the fluid flowing over the AUH does not generate a vortex. The drag resistance will gradually increase: as the AOA increases, the higher the speed and the higher the resistance. The lift force and AOA increase at a linear rate, which makes the AUH unbalanced and makes it difficult to adjust the buoyancy system. Additionally, the high speed also contributes to a greater lift force. Most notably, when analyzing the AUH's operation at angles of attack (AOAs) of -20 , -15 , 15 , and 20 degrees, the simulation results reveal substantial variations in both drag and lift forces. The drag force increases by two to four times compared to when the $AOA = 0^\circ$. Similarly, the lift force undergoes significant changes, increasing from single-digit values ($AOA = 0^\circ$) to several hundred. This gives us a suggestion that in controlling the AUH, we should operate the AUH with an angle of attack between 10° and -10° . In this range, drag and lift are small and there is no need to use high-power engines.

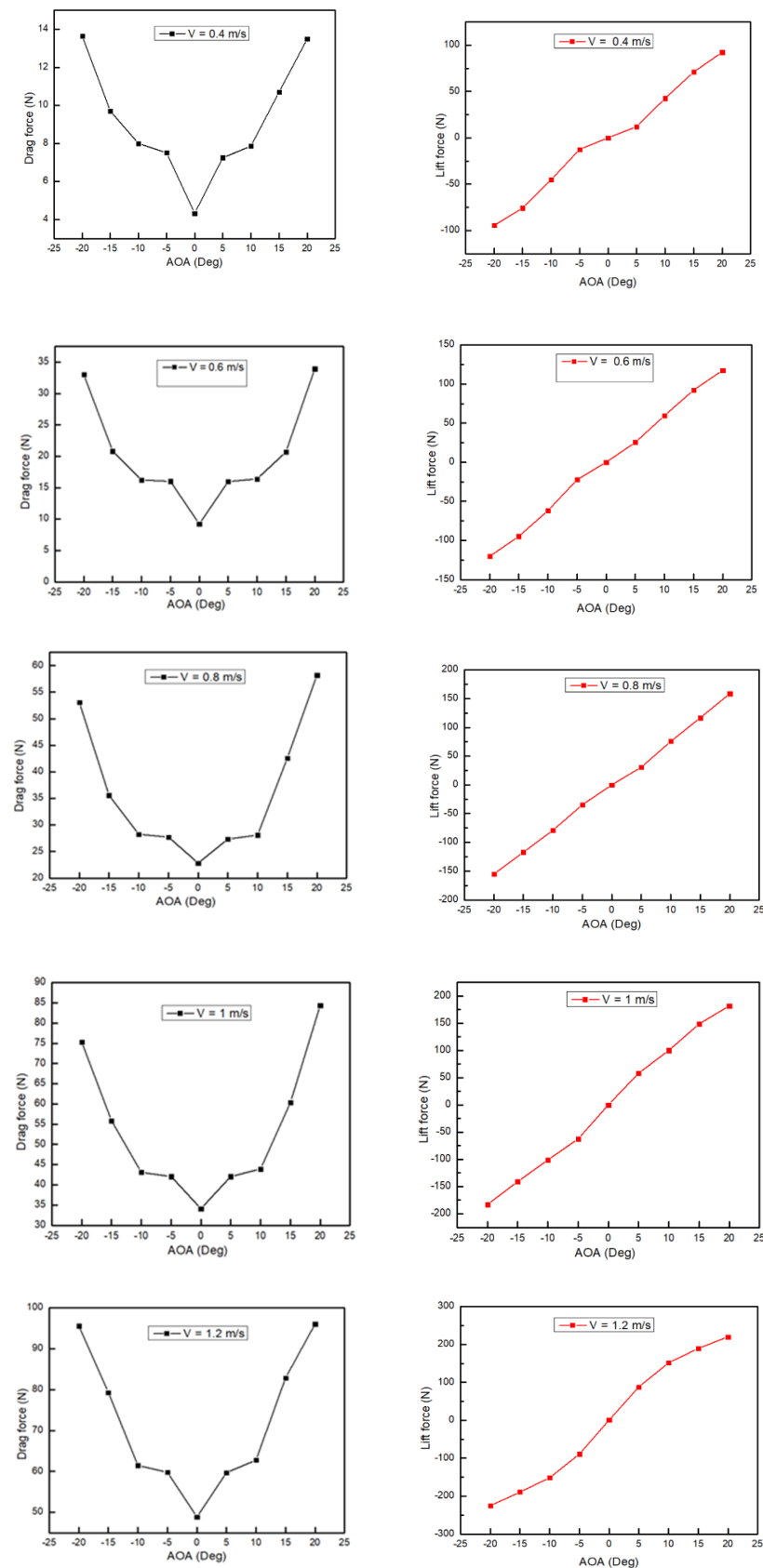


Figure 12. The lift and drag forces in relation to the angle of attack at various velocities of the AUH.

This study examines the impact of AUH length on hydrodynamic coefficients. Figure 13 illustrates the modification of the AUH's profile. The height of the AUH re-

mains at 400 mm. Conversely, the length varies between 600 mm and 1200 mm. At a velocity of $U = 0.8$ m/s, Figure 14 illustrates the fluid flow distribution surrounding the disk-shaped hull with varying length/height (L/H) ratios. Across all cases, high-pressure zones are concentrated at the bow of the AUH, whereas low-pressure zones are developed at the rear. The simulation results present increasing L/H ratios, and the high-pressure regions tend to decline. Figure 15 illustrates the hydrodynamic coefficient at various L/H ratios. The numerical results indicate that an increased (L/H) ratio correlates with elevated drag and lift coefficients. This is because in the horizontal direction (X -axis), the wet cross-sectional area of the AUH will increase as the L/H ratio increases. According to the simulation results, the black solid line (C_d) has a speed greater than the raised speed of the red solid line (C_l). Therefore, the lift coefficient/drag coefficient ratio decreases as the L/H ratio becomes larger. However, drag and lift should be restricted to ensure the AUH's ability to operate. By analyzing the dimensionless hydrodynamic coefficient, we propose that the origin AUH model (Figure 13c) approaches suitable hydrodynamic characteristics and enough space to contain the necessary equipment.

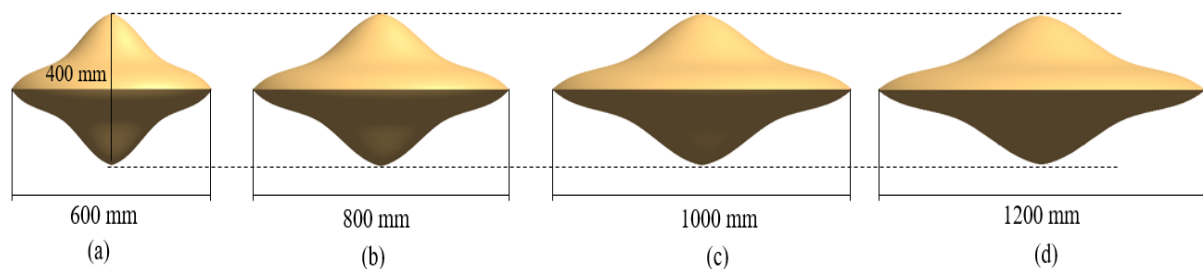


Figure 13. The modified models of the AUH (a) 600 mm (b) 800 mm (c) 1000 mm and (d) 1200 mm.

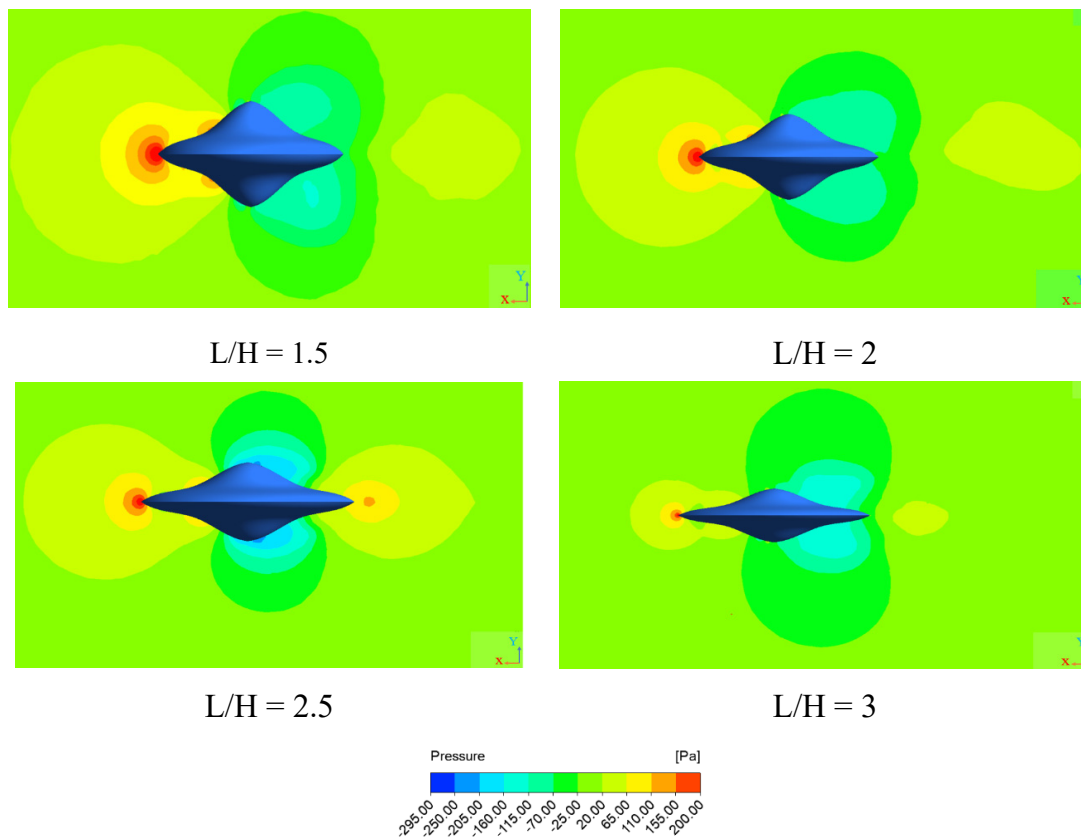


Figure 14. The pressure contours around the AUH with different length/height.

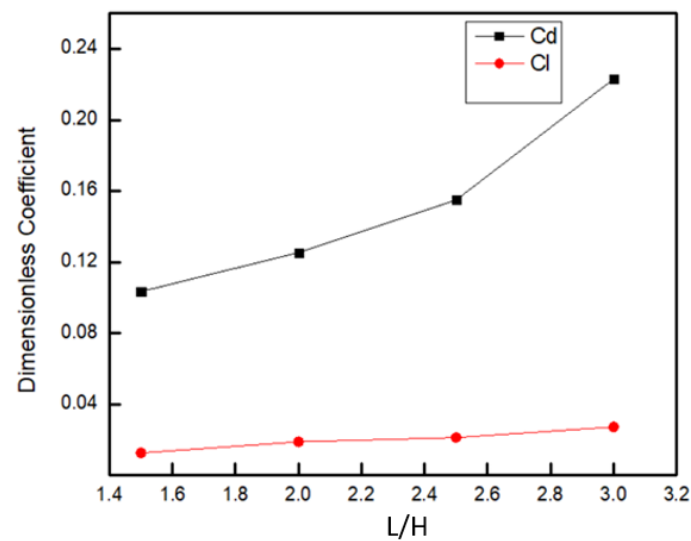


Figure 15. The lift and drag coefficients around the AUH model versus its length-to-height ratio.

4. Conclusions

This work numerically analyzed the hydrodynamic performance of a disk-shaped AUH. The AUH was examined with several altering parameters, including modifications to the angle of attack, velocity, and length-to-height ratio. The numerical results demonstrated that the apex of the AUH's snout exhibits the highest velocity value while traversing through water. The AUH operates with an angle of attack ranging from -10° to 10° and a velocity below 0.8 m/s; the disk-shaped AUV exhibits little drag and lift forces. This indicates that the AUH conserves more energy and has superior motion stability. It has been noticed that an increase in velocity correlates with an increase in drag force. Then, according to a series of CFD simulations with increasing velocity, the AUH can operate well at a velocity from 0.8 m/s to 1.2 m/s. This range of velocity helps the AUH adapt both operating speed and hydrodynamic performance. Simulation studies demonstrating variations in the length-to-height ratio suggest that the dimensionless hydrodynamic coefficients often rise. Taking an appropriate value of the L/H ratio between 2.5 and 3 is appropriate because it provides balance not only to the design space but also the performance of the AUH's propulsion system. The numerical findings corroborate prior experimental outcomes. The current results are quite suitable for future designs related to autonomous underwater vehicles. The knowledge gained from this research can contribute to the development of improved design strategies, control algorithms, and operational guidelines for autonomous underwater helicopters. This field holds great potential for advancing the capabilities and applications of AUHs in various underwater missions and inspections, and future AUH models will be further improved.

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