

Article

Experimental and Numerical Investigation of Hydrodynamic Characteristics of Aquaculture Nets: The Critical Role of Solidity Ratio in Biofouling Assessment

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Abstract

Biofouling on aquaculture netting increases hydrodynamic drag and restricts water exchange across net cages. The solidity ratio is introduced as a quantitative parameter to characterize fouling severity. Towing tank experiments and computational fluid dynamics (CFD) simulations were used to assess the hydrodynamic behavior of netting under different fouling conditions. Experimental results indicated a nonlinear increase in drag force with increasing solidity. At a flow velocity of 0.90 m/s, the drag force increased by 112.2%, 195.1%, and 295.7% for netting with solidity ratios of 0.445, 0.733, and 0.787, respectively, compared to clean netting ($S_n = 0.211$). The drag coefficient remained stable within 1.445–1.573 across Re of 995–2189. Numerical simulations demonstrated the evolution of flow fields around netting, including jet flow formation in mesh openings and reverse flow regions and vortex structures behind knots. Under high solidity ($S_n = 0.733$ – 0.787), complex wake patterns such as dual-peak vortex streets appeared. Therefore, this study confirmed that the solidity ratio is an effective comprehensive parameter for evaluating biofouling effects, providing a theoretical basis for antifouling design and cleaning strategy development for aquaculture cages.

Keywords: netting panel; biofouling; drag coefficient; CFD; flow field

1. Introduction

Marine aquaculture is one of the fastest-growing sectors within the global food production system and plays a key role in ensuring food security and supplying high-quality protein [1]. As a primary form of modern marine aquaculture, the performance of cage farming systems directly affects production efficiency and economic outcomes. A major challenge for the industry is biofouling, which involves the attachment and growth of marine organisms such as algae, shellfish, hydroids, and mollusks on net surfaces [2]. This process substantially increases structural load, as the drag of fouled netting can exceed that of clean netting by more than a factor of three [3], and it also restricts water exchange, leading to lower dissolved oxygen levels and localized eutrophication that threaten the health of farmed species.

Although several biofouling mitigation techniques exist, including antifouling coatings and mechanical cleaning [4], these methods often involve high economic costs and potential environmental concerns. Recent studies have explored biological controls such as



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deposit-feeding sea cucumbers, though their efficacy depends on competing food sources in salmon cages [5]. Comprehensive analysis of the mechanisms through which biofouling alters net hydrodynamic properties is therefore essential for the safe design and informed maintenance of cage systems.

Research on the hydrodynamic characteristics of clean netting has produced systematic findings [6–9]. Balash et al. [10] investigated the drag characteristics of netting under varying flow conditions through experiments and the lumped mass method. Tang et al. [11] evaluated the effects of knot type and solidity on hydrodynamic coefficients, while Bi et al. [12] applied porous media models to simulate flow fields around netting. These studies provide the foundation for analyzing the hydrodynamic behavior of fouled netting. It is worth noting that the accurate prediction of net hydrodynamic loads is not only critical for understanding biofouling impacts but also forms an essential input for the broader structural analysis and design of cage systems under various environmental conditions. In this context, advancements have been made in modeling the fluid–structure interaction of net cages, including analytical approaches for flexible structures [13] and reviews synthesizing theoretical developments for assessing system efficiency and survivability [14]. These works underscore the importance of reliable hydrodynamic parameters, such as drag coefficients under fouled conditions, as fundamental inputs for overall structural integrity evaluation.

Current research on biofouling effects relies on two main approaches: long-term field deployment to obtain naturally fouled samples and controlled simulation with artificial materials. The former is constrained by environmental conditions, making fouling parameters difficult to control, while the latter cannot fully capture the complexity of real-world fouling. Swift et al. [3] observed substantial drag increases in fouled netting but were unable to isolate the effects of different fouling types. Liu et al. [15] sampled fouled netting in Fujian’s East China Sea waters and reported dominant fouling by crustaceans, mollusks, and algae, with average thicknesses of 12.4–30.9 mm and seasonal variation, with higher levels in summer and lower levels in winter. Their flume tests revealed that PET netting had the lowest drag coefficient (≈ 0.53), while UHMWPE and PE netting exhibited 161.2% and 133.5% higher drag, respectively. Their BP neural network model, based only on fouling thickness and density, lacked accuracy due to discrepancies between in situ flow conditions and static laboratory measurements. Lader et al. [7] conducted controlled experiments with artificial hydroids on netting and found that drag increased by 1.5–2.2 times for 9 mm hydroids and by 2–3.8 times for 21 mm hydroids compared with clean netting. Farshad et al. [8] developed a full-scale gravity cage model, using polyester netting wrapped with nylon ropes to simulate fouling at varying densities. Previous studies have provided valuable insights into the hydrodynamic effects of biofouling on aquaculture nets. For instance, Bi et al. [9] and Cornejo et al. [16] focused on flow field alterations, demonstrating that fouling modifies both internal and external flow patterns around net cages. Lader et al. [7] systematically examined the influence of fouling organism morphology and flow conditions, confirming that net stress depends on key factors such as organism length, growth duration, and Reynolds number (Re). In terms of experimental simulation, Gansel et al. [17] employed physical modeling to investigate the effects of hydroid fouling and established empirical relationships between net drag and fouling density. To further integrate and simplify fouling-related parameters, Chen et al. [18] proposed using solidity as a unified indicator for hydrodynamic assessment, combining rigid (acrylic plates) and flexible (PA monofilament) materials to mimic diverse fouling characteristics. This approach balances parameter control with biological realism and offers new insight into how fouling thickness and density influence hydrodynamic responses.

Fouling in Zhejiang's coastal waters exhibits distinct traits (Figure 1). Biological secretions form sticky matrices on net twines, gradually sealing mesh openings, with attachment patterns that vary with season and temperature. These secretions host hydroid colonies, producing composite fouling that is neither purely rigid nor flexible. The basal layer resembles cured bio-coating, while surface hydroids show dynamic responses. Existing simulation methods do not capture this complexity. To address the above limitations, this study proposes and follows a core research paradigm: transforming the complex morphological problem of biofouling into a problem defined by a key, quantifiable, and precisely controllable hydrodynamic parameter. For this purpose, we introduce the solidity ratio (S_n) as a comprehensive proxy parameter to characterize the degree of fouling. For the first time, we systematically employ a controllable resin-coating technique to prepare experimental netting samples with precisely graded S_n values ($S_n = 0.211\text{--}0.787$). This methodological innovation represents the primary original contribution of this study. It enables the parameterized and repeatable laboratory simulation of the hydrodynamic effects of "secretion–organism" composite fouling.



Figure 1. Biofouling accumulation on netting panels in Zhejiang coastal waters (**Left:** May–June; **Right:** May–August).

Based on this, the clear objective of this study is to quantitatively reveal the decisive influence and underlying mechanisms of the solidity ratio (S_n), as a single controlling variable, on the drag characteristics, drag coefficients, and surrounding flow-field structures of netting. This will be achieved through systematic towing tank experiments and computational fluid dynamics (CFD) simulations. This work aims to provide direct theoretical parameters and a universal predictive basis for the hydrodynamic design of anti-fouling cages. It thereby addresses the current research gap in extracting general design principles from complex fouling phenomena.

2. Materials and Methods

2.1. Fouling Netting Model

The experimental samples consisted of polyethylene knotless warp-knitted netting with a mesh size of 20.0 mm and a twine diameter of 2.0 mm. The netting was cut into six rectangular pieces measuring 50 cm × 50 cm, using a transverse hanging ratio of 0.707. Each piece was mounted onto stainless steel rectangular frames of the same dimensions (50 cm × 50 cm). To prevent deformation during testing, the edges of the netting were secured to the frames by tying each mesh with thin threads. Ten randomly selected twines were measured using a micrometer to verify diameter consistency. To simulate varying degrees of biofouling, five of the netting panels were uniformly coated with different concentrations of resin (Figure 2B–F). After air-drying at room temperature, the treated panels represented different levels of biofouling accumulation. The specific treatment effects are shown in Figure 2.

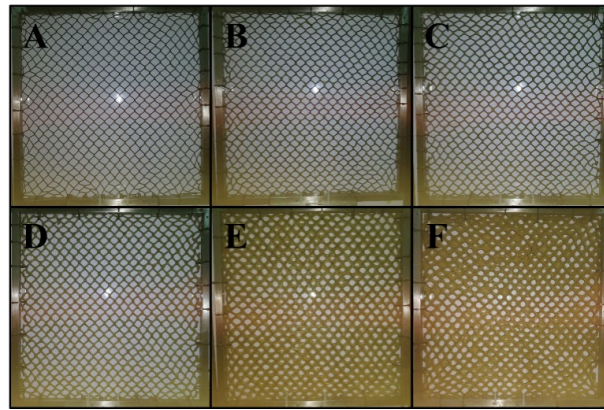


Figure 2. Clean (A) and fouled netting (B–F) diagrams.

2.2. Experimental Setup and Procedures

2.2.1. Experimental Equipment

The experiment was conducted in the still water tank at the East China Sea Fisheries Research Institute (ECSFRI). The tank is 90.0 m long, 6 m wide, and 3 m deep (freshwater density: 998.2 kg/m^3 ; temperature: $17.6\text{--}18.4 \text{ }^\circ\text{C}$). Hydrodynamic performance testing of the netting panels was carried out using towing tank experiments. Towing carriage: It was driven by a servo motor to provide stable and adjustable towing speeds for the test net panel. Towing speed accuracy met a relative precision of $p \leq 1\%$. A current meter (three-component ECVI ACM3-RS, JFE Advantech Co., Ltd., Nishinomiya, Japan) was installed approximately 2.0 m upstream of the netting panel to measure flow velocity. A three-component load cell (LSM-B-500NSA1-P, KYOWA Electronic Instruments Co., Ltd., Tokyo, Japan) with a 500 N capacity and a specified accuracy of 2%: Installed between the carriage and the test frame, it directly measured the hydrodynamic forces (drag and lift) acting on the net sample. The load cell signals were amplified using a dynamic strain amplifier (DPM-6H) and transmitted, along with flow velocity data, to an A/D converter and a computer. Data were sampled at 100 Hz (Figure 3).

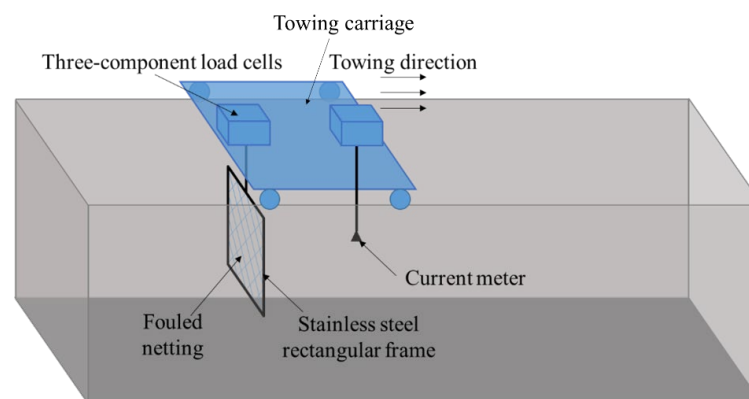


Figure 3. Schematic diagram of the experimental setup to measure the hydrodynamic force of the fouled netting.

2.2.2. Experimental Procedures

Net drag force was obtained by subtracting the stainless steel frame drag from the combined drag of the net and frame. First, the stainless steel frame was attached to the three-component load cell with the frame plane perpendicular to the towing direction. The load cell was calibrated and zeroed before and after each test, and linearity was verified. Frame drag was measured at towing speeds from 0.3 to 1.1 m/s in 0.1 m/s increments. Second, 42 tests (6×7) were conducted on the combined structure at seven towing speeds

($u_0 = 0.5, 0.6, 0.7, 0.8, 0.9, 1.0$, and 1.1 m/s). The frame and net were mounted on the load cell with the frame plane kept perpendicular to towing. The relationship between drag coefficient and Reynolds number was analyzed to assess fouling effects. Data points at 4 Hz were recorded during 70 m of towing, and average values were calculated from these measurements.

2.3. Data Extraction and Processing

Figure 4 presents a schematic diagram illustrating the projection processing of clean and fouled netting, with panels A–F corresponding to the samples shown in Figure 2. To accurately calculate the projected area of fouled netting, the pixel ratio method was employed. The procedure involves importing the photographs of netting samples taken perpendicular to the shooting direction into Adobe Photoshop CC 2014. Using the ‘Magic Wand’ or ‘Pen’ tool, the outer rectangular outline of each netting sample was precisely selected to obtain the total pixel value, defined as the outline area pixel (P_o). Within the same image, all areas rendered opaque by fouling coatings—namely, net threads and fouling materials that obstruct the background—were selected, and their combined pixel value was recorded as the projected area pixel (P_p). Figure 4 visually demonstrates the variation in projected regions from clean netting to netting with different fouling levels: transparent grid areas represent mesh openings that permit flow, while red-filled areas indicate non-permeable projections resulting from fouling. The solidity ratio (S_n) is then derived using formula (1) based on the ratio of P_p to P_o , and the results are shown in Table 1.

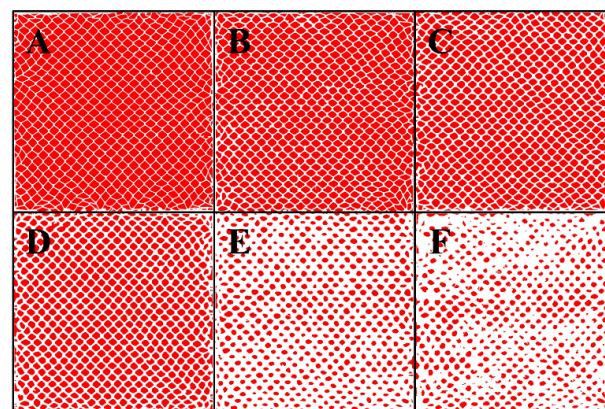


Figure 4. Clean (A) and fouled netting (B–F) projection diagrams.

Table 1. Pixel-based projected area measurements of clean and fouled netting.

Netting	Outline Area Pixels	Projected Area Pixels	Solidity Ratio	Projected Area of Fouled Netting (m ²)
Clean netting (A)	250,000	52,861	0.211	0.0529
Fouled netting (B)	250,000	76,275	0.305	0.0763
Fouled netting (C)	250,000	91,598	0.366	0.0916
Fouled netting (D)	250,000	111,369	0.445	0.1114
Fouled netting (E)	250,000	183,357	0.733	0.1834
Fouled netting (F)	250,000	196,805	0.787	0.1968

The solidity ratio was calculated using Equation (1) as follows:

$$S_n = \frac{A_p}{A_o} = \frac{P_p}{P_o} \quad (1)$$

The drag forces (R_D) of the netting were calculated by subtracting the drag measured for the stainless steel frame at each flow velocity from the drag measured for the combined netting and frame:

$$R_D = R_{D(\text{netting+frame})} - R_{D(\text{frame})} \quad (2)$$

The drag coefficient was calculated as follows:

$$C_x = \frac{2R_D}{\rho A_p u^2} \quad (3)$$

where C_x is the drag coefficient, R_D is the drag force of netting, ρ is the density of water ($=998.2 \text{ kg/m}^3$), and u is the flow velocity.

The Reynolds number, representing the ratio of inertial to viscous forces, was calculated as follows:

$$Re = \frac{ud}{\nu} \quad (4)$$

where d is the twine diameter of netting, ν is the kinematic viscosity ($=1.005 \times 10^{-6} \text{ Pa}\cdot\text{s}$), Re is the Reynolds number.

2.4. Simulation Model Construction

Knotless plane diamond polyethylene netting was used in this study. The netting had a density of 1050 kg/m^3 , a Young's modulus of 850 MPa , and a Poisson's ratio of 0.4101 . The horizontal (μ_1) and vertical (μ_2) contraction ratios were both 0.707 . To improve computational efficiency, the model netting was simplified into grid elements based on the actual netting and its solidity ratio. The model dimensions were $100 \text{ mm} \times 100 \text{ mm}$, representing $1/25$ of the actual netting area. As shown in Figure 5, the mesh twine length (a) was 20 mm , with a twine thickness (d) of 2 mm . The twine width was calculated according to the actual solidity ratio as the sum of the twine diameter and fouled thickness. Figure 6 shows the numerical model for the clean and fouled netting. The numerical model maintained close dimensional similarity to the actual netting structure.

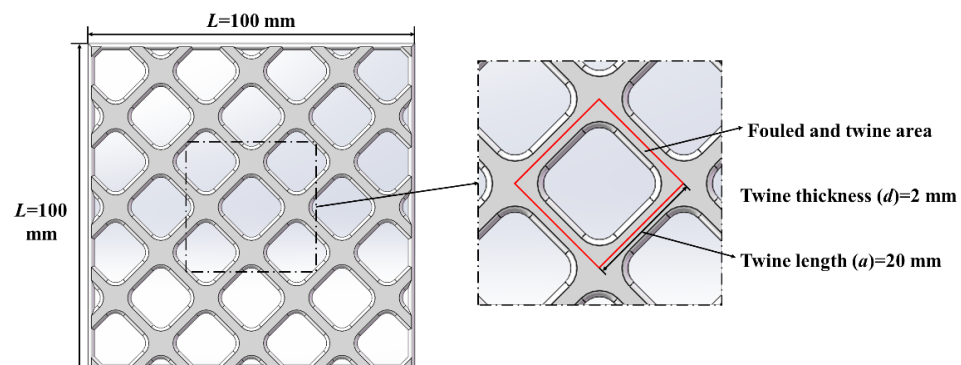


Figure 5. Schematic diagram of the netting structure in the numerical model.

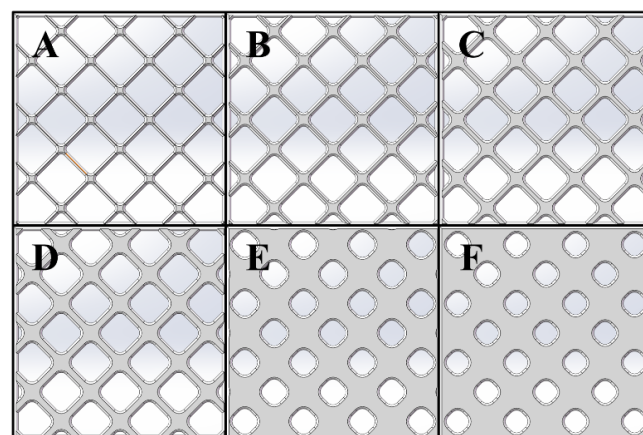


Figure 6. Netting with different fouling conditions ((A): clean netting, (B–F): Fouled netting).

2.5. Computational Domain and Grids

The angle of attack (AOA) between the netting panel and the fluid direction was 90° , as shown in Figure 7. To improve numerical accuracy and computational efficiency, the simulation domain was divided into inner and outer computational domains (Figure 7a). The domain size was defined by the netting length (L). In the inner computational domain, the distances from the upstream boundary, downstream boundary, and sidewalls to the netting were set as L , $6L$, and $0.5L$, respectively. In the outer computational domain, these distances were set as $4L$, $9L$, and $2L$, respectively. A velocity inlet boundary condition was applied at the upstream boundary, and inlet velocities matched the experimental settings. The outlet boundary was defined as a free outflow boundary. All walls were treated as no-slip solid surfaces. The interface between the inner and outer domains was set as a data exchange boundary, enabling bidirectional coupling of flow parameters while allowing independent mesh generation in each domain. The entire fluid region and the netting solid region were included in the computational domain.

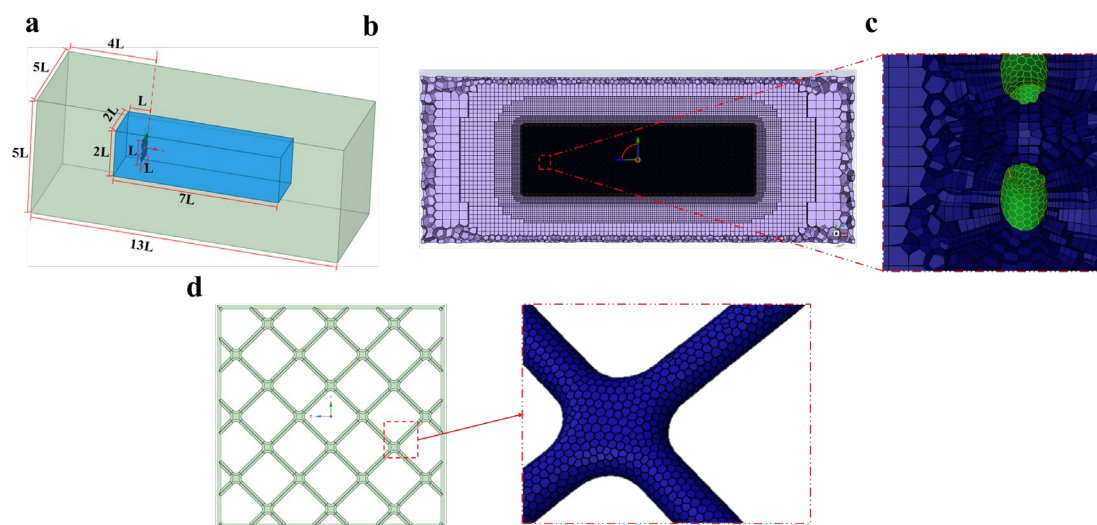


Figure 7. Three-dimensional computational domain and grids system ((a): Inner and outer computational domains, (b): Domain mesh discretization status, (c): Locally magnified view of mesh distribution, (d): Surface mesh discretization of netting).

The numerical simulations used hexagon-shaped netting panels, as shown in Figure 7d. The netting model was converted into an unstructured tetrahedral mesh, with mesh refinement applied at the fluid–solid interface. Ten concentric boundary layers were constructed around the elliptic cylinder elements, using a progressive growth ratio of 1.2 between adjacent layers (Figure 7c). This configuration provided high-resolution discretization near structural surfaces and coarser mesh in regions farther from the netting.

The mesh convergence of the numerical model is demonstrated through a grid sensitivity analysis and a carefully designed mesh scheme. During model setup, key results such as net drag force were compared across different grid resolutions, with particular attention to near-wall y^+ values and wake region grid size. Based on this analysis, mesh generation criteria were established to ensure sufficient boundary layer grids on the netting surface ($y^+ < 1$) for accurately resolving viscous sublayer flow, while employing a gradually coarsened grid in the overall domain to reliably capture core flow features such as jets and vortex structures, all within reasonable computational costs.

The final computational domain consisted of approximately 11.41 ± 0.08 million polyhedron–hexahedron elements across the six netting cases, subdivided into an inner domain of 8.31 ± 0.07 million elements and an outer domain of 3.10 ± 0.01 million elements. This polyhedron–hexahedron mesh type reduced the total cell count by three to five times

compared to the initial unstructured tetrahedral mesh, while simultaneously improving calculation accuracy (Figure 7b). The adopted mesh scheme shows good convergence, as further grid refinement does not lead to significant changes in key computational results.

2.6. CFD Calculation Model and Boundary Conditions

Computational Fluid Dynamics (CFD) was chosen for numerical simulation due to its cost-effectiveness and efficiency, as it allows for the rapid simulation of multiple fouling conditions and flow scenarios at a lower cost compared to constructing full-scale models or conducting extensive variable-parameter tank experiments. Additionally, CFD provides detailed flow field information, such as velocity vectors, pressure distributions, and vorticity contours, that are challenging to obtain experimentally with full-domain, high-resolution accuracy, thereby offering critical insights into how fouling influences microscopic flow structures like jet flows through mesh openings and vortices behind net knots. The method also supports parametric studies by enabling easy adjustments to geometric parameters (e.g., solidity ratio, twine shape) and flow conditions, which facilitates systematic sensitivity analysis. Furthermore, CFD complements and validates experimental work by simulating idealized conditions difficult to achieve in physical tests, and cross-verification with experimental data enhances the reliability of the findings. In this study, the widely validated SST $k-\omega$ turbulence model was employed to balance accuracy in near-wall flow resolution with computational efficiency.

The numerical simulations were performed using ANSYS FLUENT 2022 R1. To resolve turbulence characteristics, the shear stress transport (SST) $k-\omega$ model [19] was adopted. This model combines the strengths of the $k-\omega$ and $k-\epsilon$ formulations. The $k-\omega$ approach was applied in the near-wall region to improve boundary layer resolution, while the $k-\epsilon$ formulation was activated in the freestream to reduce sensitivity to inlet turbulence conditions. This hybrid strategy enhances predictive capability for flow separation and adverse pressure gradients, making the SST $k-\omega$ model suitable for vortex-induced vibration (VIV) analysis under the Reynolds-averaged Navier–Stokes (RANS) framework. Given the low Reynolds numbers in the test configurations ($Re < 5000$), the model's near-wall treatment provided reliable performance.

The governing equations were discretized using the finite volume method (FVM). A second-order upwind scheme was applied for momentum spatial discretization, with first-order temporal integration. Pressure–velocity coupling was handled using the SIMPLE algorithm, and high-resolution schemes were applied to convective terms. Iterative convergence was achieved by setting the residual tolerance to 10^{-5} for all key variables.

Netting roughness was considered in the numerical model and described for the water–netting interaction wall as follows:

$$\frac{U_z u^*}{\tau_w / \rho} = \frac{1}{k} \ln \left(E \frac{\rho u^* y}{\mu L} \right) - \Delta B \quad (5)$$

where $E = 9.793$ is an empirical constant, y is the distance to the wall, U_z is the mean velocity of the fluid at point y , τ_w is the wall shear stress, and u^* is the friction velocity, which can be defined as follows:

$$u^* = C_{\mu, std}^{0.25} k^{0.5} \quad (6)$$

The constant ΔB depends on roughness shape and roughness height and is defined as follows:

$$\Delta B = \frac{1}{k} \ln \left(C_s \frac{\rho K_s u^*}{\mu L} \right) \quad (7)$$

where K_s is the physical roughness height, set as one-tenth of the twine diameter for each netting, and C_s is the roughness coefficient. Because fouling was present on the netting surface, C_s was set to 1.5 in this study.

3. Results and Discussion

3.1. Drag Force of Fouled Netting

Biofouling is a persistent challenge in marine aquaculture, and its adverse effects on the hydrodynamic performance of aquaculture structures are well documented. Based on the field studies reported by Bi et al. [12], this study clarifies the mechanisms through which different levels of biofouling influence the hydrodynamic behavior of net panels using the quantitative parameter “solidity ratio”.

Experimental data show a marked nonlinear increase in drag force with rising flow velocity across all solidity levels (Figure 8a) (all $R^2 \approx 1$). At a solidity ratio of 0.366, the measured hydrodynamic resistance increased from 19.52 N to 83.11 N as flow velocity increased from 0.50 m/s to 1.10 m/s, yielding a 325% increase. This nonlinear pattern features mild pressure growth in the low-velocity range (0.50–0.70 m/s) and a steeper increase beyond 0.90 m/s, associated with elevated turbulence intensity driven by increased fluid kinetic energy.

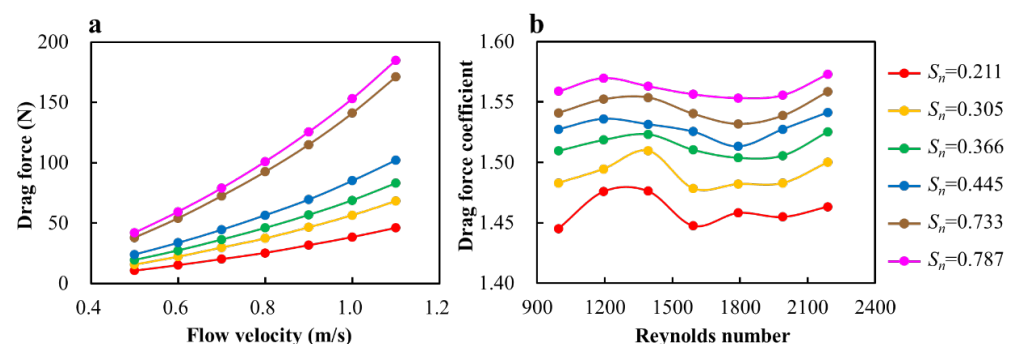


Figure 8. Relationship between hydrodynamic force and flow velocity (a) (all $R^2 \approx 1$) and drag coefficient and Reynolds number (b) for six netting panels.

The solidity ratio exerts strong control over hydrodynamic resistance, and this control is fundamentally nonlinear due to a phase transition in the flow–structure interaction mechanism. At a flow velocity of 0.90 m/s, increasing the solidity ratio from 0.211 to 0.787 raised the measured resistance from 31.72 N to 125.52 N, a 295.71% increase. The steepest gradient occurred in the medium solidity range (0.305–0.445), identifying this interval as the most sensitive region for flow–structure interaction, a critical transition zone where the net’s hydrodynamic behavior shifts from a “porous medium” to a “quasi-solid plate.” In the low solidity stage ($S_n < 0.3$), the net primarily acts as a porous medium where fluid passes relatively smoothly, with resistance growth mainly from surface friction on individual threads and minor vortices, resulting in a relatively gentle increase. However, as solidity enters the medium-to-high range ($S_n > 0.445$), heavy fouling drastically reduces the effective flow area, intensifying flow separation and forming larger, stable vortex regions behind net threads and fouling bodies. At this stage, pressure drag (form drag) becomes dominant, exhibiting a strong correlation with the square of flow velocity and the growth of blocked area, thereby driving the observed nonlinear, sharp increase in resistance. The structural mechanism is consistent with the findings of Zhou et al. [20] on knotless nylon nets, whose “dual effect” theory indicates that the impact of solidity on hydrodynamic resistance depends on spatial orientation, as fouling not only increases the projected frontal area but also fundamentally alters the local angle of attack and streamline pattern, leading to a restructuring of the drag coefficient and a nonlinear enhancement of resistance. This theory provides a clear explanation for the complex resistance response induced by fouling.

The drag coefficient distribution supports these observations (Figure 8b). Across all conditions, the drag coefficient ranged from 1.445 to 1.573. At a solidity ratio of 0.787, values remained at relatively high levels (1.553–1.573), reflecting strong flow impedance

produced by fouling. As the Reynolds number increased from 995 to 2189, the drag coefficient displayed phasic behavior: an upward trend in the lower Reynolds number range (995–1393), with a 1.07% increase at a solidity ratio of 0.305; and a stable regime at higher Reynolds numbers (1592–2189), with maximum variation below 1.5%. These outcomes align with the findings of Liu et al. [15] and indicate stability during turbulence development.

The influence of solidity ratio on the drag coefficient was also nonlinear. Under $Re = 995$, increasing the solidity ratio from 0.211 to 0.787 produced a 7.85% increase in the drag coefficient. Under $Re = 2189$, the same change yielded a reduced increase of 7.50%. This nonlinear pattern and the reduced sensitivity at higher Reynolds numbers suggest that higher inertial forces at elevated Reynolds numbers partly offset the effects of structural density, indicating a moderating role of hydrodynamic factors. This further corroborates the flow regime transition described above, where increased fluid inertia interacts with the altered structure to modulate the net effect of solidity on resistance.

3.2. Agreement Between Experimental and Simulated Data

Comparative analysis of measured data and simulation results (Figure 9) shows strong agreement in overall trends, with deviations lying within an error range of 5.33–22.62%. These discrepancies increase with higher solidity ratios and lower flow velocities. At a solidity ratio of 0.787 and flow velocity of 0.50 m/s, the measured value (42.02 N) exceeded the simulated value (32.52 N) by 22.62%. Several factors may contribute to this deviation. Three-dimensional flow effects and boundary layer separation in actual conditions are not fully resolved in the two-dimensional simulation. Limitations in turbulence model accuracy under high Reynolds number conditions may also play a role. In addition, geometric variation caused by manufacturing tolerances in the net panels may affect the comparison. The closest agreement between experiment and simulation appears at low solidity ratios (0.211), where the average error is only 10.33%, confirming the reliable performance of the numerical model within the low to medium solidity range most relevant to typical early-stage biofouling.

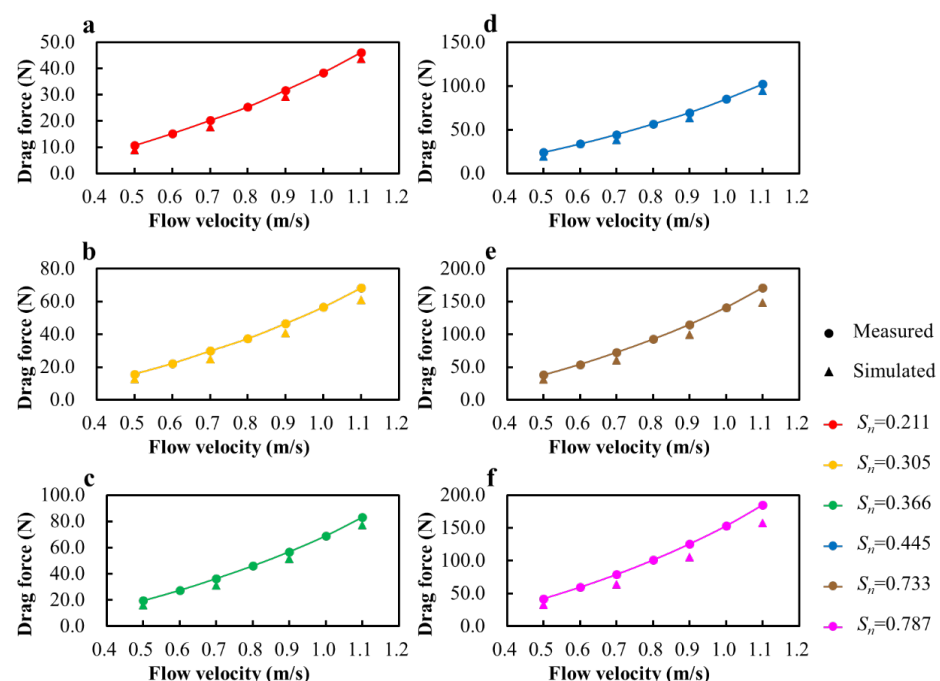


Figure 9. Relationship between hydrodynamic force and flow velocity for six netting panels under towing tank testing (all $R^2 \approx 1$) and numerical simulation ((a): $S_n = 0.211$, (b): $S_n = 0.305$, (c): $S_n = 0.366$, (d): $S_n = 0.445$, (e): $S_n = 0.733$, (f): $S_n = 0.787$).

The general applicability of this model has been supported by multiple independent studies. Zhou et al. [20], in their investigation of high-performance knotless nylon nets, reported results consistent with those obtained here, reinforcing the model's strength in capturing hydrodynamic behavior. Zou et al. [21] employed a one-way fluid–structure interaction model and reported average errors of 9.17% and 11.58% for parallel and normal resistance components, respectively, providing further confirmation from an advanced computational framework. Collectively, these validations indicate that the simplified porous media model, despite its limitations at extreme solidity, successfully captures the key physical mechanisms governing the hydrodynamic response of netting structures to biofouling, which is the primary focus of this study.

3.3. Flow Field Structure Around Net Panels

The flow field around net panels is a classical topic in fluid mechanics, and numerous experimental and numerical studies have been conducted on this subject [22,23]. In general, a localized low-velocity zone forms upstream of the net panel, while a larger velocity attenuation region develops downstream. The wake shows a relatively uniform distribution immediately behind the net, gradually contracting toward the centerline with increasing distance, accompanied by velocity enhancement in the lateral regions. Limited wake mixing results in weak deflection effects, and the reduction in flow velocity is primarily due to the blocking effect of the net structure. The velocity decay and complex vortex structures observed in this study, which intensify with solidity, directly elucidate the fluid-mechanical basis for the “shielding effect” reported in field studies by Bi et al. [12]. Net panels with high solidity ratios induce substantial energy dissipation and flow obstruction.

Notable discrepancies remain in the quantitative characterization of this blocking effect. Gansel et al. [24] demonstrated that assuming a fixed internal velocity reduction (e.g., 20%) versus a dynamic reduction that varies with incoming flow velocity produces markedly different predictions of net cage resistance. Their findings provide important context for the internal flow structures shown in Figures 10–12 of this study, which vary significantly with solidity ratio. The results indicate that velocity reduction inside a net cage is not a fixed value but depends strongly on fouling conditions (solidity ratio) and incoming flow. Future net cage design standards and numerical models must therefore move beyond static assumptions and adopt refined dynamic flow descriptions to accurately predict deformation and resistance.

In this study, contour plots on the $Z = 0$ plane were used to visualize the flow field around net panels with different solidity ratios, highlighting the velocity suppression induced by biofouling. The color scale ranged from -0.5 to 1.5 times the incoming velocity to clearly display velocity distributions. Figure 10 shows flow field patterns around net panels at a flow velocity of 0.5 m/s. The extent of upstream velocity attenuation increases with solidity ratio. As fluid passes through mesh openings, noticeable acceleration occurs within the pores, while reverse flow zones (negative velocity regions) form behind the knots. Both the accelerated regions and reverse flow zones expand as solidity increases. Velocity acceleration also appears along the upper and lower edges of the net panel, and these regions enlarge with increasing solidity. Under high solidity conditions ($S_n = 0.733$ – 0.787), a second significant negative velocity region emerges within the X -range of 0.1 – 0.2 , with its extent increasing markedly as solidity increases. Figure 11 presents flow field contours at 1.1 m/s, showing overall patterns consistent with those in Figure 10. These results indicate that while the absolute velocities scale with inflow, the normalized flow field structures and the governing mechanisms are similar across different incoming flow conditions. The observations agree with the numerical findings of Zou et al. [25,26] and Bi et al. [22], further confirming the typical flow characteristics around net panels.

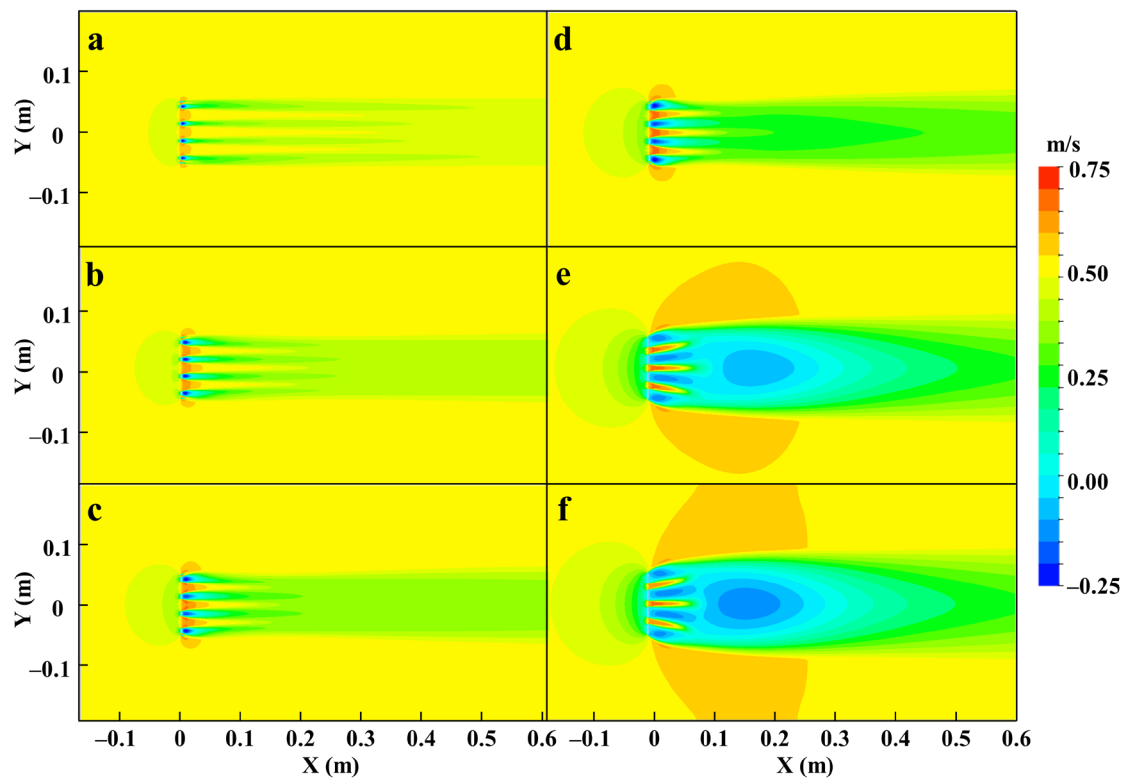


Figure 10. Contour plots of the streamwise velocity around the netting at $Z = 0$ at $u_0 = 0.5$ m/s ((a): $S_n = 0.211$, (b): $S_n = 0.3.5$, (c): $S_n = 0.211$, (d): $S_n = 0.366$, (e): $S_n = 0.733$, (f): $S_n = 0.787$).

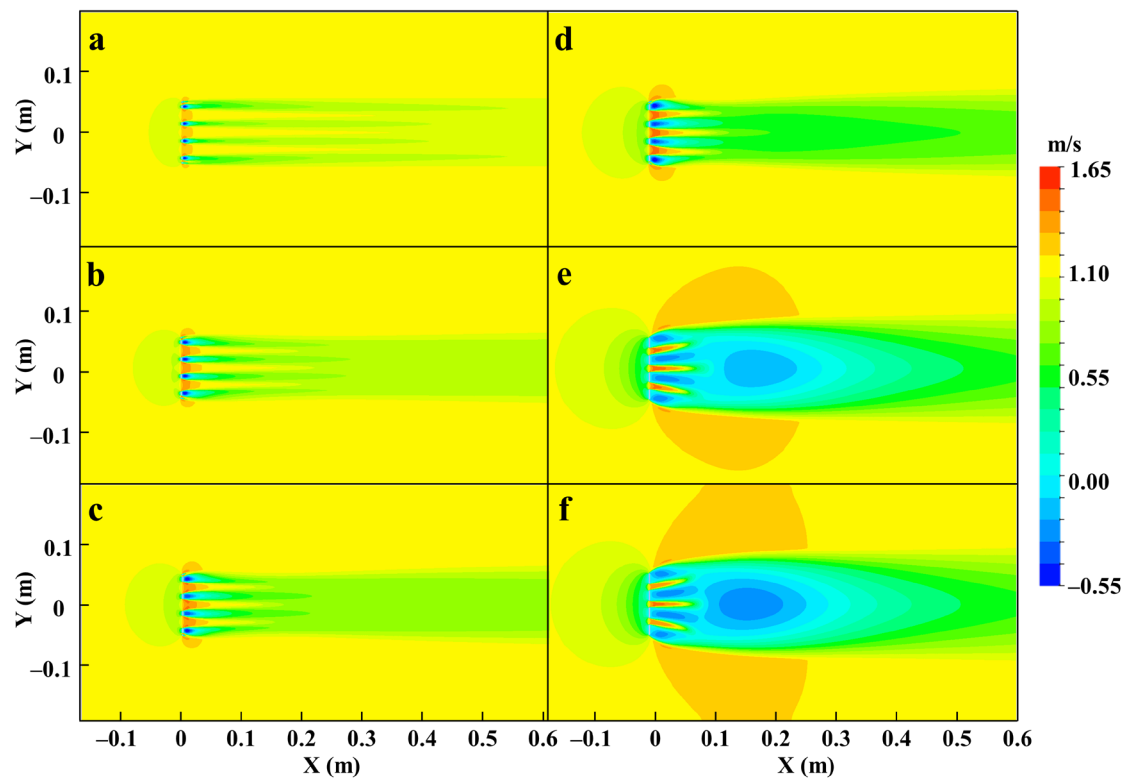


Figure 11. Contour plots of the streamwise velocity around the netting at $Z = 0$ at $u_0 = 1.1$ m/s ((a): $S_n = 0.211$, (b): $S_n = 0.3.5$, (c): $S_n = 0.211$, (d): $S_n = 0.366$, (e): $S_n = 0.733$, (f): $S_n = 0.787$).

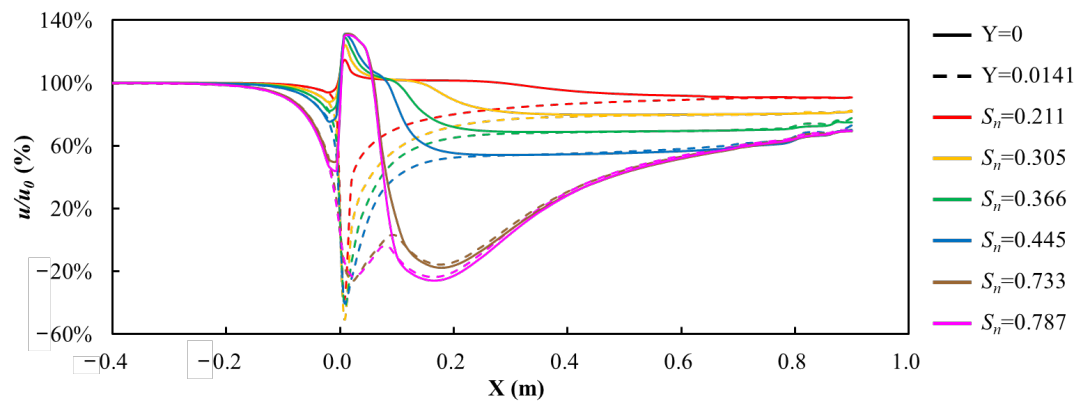


Figure 12. Streamwise velocity percent around the netting at $Z = 0$.

3.4. Velocity Distribution of Fouled Netting

Figure 12 shows the velocity distribution along the x -axis passing through mesh openings ($Y = 0$ m) and the x -axis passing through knots ($Y = 0.0141$ m), providing a quantitative dissection of the influence of different solidity ratios on flow structures. In the upstream region of the net panel ($X = -0.4$ m to 0 m), the velocity ratio along both axes decreases synchronously from 1.0 . The mesh-opening axis consistently retains higher velocities. At $X = -0.0061$ m under a solidity ratio of 0.787 , the velocity ratio along the knot axis decreases to 21.89% , while the mesh-opening axis maintains 44.71% , demonstrating the disproportionately strong flow obstruction caused by the knot structures.

As flow passes through the net, the two axes diverge significantly. The mesh-opening axis maintains forward flow with acceleration, reaching a maximum velocity ratio of 130.55% at a solidity ratio of 0.445 , showing a typical jet effect. The knot axis primarily produces reverse flow, reaching -49.18% at $X = 0.0071$ m under a solidity ratio of 0.305 . This stable reverse-flow zone is quantitatively identified as a major contributor to hydrodynamic resistance.

Downstream flow patterns display clear solidity-dependent behavior. Low-solidity nets ($S_n = 0.211$ – 0.445) show rapid recovery along the mesh-opening axis to incoming flow levels, while reverse flow along the knot axis quickly transitions to forward flow. High-solidity nets ($S_n = 0.733$ – 0.787) exhibit more complex flow structures, including initial deceleration followed by reverse flow. The knot axis displays two distinct reverse-flow extremes at $X = 0.0202$ m and $X = 0.1780$ m, providing clear evidence of a multi-vortex wake structure. These observations confirmed that stronger velocity decay with increasing attack angle and solidity, consistent with the findings of Zhao et al. [27]. Collectively, the results show that biofouling reshapes wake structures by modifying equivalent solidity and local attack angles, providing a theoretical foundation for understanding hydrodynamic characteristics of complex net-cage systems.

3.5. Flow Field Characteristics of Fouled Netting

Analysis of the flow field around net panels shows distinct vortex structures forming downstream after fluid passes through the nets. The streamline diagram in Figure 13 shows that excessive biofouling alters the flow field by changing local flow patterns. Under low-solidity conditions ($S_n = 0.211$ – 0.445), the downstream flow remains laminar, producing small symmetric von Kármán vortex streets behind the knots. Under high-solidity conditions ($S_n = 0.733$ – 0.787) mesh blockage triggers a transition to turbulence, forming a “dual-peak vortex street” at $X = 0.3$ m. This represents a distinct, high-drag flow regime characterized by complex multi-vortex coupling.

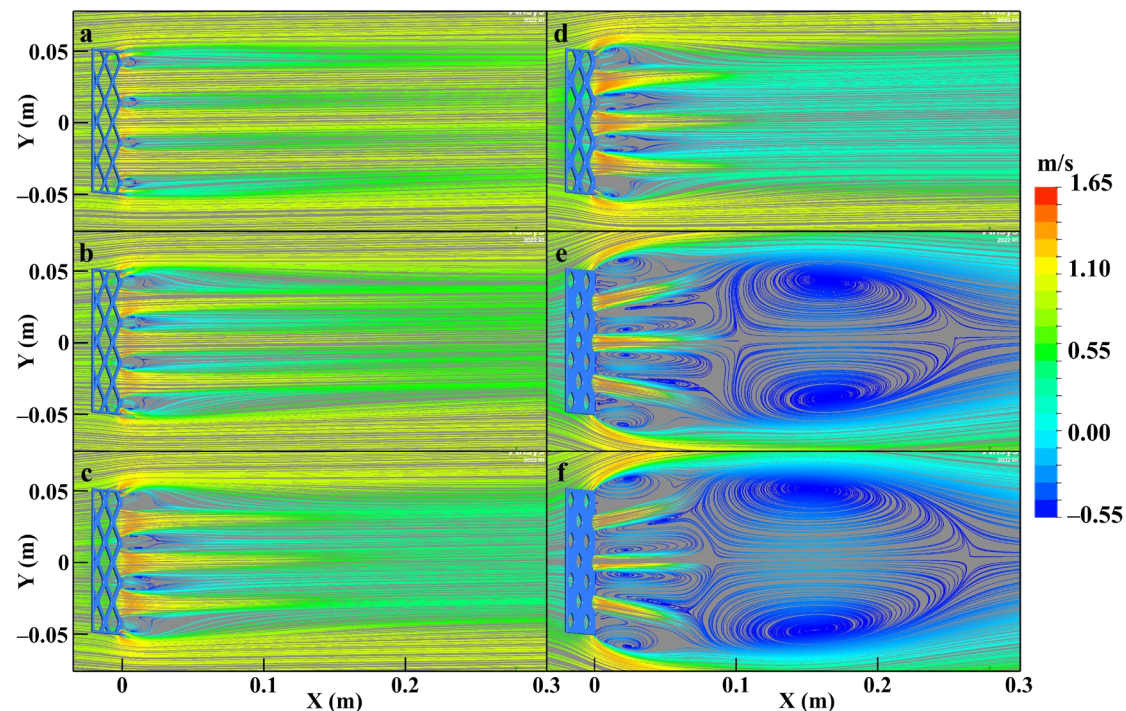


Figure 13. Streamline profiles around the plane nettings with solidity ratios of 0.211–0.787 at $Z = 0$ at $u_0 = 1.1$ m/s ((a): $S_n = 0.211$, (b): $S_n = 0.35$, (c): $S_n = 0.211$, (d): $S_n = 0.366$, (e): $S_n = 0.733$, (f): $S_n = 0.787$).

These flow patterns align with classical fluid mechanics principles. Bi et al. [22] revealed in their study of cross-shaped cylinders that structural orientation controls vortex evolution by altering separation points, which matches the geometric effects produced by biofouling on net panels. Zou et al. [25] demonstrated that interactions among microscopic vortices around many nodes shape macroscopic wake structures. Their equivalent “ D/d ratio” corresponds to the solidity parameter mechanism used here, together explaining the nonlinear drag increase with fouling level. The fluid–structure interaction analysis by Zou et al. [21] further indicates that complex vortex streets in heavily fouled nets originate from combined effects of strong fluid–structure interaction under high solidity conditions and modifications in net stiffness caused by fouling organisms. These integrated findings from the present and prior studies provide a theoretical framework linking the microscopic vortex dynamics (Sections 3.3 and 3.4) with the macroscopic wake structures and force measurements, offering a scientific basis for optimizing cleaning strategies based on flow regime transition.

3.6. Analysis of Computational Cost

The computational cost was analyzed to evaluate the engineering practicality of the numerical model. All simulations were performed on a workstation with an Intel(R) Core(TM) i7-14700F (28 cores). A single steady-state simulation for a given solidity ratio and flow velocity required 2 h to converge (residuals $< 10^{-5}$). The total computational time for all parametric simulations was approximately 48 h.

The adoption of a polyhedral–hexcore hybrid mesh reduced the total cell count by about 40% while maintaining accuracy, significantly improving computational efficiency. This cost is acceptable on standard research platforms, demonstrating that the model balances accuracy with efficiency and shows potential for engineering applications.

4. Conclusions

This study employed an integrated experimental and numerical approach to dissect the mechanisms through which biofouling affects the hydrodynamic characteristics of aquaculture net panels. The work moves beyond empirical correlation to provide a causal, physics-based explanation for increased drag. The main conclusions are as follows:

1. Net panel resistance shows a strong positive correlation with solidity ratio. A key finding is the identification of the medium solidity range ($S_n = 0.305\text{--}0.445$) as the most sensitive interval for resistance variation, suggesting a potential critical threshold in fouling progression that warrants attention in farm management.
2. The flow field analysis reveals a fundamental anisotropy: the mesh-opening axis maintains higher flow velocities and shows jet-like acceleration, while the knot axis forms stable reverse-flow zones that constitute the primary source of hydrodynamic resistance. Furthermore, under high solidity conditions ($S_n \geq 0.733$), the wake transitions to a dual-peak vortex street, indicating the onset of a complex, multi-vortex coupling flow regime associated with significantly altered system dynamics.
3. Numerical simulations show good agreement with experimental results, confirming the feasibility of the resin-coating approach for simulating composite biofouling conditions and validating the use of the numerical model as a predictive tool within these bounds. The identified discrepancies at very high solidity highlight specific directions for future model refinement.
4. Biofouling induces a nonlinear increase in resistance through two interconnected mechanisms: a direct increase in the projected area and a fundamental modification of flow separation and vortex development patterns.

These findings collectively improve the mechanistic understanding of fluid–structure interaction in biofouled netting. They provide scientific support for net cage design (e.g., by defining critical solidity thresholds), fouling prevention (e.g., by targeting knot geometry), and operational management (e.g., by linking flow visual characteristics to load predictions). Future studies should build on this mechanistic foundation to examine how different, realistic fouling morphologies influence the specific flow structures identified here and to develop predictive cleaning schedule criteria based on quantitative flow field characteristics, such as vortex street metrics or reverse-flow zone dimensions.

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Abbreviations

Abbreviation	Nomenclature
A_o	Net panel outline area (m ²)
A_p	Projected area of fouled netting (m ²)
CFD	Computational Fluid Dynamics

C_x	Drag coefficient
d	Twine diameter (m)
Re	Reynolds number
R_D	Drag force on net panel (N)
S_n	Solidity ratio ($=A_p/A_o$)
u	Flow velocity (m/s)
ρ	Water density (kg/m ³)
ν	Kinematic viscosity of water (m ² /s)

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