

Article

Effect of Middle Vertical Slot Width on the Hydraulic Characteristics of Vertical-Slot Double-Chamber Fishways

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Abstract

The hydraulic characteristics of vertical-slot double-chamber fishways are critical determinants of fish passage efficiency. Various geometric dimensions and hydraulic operating parameters jointly determine the internal flow characteristics of vertical-slot double-chamber fishways, such as chamber aspect ratio, side slot width, bed slope and inlet discharge. Focusing on the relative width of the middle vertical slot (b_0/B), this study employs computational fluid dynamics (CFD) simulations to investigate its regulatory mechanism on hydraulic performance. The evolution of the flow-field structure in a double-chamber fishway was analyzed under 12 groups of relative slot-width conditions, and the influence of b_0/B on key hydraulic parameters was quantitatively evaluated, including flow velocity distribution, vortex structure, mainstream attenuation, and water exchange between chambers. The results indicate that the impact of b_0/B on hydraulic characteristics exhibits a distinct phased behavior. By modifying the momentum distribution between the vertical slot and the pool, b_0/B regulates the formation, development, and interaction of the dominant vortex system. When b_0/B ranges from 0.13 to 0.16, the flow-field structure is optimal, characterized by a high effective utilization rate of the mainstream, a stable along-course energy attenuation rate of approximately 40%, a relatively uniform flow velocity distribution at the vertical-slot section, and a turbulence kinetic energy level in the chamber that falls within the literature-based reference range for fish-passage hydraulics. This study characterizes the internal evolution mechanism of fishway hydraulic characteristics regulated by the relative width of the vertical slot, providing a robust theoretical basis and practical parameter-selection guidance for the refined design and performance optimization of vertical-slot double-chamber fishways.

Keywords: vertical-slot fishway; double-chamber; relative width of the middle vertical slot; hydraulic characteristics; regulation mechanism



Received: 15 May 2026

Revised: 15 July 2026

Accepted: 24 July 2026

Published: 29 July 2026

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1. Introduction

As a key ecological compensation project to mitigate the negative impacts of hydropower dams on river ecosystems, fish passages have emerged as a research hotspot at the intersection of hydraulic engineering and ecological protection by restoring river connectivity [1–3]. Among different fishway types, the vertical-slot fishway (VSF) has been widely used because of its simple structure, stable flow pattern, adaptability to upstream

and downstream water-level variations, and suitability for fish with different swimming capacities [4,5].

Domestic and international scholars have conducted extensive physical model experiments and numerical simulations on the hydraulic characteristics of VSFs. Wu et al. [4] experimentally studied the flow structure in a VSF and found that when the fishway slope was less than 5%, the upper and lower flow patterns were similar, showing clear two-dimensional characteristics. Marriner et al. [5] analyzed the hydraulics of the multi-species Vianney–Legendre VSF and showed that velocity distribution and recirculation structure are important hydraulic indicators for fishway evaluation. Bian and Sun [6] studied the hydraulic characteristics of traditional VSFs and found that the vertical velocity component was much smaller than the horizontal velocity component, indicating strong planar flow characteristics. Cao et al. [7] investigated an opposite-side VSF and further confirmed that the flow field in the pool chamber was mainly controlled by horizontal velocity components.

Structural parameters also have important effects on VSF hydraulics. Zhang and Sun [8] studied the effect of vertical-slot width on the flow structure and found that slot width directly affects mainstream trajectory and recirculation pattern. Guo et al. [9] numerically simulated a same-side VSF and showed that slot arrangement significantly influences velocity distribution and energy dissipation. Li et al. [10] investigated the influence of vertical-slot width in a double-sided VSF and found that changes in slot width can alter local velocity distribution and flow-field structure. Bombač et al. [11] studied VSF slot layout optimization and reported that the arrangement of slots affects jet direction, maximum velocity, and recirculation regions. Ahmadi et al. [12] numerically investigated upgraded VSF configurations and showed that structural optimization can improve hydraulic conditions in the pool chamber.

Recent studies have further linked fishway hydraulics with fish passage performance. Tan et al. [13] experimentally examined the effects of turbulence and velocity on the movement behavior of bighead carp in a VSF and found that local velocity and turbulent structures affect fish movement trajectories. Puzdrowska and Heese [14] analyzed turbulent kinetic energy distribution in fishways and emphasized the importance of turbulence-related indicators in fishway evaluation. Quaranta et al. [15] reviewed CFD studies on nature-like and technical fishways and pointed out that numerical simulation is an effective tool for evaluating velocity distribution, turbulence characteristics, and hydraulic suitability.

To improve the hydraulic performance of traditional VSFs, the vertical-slot double-chamber fishway (VSDCF) was proposed, as shown in Figure 1. Xie et al. [16] designed a new vertical-slot double-pool fishway and analyzed its hydraulic characteristics, showing that the added middle vertical slot can improve energy dissipation and flow organization. Qi et al. [17] carried out two-dimensional and three-dimensional numerical simulations of this type of fishway and found that the vertical velocity component was small, while the two-dimensional results were close to the vertically averaged three-dimensional results. Fu et al. [18] compared the hydraulic characteristics of the VSDCF and the traditional VSF and showed that the VSDCF has advantages in velocity distribution and energy attenuation.

However, existing studies on VSDCFs are still limited compared with those on traditional VSFs. Previous research mainly focused on verifying the two-dimensional hydraulic characteristics of the VSDCF or comparing its overall performance with traditional VSFs [16–18]. The influence mechanism of the relative width of the middle vertical slot, b_0/B , has not been systematically clarified. In particular, the effects of b_0/B on mainstream trajectory, recirculation structure, velocity attenuation, and turbulent kinetic energy remain insufficiently understood.

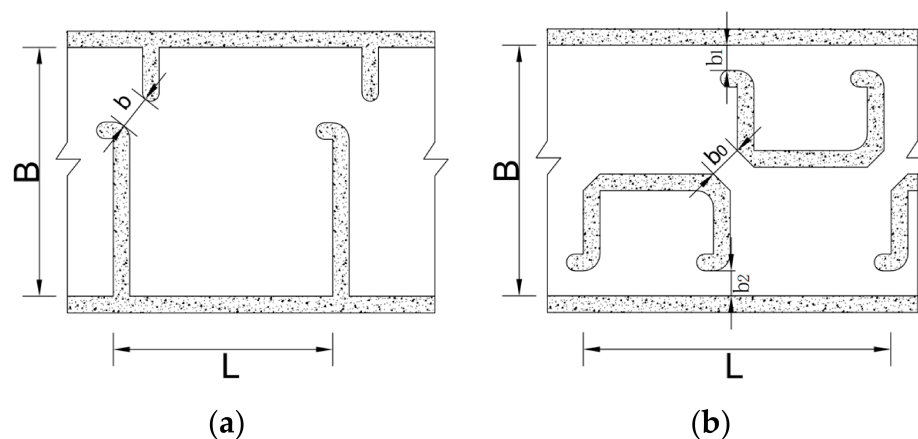


Figure 1. Comparison of chamber configurations between traditional VSF and VSDCF. (a) Traditional VSF chamber; (b) VSDCF chamber.

Therefore, this study focuses on the influence of the relative middle-slot width b_0/B on the hydraulic characteristics of a VSDCF. Twelve b_0/B conditions were established for numerical simulation. The flow-field structure, mainstream trajectory, along-course velocity attenuation, velocity distribution at the middle vertical slot, and turbulent kinetic energy distribution were analyzed. The objective is to reveal the hydraulic regulation mechanism of b_0/B and provide parameter guidance for the refined design and optimization of VSDCFs.

2. Materials and Methods

2.1. Physical Model and Working Condition Design

A 1:1 scale numerical model of the fishway, based on the physical model, was established with a total length of 18.4 m. A single tank chamber measures 0.66 m in length (L), 0.48 m in width (B), and 0.4 m in height (H). The width of the middle vertical slot (b_0) is 0.064 m, and the widths of the side vertical slots ($b_1 = b_2$) are 0.048 m. The thickness of the U-shaped partition is 0.032 m, with a 90° elbow and an arc-shaped outer edge. The inflow section is 7.0 m long, featuring a slope of less than 5% and an energy dissipation net to maintain uniform flow upstream of the first-level fishway. The working section extends 8.4 m and consists of 11 identical pool chambers, numbered from upstream to downstream (①~⑪). The outflow section measures 3.0 m. The fishway layout is depicted in Figure 2. Fluent software (ANSYS Fluent 2022 R1) was utilized to establish a two-dimensional model to simulate the flow characteristics of the vertical-slot double-chamber fishway.

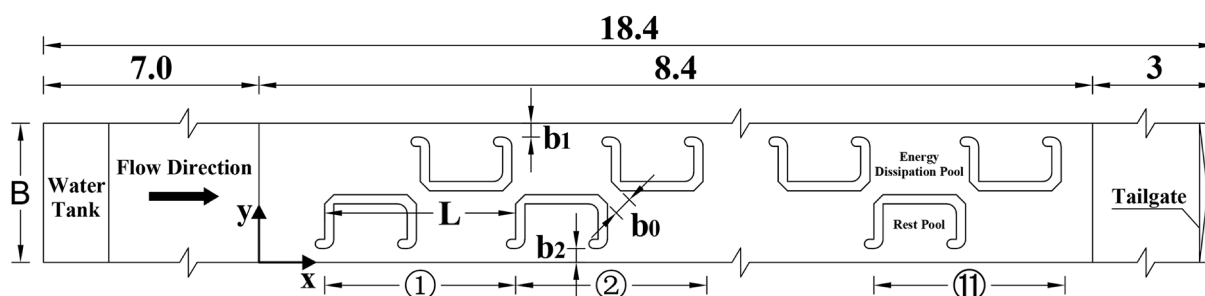


Figure 2. Layout of the physical model of the vertical-slot double-chamber fishway (unit: m).

For the vertical-slot double-chamber fishway (VSDCF) adopted in this study, the rationality of the two-dimensional numerical model has been fully verified by the comparative 2D and 3D numerical simulation results of an identical structure from our research group [17]. The 3D simulation results show that the vertical velocity component at all

sampling points inside the chamber is lower than 0.1 m/s, which is negligible compared with horizontal mainstream velocity. The depth-averaged flow field data extracted from 3D calculation are highly consistent with the 2D simulation outcomes: the average relative errors of mainstream lateral position and dimensionless maximum velocity are less than 10%. Although local weak three-dimensional flow exists near vertical slots and U-shaped partitions, it cannot change the overall planar flow evolution rule and the variation trend of macroscopic hydraulic parameters under different relative slot width conditions. Considering the large-scale batch parametric calculation of 12 working conditions in this paper, the 2D model is adopted to balance calculation efficiency and analysis accuracy for planar hydraulic characteristics.

Twelve different groups of relative slot widths (b_0/B) were established for numerical simulations based on previous studies and preliminary trial calculations, with a minimum interval of 0.01 (see Table 1). To minimize the influence of boundary conditions on the flow pattern, the sixth chamber, located centrally in the fishway, was selected as the research object.

Table 1. Values of the relative slot widths for different intermediate vertical slots.

Number	1	2	3	4	5	6	7	8	9	10	11	12
b_0/B	0.05	0.08	0.10	0.12	0.13	0.14	0.15	0.16	0.17	0.18	0.20	0.23

2.2. Computational Domain and Meshing

To optimize calculation accuracy and numerical simulation workload, the inflow section is set to 0.576 m and the working section to 7.25 m, totaling 8.4 m. Each fishway chamber has a net length of 0.66 m and a net width of 0.48 m, resulting in an aspect ratio of 11:8.

ICEM CFD (ANSYS ICEM CFD 2022 R1) was utilized to discretize the fishway model into triangular meshes, minimizing mesh distortion, ensuring uniformity, and effectively accommodating complex geometric features such as arcs, allowing the triangular meshes to conform to the U-shaped partition.

Three different scale grids were employed for the grid independence test. The grid size and number of unit nodes are detailed in Table 2. The flow velocity on the I–I cross-section line in the middle (⑥) chamber was selected for comparison and verification. As illustrated in Figure 3, the flow velocity trends along the I–I cross-section line across the three grid sizes are consistent. The M1 grid displayed low calculation accuracy with a wide flow velocity range, while the results from the M2 and M3 grids were comparable, with a result error of less than 7% between the two. Based on the three scaled grids, the Grid Convergence Index (GCI) calculated for the grid pair M1–M2 is 17.52%, and that for the grid pair M2–M3 is 1.37%. Considering both accuracy and time cost, the M2 grid with a size of 6 mm was selected for subsequent simulation analysis.

Table 2. Grid parameters for different resolutions.

Grid Name	Maximum Grid Size (m)	Number of Elements	Number of Nodes	GCI
M1	0.008	135,946	67,873	17.52%
M2	0.006	235,704	117,752	
M3	0.004	286,840	143,320	

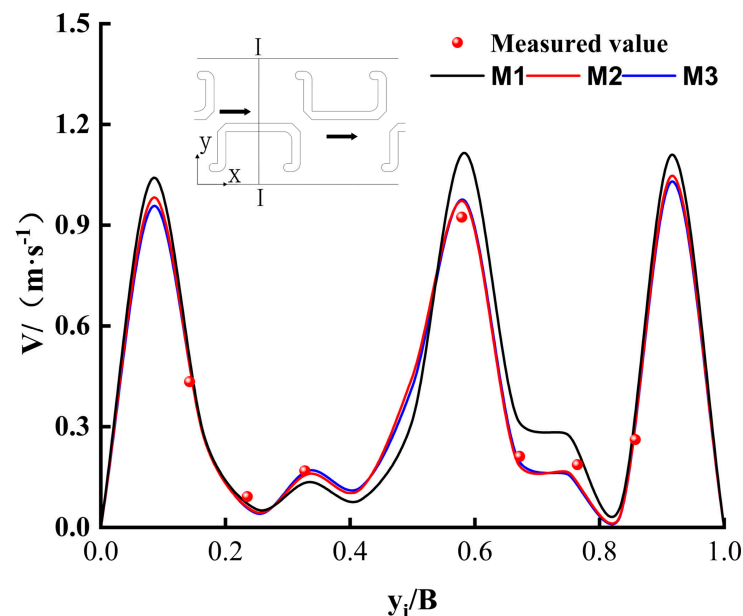


Figure 3. Comparison of flow velocity at the I–I cross-section line for three different grid sizes.

2.3. Governing Equations and Turbulence Models

Numerical simulations were performed using Fluent (ANSYS Fluent 2022 R1), with the RNG k – ϵ turbulence model and the SIMPLE algorithm for pressure–velocity coupling. The RNG k – ϵ model was adopted because it provides reliable predictions of the time-averaged hydraulic parameters examined in this parametric study, including mainstream attenuation, overall vortex distribution, and pool-scale turbulent kinetic energy, while maintaining relatively low computational cost for the 12 b_0/B cases. Previous comparative research on vertical-slot fishways has shown that the RNG k – ϵ model can achieve acceptable accuracy for time-averaged flow characteristics with substantially lower computational cost than transient turbulence models such as DES and LES. The SIMPLE algorithm was used for pressure–velocity coupling because of its stable convergence in incompressible CFD simulations. The governing equations include the continuity equation, momentum equation, k equation, and ϵ equation:

$$\frac{\partial \bar{u}_i}{\partial x_i} = 0 \quad (1)$$

$$\frac{\partial \bar{u}_i}{\partial t} + \bar{u}_j \frac{\partial \bar{u}_i}{\partial x_j} = -\frac{1}{\rho} \frac{\partial \bar{p}}{\partial x_i} + \frac{\partial}{\partial x_j} \left(\nu \frac{\partial \bar{u}_i}{\partial x_j} - \overline{u'_i u'_j} \right) \quad (2)$$

$$\frac{\partial k}{\partial t} + \bar{u}_j \frac{\partial k}{\partial x_j} = \frac{\partial}{\partial x_j} \left(\alpha_k \nu_t \frac{\partial k}{\partial x_j} \right) + 2\nu_t S_{ij} S_{ij} - \epsilon \quad (3)$$

$$\frac{\partial \epsilon}{\partial t} + \bar{u}_j \frac{\partial \epsilon}{\partial x_j} = \frac{\partial}{\partial x_j} \left(\alpha_\epsilon \nu \frac{\partial \epsilon}{\partial x_j} \right) - R + 2c_1 \frac{\epsilon}{k} \nu_t S_{ij} S_{ij} - c_2 \frac{\epsilon^2}{k} \quad (4)$$

In the equation: $\bar{u}_i$ and $\bar{u}_j$ are the time-averaged velocity (m/s); u'_i and u'_j are the fluctuating velocity components (m/s); $\overline{u'_i u'_j}$ is the Reynolds stress term; ρ is the fluid density (kg/m^3); $\bar{p}$ is the time-averaged pressure (Pa); ν is the molecular kinematic viscosity (m^2/s); k is the turbulence kinetic energy (m^2/s^2); ν_t is the eddy viscosity (m^2/s^2); ϵ is the turbulence dissipation rate (m^2/s^3); S_{ij} is the time-averaged strain rate (s^{-1}); R is an additional term in the ϵ equation of the RNG k – ϵ model; α_k , α_ϵ , c_1 , and c_2 are empirical

constants, with values of 1.39, 1.39, 1.42, and 1.68, respectively. The expressions for $\overline{u'_i u'_j}$, ν_t , S_{ij} and R are as follows:

$$\overline{u'_i u'_j} = \frac{2}{3} k \delta_{ij} - \nu_t \left(\frac{\partial \bar{u}}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i} \right) \quad (5)$$

$$\nu_t = C_u \frac{k^2}{\varepsilon} \quad (6)$$

$$S_{ij} = \frac{1}{2} \left(\frac{\partial \bar{u}}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i} \right) \quad (7)$$

$$R = \frac{C_u \eta^3 \left(1 - \frac{\eta}{\eta_0} \right) \varepsilon^2}{1 + \beta \eta^3} \frac{1}{k} \quad (8)$$

In the equation: δ_{ij} is the Kronecker delta function; η is the ratio of the turbulence time scale to the mean flow time scale, defined as $\eta = \frac{S k}{\varepsilon}$, where S is the norm of the strain rate tensor, $S = \sqrt{2 S_{ij} S_{ij}}$; η_0 is the typical value of η in uniform shear flow, taken as 4.38; and C_u and β are empirical constants, taken as 0.0845 and 0.012, respectively.

2.4. Boundary Conditions and Solution Settings

To improve the numerical simulation accuracy, the residual value was set to 1×10^{-5} . To ensure that the water flow velocity at the middle vertical slot of the sixth chamber ranges from 0.8 m/s to 1.2 m/s, the inlet flow velocity value was set to 0.4 m/s, the outlet boundary was defined as free outflow, and the fishway side walls and partitions were assigned no-slip boundary conditions.

2.5. Model Verification and Reliability Analysis

The reliability of the numerical model was verified by comparing it with model test results. The sixth tank chamber in the middle of the VSDCF was selected for the measuring point layout. The distance between measuring points in the cross-section is 0.042 m, and in the longitudinal section, this distance is 0.045 m. Seventeen measuring lines were established in the cross-section and 12 in the longitudinal section, totaling 119 measuring points. The layout of the measuring points in the VSDCF tank chamber is shown in Figure 4.

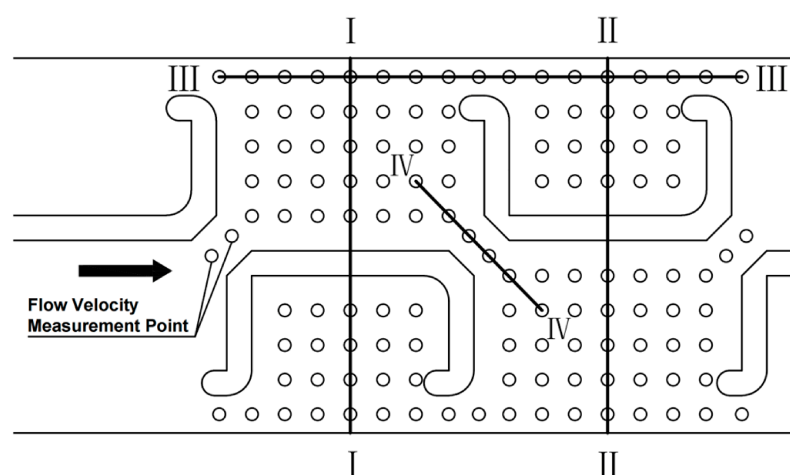


Figure 4. Plan layout of the measurement points in the 6th pool of the vertical-slot double-chamber fishway.

The velocity distribution within the pool chamber of the physical fish passage model was measured using a point-measuring probe-type velocimeter (Shandong Tianhe Environmental Technology Co. Ltd., Qingdao, China). Along the measurement lines I–I, II–II, III–III,

and IV–IV, the probe was sequentially positioned at the designated measurement points as shown in Figure 3, and the local time-averaged velocity at each measurement point was recorded. Corresponding numerical velocities were extracted from the CFD results at the same coordinate points. Subsequently, these measured and simulated point velocities were compared to validate the numerical model, and the coefficient of determination R^2 was calculated to quantify the consistency.

$$R^2 = 1 - \frac{\sum_{i=1}^n (U_{m,i} - U_{c,i})^2}{\sum_{i=1}^n (U_{m,i} - \bar{U}_m)^2} \quad (9)$$

In the equation, R^2 is the coefficient of determination; $U_{m,i}$ is the measured flow velocity at the i -th measuring point (m/s); $U_{c,i}$ is the calculated flow velocity at the corresponding numerical point (m/s); $\bar{U}_m$ is the mean value of the measured flow velocity (m/s); and n is the total number of measuring points used for comparison.

Figures 5–8 show a strong agreement between calculated and measured flow velocities. The numerical simulation values align well with experimental measurements, with R^2 values exceeding 0.95. Thus, this numerical model accurately simulates the flow field distribution and hydraulic characteristics in the VSDCF tank chamber, making it suitable for further numerical calculations and analysis.

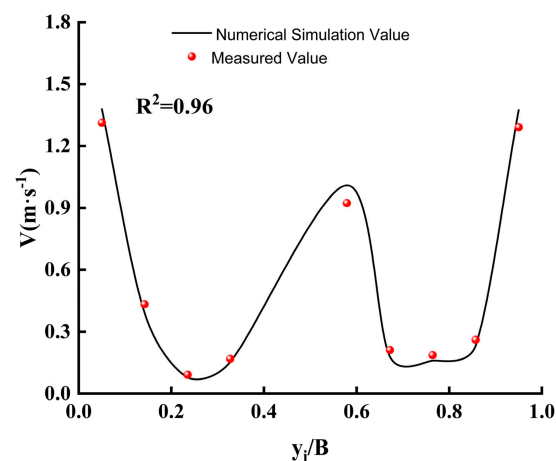


Figure 5. Comparison of flow velocity at each point on the I–I cross-sectional line.

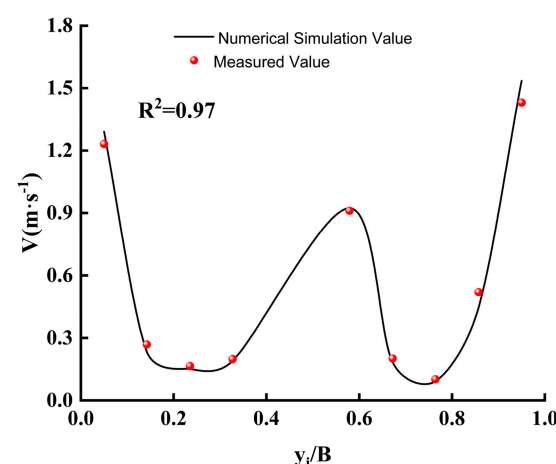


Figure 6. Comparison of flow velocity at each point on the II–II cross-sectional line.

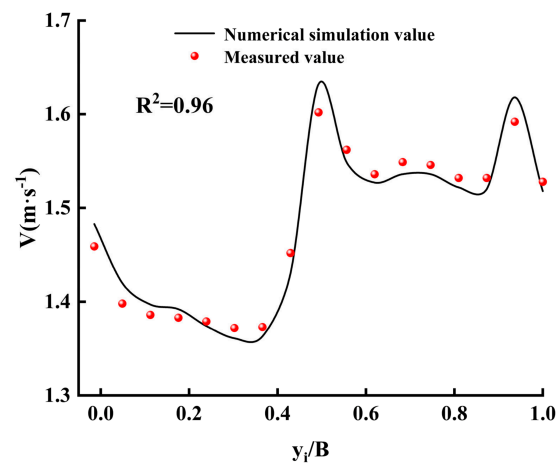


Figure 7. Comparison of flow velocity at each point on the III–III cross-sectional line.

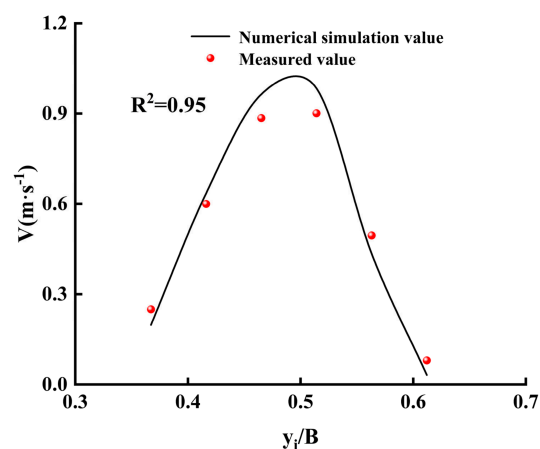


Figure 8. Comparison of flow velocity at each point on the IV–IV cross-sectional line.

3. Results and Discussion

This section presents the numerical results for the flow-field evolution, velocity distribution at the middle vertical slot, and turbulent kinetic energy distribution, with emphasis on the influence of the relative middle-slot width b_0/B on the hydraulic characteristics of the vertical-slot double-chamber fishway.

3.1. Effect of Relative Slot Width on Overall Flow-Field Structure

Internal flow evolution and mainstream characteristics: The internal flow field of the fishway features a high-velocity mainstream area and a low-velocity return flow area. The macro path of the middle mainstream area, generated by the middle vertical slot and traversing the entire pool, is influenced by the alternating arrangement of U-shaped partitions, resulting in a continuous micro S-shaped curve. In contrast, the main flow areas on both sides (collectively referred to as the “side mainstream” in this study) are relatively independent and have minimal impact on the overall flow-field structure. In this study, the terms “middle mainstream” and “side mainstream” refer to high-velocity flow branches generated by the middle and side vertical slots within the same continuous flow field.

As shown in Figure 9, when the relative width of the middle slot (b_0/B) is small, the main flow generated by the middle vertical slot experiences significant lateral deflection, moving through 2/3 of the energy dissipation tank chamber in this direction and approaching the side main flow. The two main flows converge, mix, and collide with the U-shaped partition. As b_0/B increases, the lateral deflection of the middle mainstream

decreases, reducing interference between the two main flows, and the middle mainstream no longer impacts the U-shaped partition. With further increases in b_0/B , only minor lateral deflection occurs, and the middle mainstream flows straight, nearly adhering to the wall.

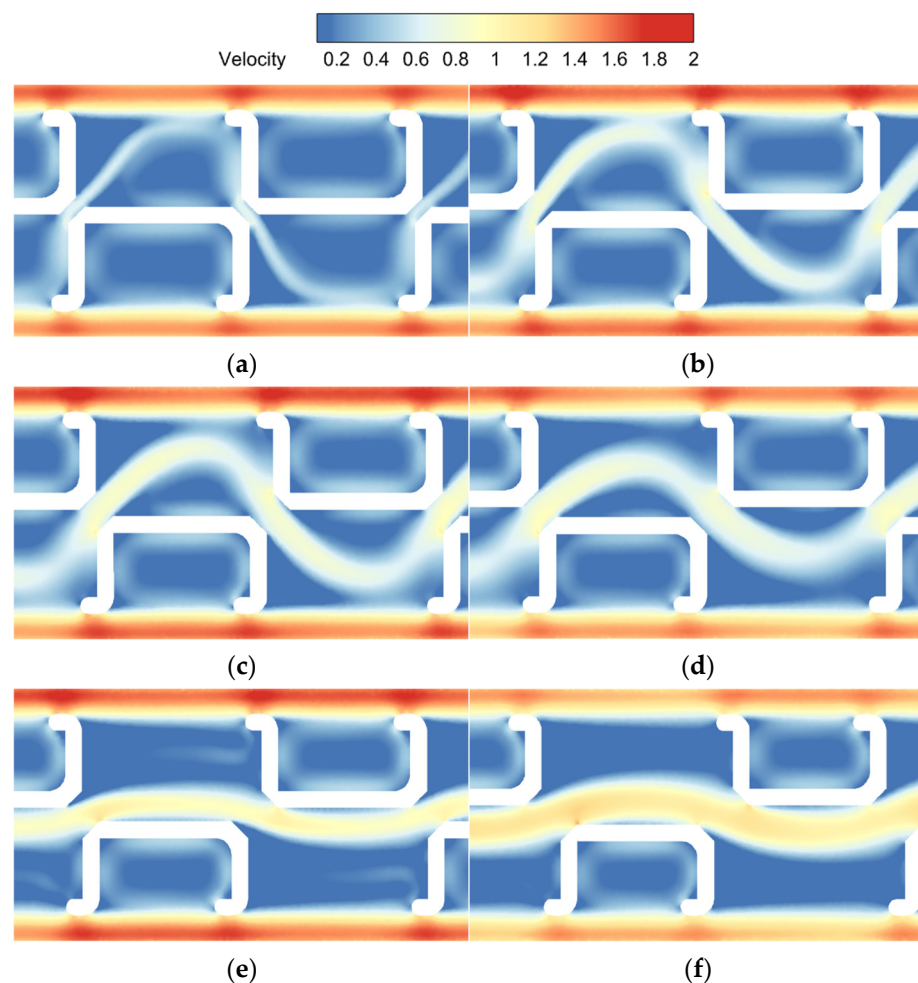


Figure 9. Typical flow velocity distribution diagram. (a) $b_0/B = 0.05$; (b) $b_0/B = 0.10$; (c) $b_0/B = 0.13$; (d) $b_0/B = 0.15$; (e) $b_0/B = 0.17$; (f) $b_0/B = 0.20$.

To quantitatively analyze the flow-field structure evolution in the energy dissipation tank chamber under varying b_0/B , the cross-sectional flow velocity distribution was extracted at 2/3 of the energy dissipation pool chamber along the water flow direction.

As shown in Figure 10, the flow velocity distribution in this section has a typical three-peak structure: the flow velocity values, from high to low, are the edge vertical slots (peak A, corresponding to the maximum flow velocity $u_{\max}$), the middle mainstream, and the reverse flow peak in the return area. Combining the flow field visualization results (Figure 9) with the variation in the geometric parameter Δy (Table 3), defined as the lateral distance between the maximum-velocity point of the middle mainstream and the reference boundary line at the 2/3 cross-section of the energy-dissipation pool chamber, where a larger Δy indicates stronger lateral separation of the middle mainstream, the flow-field structure can be categorized into three types based on the deflection degree of the middle mainstream, its mixing state with the side mainstream, and the distribution characteristics of the recirculation area.

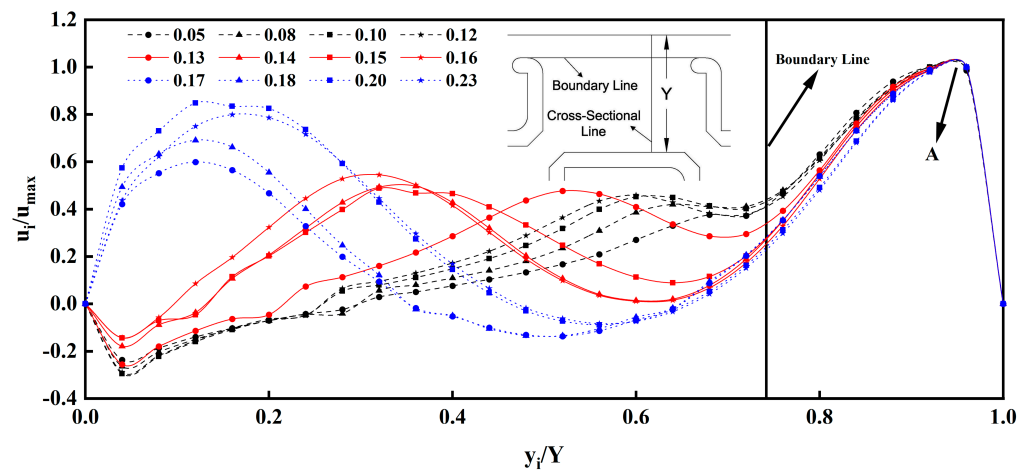


Figure 10. Flow velocity distribution at the 2/3 cross-sectional line of the energy dissipation pool.

Table 3. Distance between the maximum flow velocity in the intermediate mainstream and the boundary line (Unit: mm).

b_0/B	0.05	0.08	0.10	0.12	0.13	0.14	0.15	0.16	0.17	0.18	0.20	0.23
Δy	165	235	288	321	438	691	760	767	1091	1040	1119	1076

Before classifying the flow regimes, it should be noted that the “left” and “right” recirculation regions described below are defined relative to the flow direction of the middle mainstream branch. The following descriptions refer to the recirculation distribution in the left-side energy-dissipation pool chamber. Because the VSDCF chambers are arranged alternately on the left and right sides, the corresponding recirculation distribution in the right-side pool chamber is approximately mirrored.

(1) Category I: intermediate mainstream mixed type ($b_0/B < 0.12$)

After passing through the middle vertical slot, the flow forms a high-velocity middle mainstream branch within the continuous flow field. This branch undergoes an approximately 45° deflection in the downstream pool chamber and interacts strongly with the high-velocity branch generated by the side vertical slot. As b_0/B increases, the cross-sectional area of the middle mainstream also increases significantly, resulting in enhanced momentum, which weakens the mixing intensity with the edge mainstream. Two distinct backflow areas form on either side of the middle mainstream: the left backflow area is located on the backwater side of the U-shaped partition, constrained by the mainstream, with a smaller area and a right-angled triangle shape; the right backflow area is larger with a semi-elliptical shape. The typical structure of this flow regime is illustrated in Figure 9a,b.

(2) Category II: moderate mainstream deflection type ($0.12 \leq b_0/B \leq 0.16$)

As b_0/B increases, the flow-field structure changes significantly. The middle mainstream maintains a deflection angle of approximately 45° but separates from the side mainstream, preventing further mixing. Table 3 shows that as b_0/B increases, the Δy value, representing the lateral distance between the two mainstreams, gradually increases, indicating a greater separation. The shape of the recirculation area adjusts accordingly: the right-side recirculation area is compressed by the main flow, decreasing in size while maintaining a semi-elliptical shape; conversely, the left recirculation area increases, evolving into a unique undercut shape. The typical structure of this flow regime is illustrated in Figure 9c,d.

(3) Category III: middle mainstream flow pattern ($0.17 \leq b_0/B \leq 0.23$)

As b_0/B increases, the momentum of the middle mainstream dominates, leading to qualitative changes in the flow-field structure. The deflection angle of the middle mainstream is significantly reduced, causing the streamlines to straighten and flow almost parallel to the wall of the U-shaped partition, directly entering the pool chamber without interacting with the side mainstream. This change results in the complete disappearance of the right reflux area, leaving an extensively developed left reflux area that occupies most of the pool chamber. As shown in Table 3, the Δy value no longer increases monotonically with b_0/B but fluctuates around a specific value, indicating that the lateral relative positions of the two mainstreams have stabilized and the flow-field structure is less sensitive to changes in b_0/B . The typical structure of this flow regime is illustrated in Figure 9e,f.

3.2. Effect of Relative Slot Width b_0/B on the Evolution of Vortex Structure Inside the Energy Dissipation Pool Chamber

In the vertical-slot double-chamber fishway, the shape, size, strength, and stability of the vortex in the pool directly affect the fishway's energy dissipation efficiency, flow pattern, continuity of the fish's upward path, and effectiveness of the rest area. Through flow field visualization and quantitative analysis, this study reveals the dominant control effect of the relative slot width b_0/B on the evolution of the vortex structure in the double-chamber system. The evolution of the vortex structure exhibits distinct characteristics across the three typical flow regimes classified earlier.

(1) Small slot width ($b_0/B < 0.12$): Mainstream mixing and eddy current breaking

When b_0/B is small, the velocity of the mainstream ejected from the vertical slot is high, but its overall momentum is limited. In the first-stage pool chamber, the shear interaction between the high-speed jet and the pool chamber's side wall induces the formation of a large-scale, high-intensity main vortex. However, upon entering the second-stage chamber, the middle mainstream and the side mainstream, deflected by approximately 45° , collide violently, undergoing strong shear mixing (as shown in Figure 9a,b), which destabilizes the vortex structure.

The interaction between the two main streams disrupts the main vortex, causing it to divide, compress, and break into small-scale, high-turbulence secondary vortices. Similar vortex fragmentation and recirculation structures have also been reported in other hydraulic systems with strong boundary-induced flow separation [19,20], such as flow downstream of baffles in chlorine contact tanks and flow over corrugated pipe surfaces. These comparable phenomena suggest that the vortex fragmentation observed in the present VSDCF is a plausible hydrodynamic response to local jet interaction and boundary constraints.

This turbulent and unstable flow pattern is characterized by a high local energy dissipation rate and may provide less favorable hydraulic conditions for fish passage. The strong interaction between the middle and side mainstreams disrupts the continuity of the guidance flow and weakens the stability of the low-velocity recirculation zones. As a result, the flow field may reduce the availability of continuous migration paths and resting areas within the pool chamber.

(2) Medium slot width ($0.12 \leq b_0/B \leq 0.16$): main flow separation and stable double vortex

As b_0/B increases to the medium range, the vortex structure in the pool chamber becomes optimal. Under these conditions, the deflection angle of the middle mainstream decreases, the lateral distance from the side mainstream increases, and the interaction between the two weakens significantly, resulting in a stable mainstream-separation flow state (Figure 9c,d). This flow pattern creates two large-scale backflow areas with stable shapes and clear boundaries within the pool.

A main recirculation area and a secondary recirculation area form on both sides of the middle main flow. The left main recirculation area is larger, exhibiting an under-concave shape that provides a low-flow resting area suitable for fish habitats. The right secondary recirculation area is smaller and resembles a semi-ellipse, primarily stabilizing the flow field and assisting in energy dissipation. These two vortices, with distinct rotation directions and stable structures, work together with the middle mainstream to create a highly ordered mainstream-vortex coupled flow field.

This flow pattern represents the ideal operating condition for the vertical-slot fishway. The clear middle mainstream, with moderate flow speed, offers a continuous navigation path for fish moving upstream, functioning as a high-speed channel. The stable large-scale backflow areas on both sides serve as effective energy replenishment stations, allowing fish to recover their strength when crossing the gap between the mainstream, which is crucial for fish or juvenile fish with limited swimming ability. This optimized path-rest area configuration may improve hydraulic continuity and resting-space availability.

- (3) Large gap width ($0.17 < b_0/B < 0.23$): mainstream adheres to the wall, and single vortex dominates

As b_0/B increases, the momentum of the middle mainstream dominates, leading to fundamental changes in the flow-field structure. The deflection angle of the middle mainstream significantly decreases, streamlines become nearly straight, and a wall-adhering flow forms along the U-shaped partition wall, penetrating the pool chamber with minimal interaction with the side mainstreams (see Figure 9e,f).

This wall-adherent mainstream effect results in the complete disappearance of the right reflux area, leaving only a dominant left main reflux area in the pool chamber. Consequently, the flow-field structure transitions from a double vortex mode to a single vortex mode characterized by simplicity and reduced diversity.

This flow regime exhibits notable duality. The advantage is that the straight middle mainstream provides a clear navigation path, and the mainstream flow speed may decrease with the increased flow cross-section, facilitating the passage of fish with strong swimming abilities. However, the drawbacks are significant: first, the resting space is significantly reduced, leaving only a limited area in the left large vortex, which is unfavorable for small or weak-swimming fish. Second, the energy dissipation mechanism is weakened; without shear interaction between the main streams and the energy exchange of the double vortex system, energy dissipation relies primarily on side wall friction and viscous dissipation of a single vortex, diminishing overall performance and efficiency. Moreover, the loss of flow pattern diversity reduces the fishway's universality for species with different ecological habits. In summary, the fishway in this flow regime demonstrates the characteristics of strong guidance, weak energy dissipation, and low diversity.

3.3. Mainstream Trajectory Deflection and Flow Velocity Attenuation Rules

The shape of the middle mainstream and the along-course attenuation of kinetic energy are core indicators for evaluating the hydraulic characteristics of the tank chamber. To explore the influence of b_0/B on these aspects, the maximum flow velocity points from 34 cross-sections were extracted along the sixth-stage chamber. The along-course maximum flow velocity change curve (Figure 11) was constructed. For quantitative analysis, the dimensionless flow velocity ($u_{\max,i}/U_{\max}$), where $u_{\max,i}$ is the maximum flow velocity at the i -th extracted cross-section and $U_{\max}$ is the maximum value of $u_{\max,i}$ along the middle mainstream under the same b_0/B condition, and the maximum longitudinal attenuation rate (Table 4) were introduced.

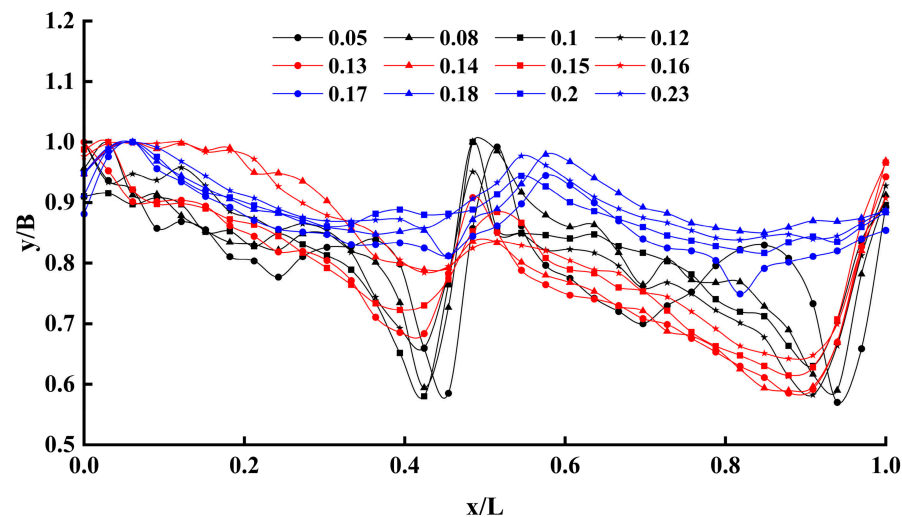


Figure 11. Longitudinal variation in the maximum flow velocity in the intermediate mainstream zone.

Table 4. Maximum longitudinal attenuation rate of the maximum flow velocity in the intermediate mainstream.

B_0/B	0.05	0.08	0.10	0.12	0.13	0.14	0.15	0.16	0.17	0.18	0.20	0.23
Attenuation rate/%	48.5	42.3	42.0	41.8	41.5	41.1	38.5	35.8	29.1	18.9	18.3	16.2

Notes: $u_{\max,i}$ is the maximum flow velocity at the i -th extracted cross-section along the middle mainstream, and $U_{\max}$ is the maximum value of $u_{\max,i}$ under the same b_0/B condition. The maximum longitudinal attenuation rate is calculated as $[1 - \min(u_{\max,i}/U_{\max})] \times 100\%$.

Figure 11 and Table 4 illustrate the critical role of b_0/B in energy dissipation within the main flow. For smaller slot widths ($0.05 \leq b_0/B \leq 0.16$), strong lateral diffusion and mixing of water flow lead to significant attenuation of the mainstream's maximum flow velocity, exhibiting a large variation amplitude. In contrast, for larger slot widths ($0.17 \leq b_0/B \leq 0.23$), lateral diffusion is limited, resulting in a more concentrated mainstream flow with a gentler decay of maximum flow velocity. Notably, when $b_0/B \geq 0.18$, the along-course maximum attenuation rate of the maximum flow velocity is less than 20%, indicating that the variation in flow velocity along the path has become negligible.

Research indicates a critical vertical slot relative width of approximately $b_0/B = 0.17$ that determines the mainstream flow pattern. When the relative middle slot width satisfies $b_0/B < 0.17$, the mainstream high-speed core maintains a fixed lateral position without mixing with the side recirculation zones, showing stable jet trajectory and uniform velocity attenuation. In contrast, for $b_0/B > 0.17$, the wider jet expands transversely, the mainstream trajectory deviates significantly toward the pool sides, and obvious flow mixing between mainstream and low-speed recirculation zones can be observed. It is essential for optimizing fishway design and balancing water flow directionality and energy dissipation.

3.4. Refined Control of Hydraulic Parameters of Key Sections by Relative Seam Width (b_0/B): Flow Velocity Distribution and Uniformity of Vertical Joint Section

The hydraulic characteristics of the middle vertical seam section are crucial for determining the fish passage efficiency of VSDCF. This study analyzes the flow velocity structure of this section, focusing on the distribution patterns of longitudinal and transverse flow velocity and their response to vertical slot width.

Figure 12 illustrates the flow velocity distribution and local coordinate system at the middle vertical-slot section. Due to the wall boundary conditions, the flow velocity at the middle vertical-slot section is relatively low near both sides and higher in the central

region. This non-uniform velocity distribution is an important hydraulic characteristic of the middle vertical slot. In addition, the upstream and downstream pool flow structures generate a transverse velocity component at each point on the middle vertical-slot section, resulting in local flow deflection. A larger transverse velocity component may increase the lateral disturbance to fish passage; therefore, its magnitude is also an important hydraulic indicator. To analyze the velocity distribution at the middle vertical-slot section, the local velocity values U_i at each point were extracted, and the section-averaged velocity U_0 was used as the reference value for dimensionless processing under each simulated condition. The longitudinal and transverse velocity-component distributions at the middle vertical-slot section were then plotted, as shown in Figures 13 and 14. Here, x_i denotes the distance from the starting point along the middle vertical-slot section, b_0 is the width of the middle vertical slot, and U_x and U_y represent the transverse and longitudinal velocity components at each point on the section, respectively. In this study, the transverse and longitudinal directions are defined according to the local coordinate system of the middle vertical-slot section shown in Figure 12, rather than the coordinate system of the whole fishway.

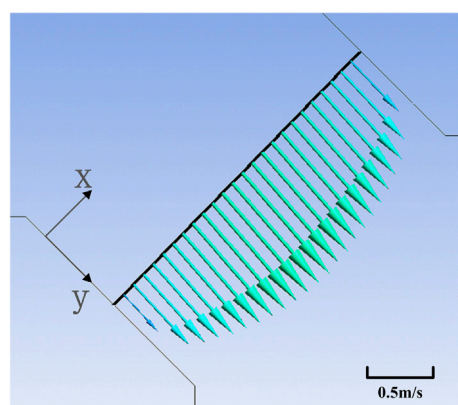


Figure 12. Flow velocity distribution at the intermediate vertical-slot ($b_0/B = 0.14$).

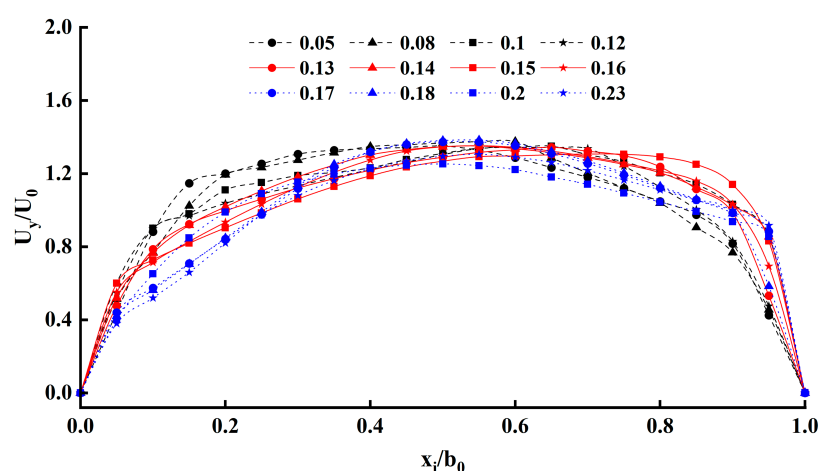


Figure 13. Longitudinal flow velocity distribution at the intermediate vertical-slot section.

Figure 13 shows the longitudinal flow velocity distribution under different working conditions. Specifically, in the interval $0 \leq x_i/b_0 \leq 0.2$, the longitudinal flow velocity at the middle vertical-slot section increases rapidly. For $0.2 \leq x_i/b_0 \leq 0.9$, $U_y/U_0 \approx 0.9$ – 1.3 , and the longitudinal flow velocity changes smoothly. In the interval $0.9 \leq x_i/b_0 \leq 1.0$, the longitudinal flow velocity decreases sharply. The flow velocity in the center area is high and uniform. In contrast, the longitudinal flow velocity near the oblique guide plates on both sides is low and exhibits a significant gradient, particularly on the right side. The flow

path of the central mainstream is shorter on the right side, enabling water to pass through the middle vertical slot earlier and inducing more pronounced velocity fluctuations along the right wall. Research indicates that vertical slot width does not significantly impact the overall distribution shape of longitudinal flow velocity.

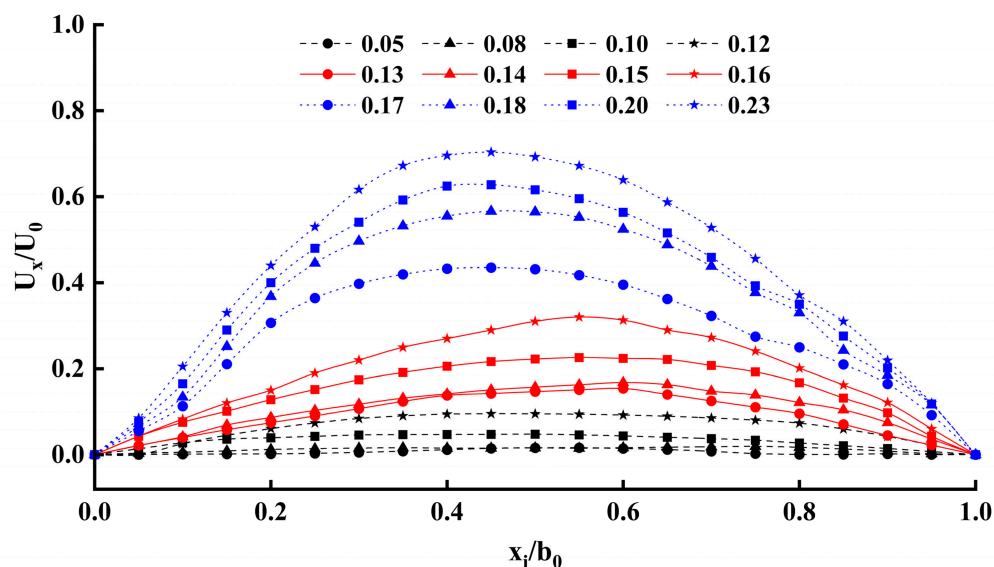


Figure 14. Lateral flow velocity distribution at the middle vertical-slot section.

In contrast, Figure 14 shows that the transverse flow velocity is sensitive to changes in vertical slot width. Its distribution fluctuates significantly, with the maximum cross-flow velocity located in the middle of the section ($0.4 \leq x_i/b_0 \leq 0.6$). The peak lateral flow velocity increases substantially with wider vertical seams. As the relative width b_0/B increases, the mainstream trajectory inside the pool presents weaker lateral deflection, while the jet expands more widely transversely at the slot outlet. Thus, reducing vertical slot width in design is crucial for controlling lateral flow velocity and improving hydraulic suitability.

3.5. Distribution Rules of Turbulent Kinetic Energy in the Energy Dissipation Pool Chamber

The Turbulence Kinetic Energy (TKE) characterizes the turbulence intensity of water flow, with its spatial distribution directly affecting fish habitat suitability in fishways. Research indicates that fish favor turbulent kinetic energy levels between 0.02 and $0.043 \text{ m}^2/\text{s}^2$ [11–13,21,22]. This study employs numerical simulation to elucidate the regulatory mechanism of relative slot width (b_0/B) on the spatial distribution of turbulent kinetic energy in VSDCF.

(1) Evolution of turbulent kinetic energy partition area

Figure 15 shows the turbulent kinetic energy distribution in the pool chamber under different b_0/B . Analysis indicates that b_0/B is a key parameter for regulating the partition area of different turbulent kinetic energy levels in the pool chamber. As b_0/B increases, the areas of the high-turbulence kinetic energy zone ($\text{TKE} > 0.043 \text{ m}^2/\text{s}^2$) and the medium-turbulence kinetic energy zone ($0.02 \text{ m}^2/\text{s}^2 \leq \text{TKE} \leq 0.043 \text{ m}^2/\text{s}^2$) increase monotonically. In comparison, the area of the low-turbulence kinetic energy zone ($\text{TKE} < 0.02 \text{ m}^2/\text{s}^2$) decreases significantly. Additionally, the low-turbulence kinetic energy core area within the U-shaped partition remains stable under various working conditions, indicating that the U-shaped partition provides a reliable low-flow resting area for fish, thereby demonstrating stable low-velocity hydraulic function.

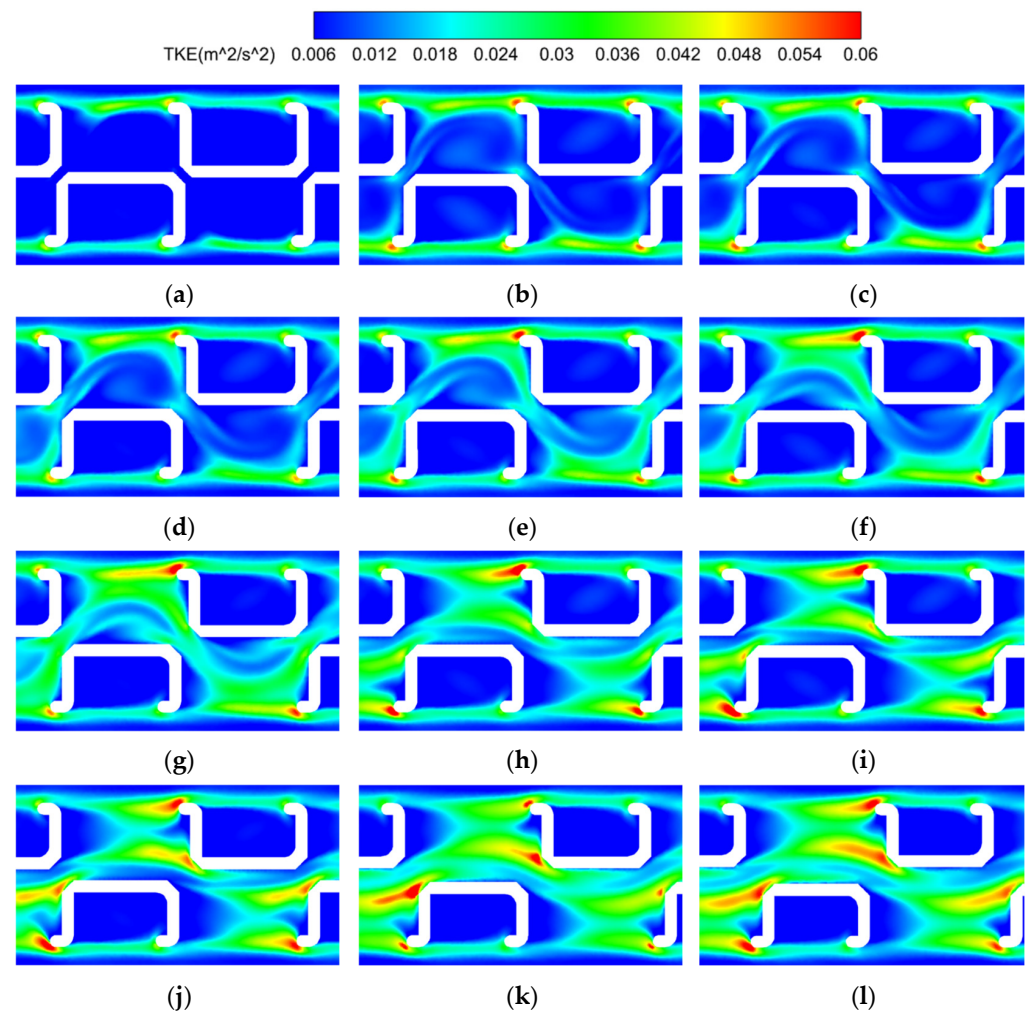


Figure 15. Turbulence kinetic energy distribution diagram. (a) $b_0/B = 0.05$; (b) $b_0/B = 0.08$; (c) $b_0/B = 0.10$; (d) $b_0/B = 0.12$; (e) $b_0/B = 0.13$; (f) $b_0/B = 0.14$; (g) $b_0/B = 0.15$; (h) $b_0/B = 0.16$; (i) $b_0/B = 0.17$; (j) $b_0/B = 0.18$; (k) $b_0/B = 0.20$; (l) $b_0/B = 0.23$.

(2) Spatial evolution of the high-turbulence kinetic energy region

The relative gap width changes the TKE partition area and reshapes the spatial pattern and morphological characteristics of the high-turbulence kinetic energy zone. Its evolution process consists of two stages:

1. Spatial location migration and formation mechanism. When the relative gap width is small ($0.05 \leq b_0/B \leq 0.16$), the low main pier flow volume causes the high-turbulence kinetic energy zone to concentrate at the pier head of the upstream U-shaped partition, resulting from the upstream impact due to the obstruction of the structure by the water flow (Figure 15a). As b_0/B increases, the momentum of the middle mainstream rises significantly, intensifying its impact on the downstream U-shaped diaphragm and inducing a new high-turbulence kinetic energy zone at the opposite side of the diaphragm pier head, known as the diverting impact effect (Figure 15b,c). These two high-turbulence kinetic energy zones result from the unique flow diversion design of the U-shaped partition and collectively constitute the main energy dissipation core in the pool chamber.
2. Evolution of morphological characteristics. Accompanying the spatial position migration is a notable change in the distribution of high-turbulence kinetic energy regions. Under the small b_0/B condition, the high-turbulence kinetic energy area manifests as a concentrated point (Figure 15a). As b_0/B increases, the mainstream's impact on the

downstream U-shaped partition stabilizes, causing the high-turbulence kinetic energy area to evolve from a point to a strip-like region that extends along the partition wall (Figure 15b,c). This morphological evolution indicates a shift in the interaction mode between water flow and structures from localized, violent impact to stable, continuous shear and friction. Consequently, the energy dissipation path becomes more concentrated and striped.

(3) Comprehensive discussion and design inspiration

In summary, the relative gap width b_0/B is a key parameter for regulating the distribution of turbulent kinetic energy in the pool chamber. Increasing b_0/B expands the area of the fish's preferred movement (middle TKE area) but also increases the scope and intensity of high-turbulence areas, posing challenges to fish movement. Therefore, fishway design must balance providing adequate habitat space with mitigating excessive turbulence, based on the eco-hydraulic characteristics of the target fish species. The TKE distribution law, as shown in Figure 15, provides a quantitative basis for this multi-objective optimization design.

3.6. Comprehensive Analysis of the Evolution Mechanism of Hydraulic Characteristics

The research results indicate that the regulatory effect of the relative gap width b_0/B is not a simple linear effect. It alters the initial momentum, diffusion space, and interaction mode of the mainstream, triggering systematic evolution of the vortex structure, energy dissipation path, and flow velocity distribution in the pool chamber. The vortex distribution law, as shown in Figure 16, indicates that b_0/B directly determines the balance between two key physical quantities: the initial momentum flux of the vertical slot jet (proportional to b_0^2) under the same water head, and the lateral diffusion and energy dissipation space provided by the pool chamber (proportional to b_0). The evolution of b_0/B adjusts the relative relationship between the mainstream's ability and the pool's capacity, leading to three levels of mechanism evolution:

(1) Evolution of mainstream diffusion and deflection mechanisms

b_0/B directly determines the behavior (diffusion, deflection, collision) of the mainstream after it is ejected from the vertical slot:

1. $b_0/B < 0.12$: Restricted diffusion and forced deflection occur when the initial momentum flux of the mainstream is small, and the lateral space of the chamber is broad. As the mainstream enters the pool chamber, there is ample space for lateral diffusion, leading to rapid attenuation of flow speed and momentum dispersion. However, due to the structural characteristics of the series double pool chambers, after the main flow in the first-stage pool chamber diffuses, its residual momentum still interacts with the side wall in the second-stage pool chamber. This interaction is guided by the U-shaped partition, causing a forced deflection of approximately 45° . This deflection is a passive outcome from geometric boundary constraints rather than an active behavior driven by the mainstream's momentum. Consequently, this leads to an asymmetric collision of the two mainstreams in the central area of the second-stage chamber, which directly causes subsequent vortex breakage and the formation of high-turbulence kinetic energy zones.
2. $0.12 \leq b_0/B \leq 0.16$ (Directional diffusion and autonomous deflection): As b_0/B increases, the initial momentum flux of the mainstream significantly rises while the lateral space of the chamber decreases. This enhances the inertia of the mainstream and suppresses lateral diffusion, leading to more concentrated directional diffusion. The mainstream gains sufficient momentum to overcome some boundary constraints and can autonomously deflect approximately 30° upon entering the second-stage

chamber. This deflection results from the interplay between the main flow volume and the boundary pressure gradient. Consequently, the main flow and side main flow achieve moderate separation, forming a stable main-flow separation pattern. This separation state prevents violent collisions and facilitates the formation of a stable double vortex structure.

3. $b_0/B > 0.16$ (Inhibit diffusion and wall-adherent flow): As b_0/B increases, the main flow flux reaches its maximum, and the pool chamber's lateral space becomes crowded. The mainstream's inertia surpasses its lateral diffusion, resulting in minimal diffusion. Instead, a wall-adhering flow forms as a high-speed jet is diverted by the U-shaped partition. The deflection angle of the main stream is minimized, and the streamlines remain straight. This behavior resembles flow in a confined channel, rather than diffusion and energy dissipation in an open pool chamber. This change fundamentally alters the interaction between the mainstream and chamber boundary, leading to the disappearance of the right backflow area and the emergence of a single-vortex dominant flow regime.

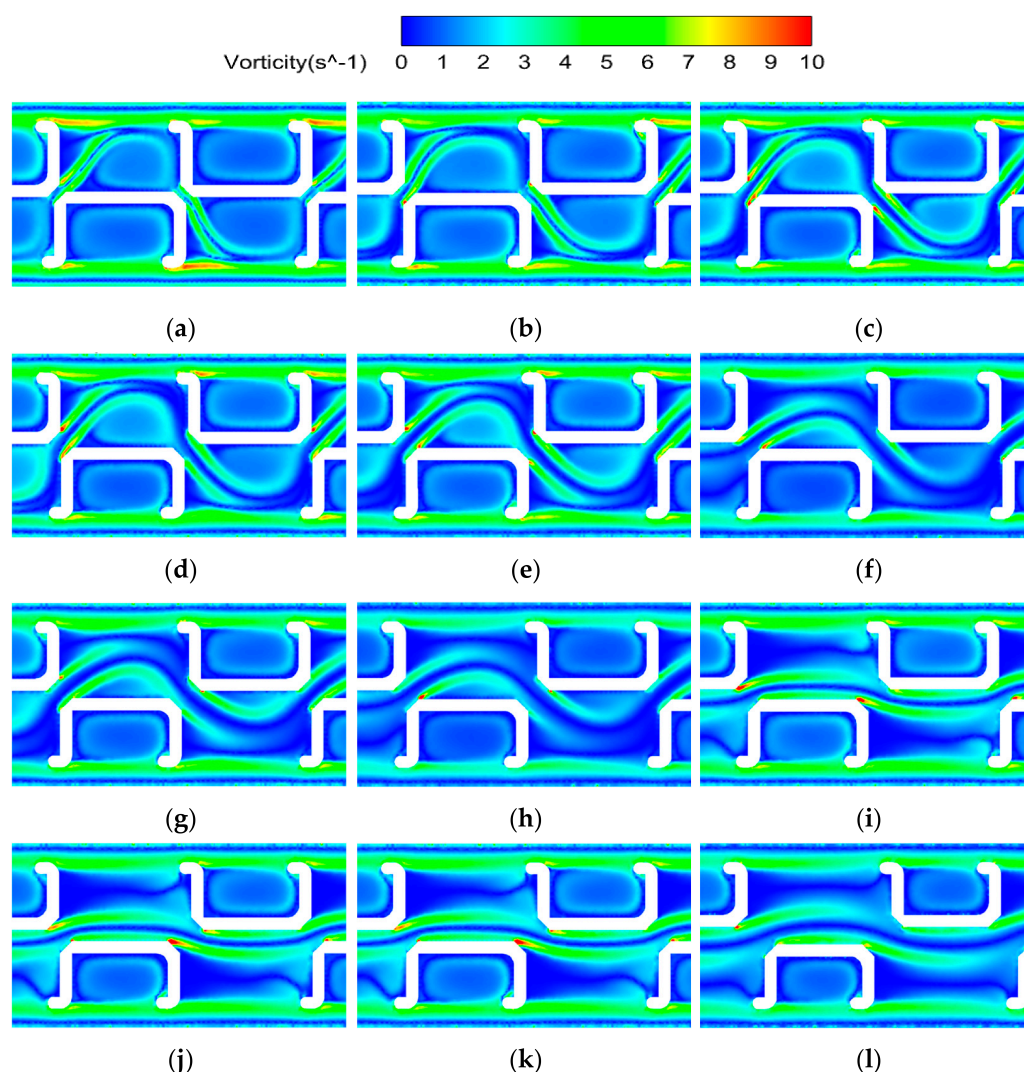


Figure 16. Vorticity distribution diagram. (a) $b_0/B = 0.05$; (b) $b_0/B = 0.08$; (c) $b_0/B = 0.10$; (d) $b_0/B = 0.12$; (e) $b_0/B = 0.13$; (f) $b_0/B = 0.14$; (g) $b_0/B = 0.15$; (h) $b_0/B = 0.16$; (i) $b_0/B = 0.17$; (j) $b_0/B = 0.18$; (k) $b_0/B = 0.20$; (l) $b_0/B = 0.23$.

(2) Evolution of vortex generation and stabilization mechanisms

Vortices result from interactions between the mainstream and boundaries, as well as between mainstreams. Their generation and stability mechanisms vary with changes in b_0/B .

1. Small b_0/B : Unstable shear generation mechanism. Vortices are generated by the strong shear layer formed after the collision of two deflected mainstreams. Due to instability in the collision position and intensity, the resulting vortices vary in scale and direction and are prone to breakdown, preventing the formation of a stable, large-scale main vortex. Energy is rapidly dissipated as small-scale turbulence, although the dissipation efficiency is low, leading to a turbulent flow pattern.
2. Medium b_0/B : Stable boundary separation generation mechanism. Vortices form from the interaction between two separated main streams (the middle main stream and the side main stream) and the pool chamber's side walls. The clear and stable main flow path stably peels off the boundary layer on both sides of the pool chamber, driving the left and right recirculation areas. The generation sources (mainstreams) of these two main vortices are stable, providing a continuous and balanced energy supply. Consequently, they establish a stable double-vortex system characterized by a large-scale, stable structure and opposite rotation directions. This system enables efficient energy transfer and dissipation: the kinetic energy of the mainstream is transferred to large-scale eddies through shearing, followed by viscous dissipation and the smooth release of the eddies, resulting in effective, low-turbulence energy dissipation.
3. Big b_0/B : Unilateral dominant generation mechanism. Vortices are primarily generated by the interaction between the high-speed wall-adhering mainstream and the left wall of the pool chamber. The lack of the main flow effect on the right side prevents the formation of an effective eddy driving force, resulting in the absence of the right recirculation area. The left main recirculation area, driven by a single high-speed mainstream, reaches its maximum size and intensity. However, the eddy structure is singular and lacks energy exchange with another eddy, leading to energy dissipation through the relatively inefficient single eddy viscous dissipation mode.

(3) Evolution of energy dissipation paths and efficiency

1. Small b_0/B : The dominant path is main flow energy $\rightarrow$ turbulent kinetic energy (via collision and fragmentation). Energy concentrates at the collision front, generating intense localized turbulence. While this facilitates rapid momentum loss, the resulting high-velocity gradients and elevated turbulence intensities create abrupt hydraulic transitions, which are generally unfavorable for fish passage.
2. Medium b_0/B : The energy evolves via main flow energy $\rightarrow$ large-scale eddy kinetic energy (stable double-vortex structure). This pathway facilitates the spatial redistribution of energy, effectively transforming concentrated axial momentum into organized rotational energy. The dissipation process is temporally stable and spatially uniform, balancing high energy dissipation rates with benign flow conditions conducive to fish passage.
3. Large b_0/B : The path simplifies to main flow energy $\rightarrow$ single vortex kinetic energy. This shortened transfer chain lacks intermediate buffering mechanisms, leading to reduced overall energy dissipation efficiency. Consequently, the flow field exhibits a distinct segregation between a high-velocity jet and a low-velocity recirculation zone, impeding the ability of fish to navigate smoothly across flow regions.

In summary, b_0/B regulates hydraulic characteristics by adjusting mainstream diffusion and deflection, eddy generation and stabilization, and energy dissipation paths

through the relationship between main flow volume and chamber space. A small b_0/B restricts mainstream diffusion and forces collisions, resulting in an unstable shear generation mechanism and inefficient turbulent energy dissipation. A medium b_0/B promotes directional mainstream diffusion and autonomous separation, creating a stable boundary separation mechanism and efficient large-scale eddy energy dissipation. A large b_0/B inhibits mainstream diffusion, leading to wall-adherent flow and a unilateral-dominated vortex generation mechanism, which reduces energy dissipation efficiency and results in a single flow pattern. This mechanism clarification provides a solid theoretical basis for understanding and optimizing the hydraulic performance of vertical-slot fishways.

4. Conclusions

A numerical simulation framework was employed to analyze the hydraulic characteristics—flow-field structure, middle mainstream area, and flow velocity at the vertical joint section—of the VSDCF pool chamber under 12 different relative widths of the middle vertical slot. The effects of slot width variation on the hydraulic performance of the VSDCF were systematically evaluated. The main conclusions are as follows:

- (1) The width of the middle vertical slot influences flow-field partitioning in the fishway. When $0.12 \leq b_0/B \leq 0.16$, the middle mainstream is stably centered in the energy dissipation tank chamber, with minimal interaction with the lateral mainstreams. The backflow areas on the left and right sides are moderately developed, resulting in a reasonable flow-field structure.
- (2) When $b_0/B = 0.13\text{--}0.17$, the trajectory of the middle mainstream exhibits moderate curvature and favorable along-course attenuation characteristics, indicating effective energy dissipation while maintaining flow continuity.
- (3) The width of the middle vertical slot has a pronounced effect on the velocity distribution within the vertical-slot section. Excessive slot width increases lateral velocity components, which may hinder fish passage. To limit transverse flow velocity and improve passage conditions, b_0/B should be maintained within the range of 0.05–0.16.
- (4) Increasing b_0/B leads to higher levels of turbulent kinetic energy within the energy dissipation pool chamber. To maintain turbulence levels within the preferred range for most fish species, the relative width of the middle vertical slot should be controlled between 0.05 and 0.16.

In summary, the optimal relative width of the middle vertical slot for VSDCF design lies in the range of 0.13–0.16. This study not only enriches the theoretical knowledge of the hydraulic characteristics of vertical slot fishways but also provides a scientific basis and technical support for the design and optimization of practical fishway engineering.

In addition, regional eco-environmental features, species-specific swimming behavior, preferred flow velocities, and turbulence tolerance were not incorporated into the present analysis. Future research should combine CFD simulations with PIV or ADV measurements and fish behavioral observation experiments or individual-based models (IBMs) to quantify the relationships between flow field parameters and fish passage success rates, thereby achieving synergistic “hydraulic–ecological” design. Additionally, further three-dimensional numerical simulations based on real engineering layouts will also be carried out to resolve the fine three-dimensional flow structures near vertical slots and baffles.

Author Contributions: Conceptualization, X.L. and D.H.; methodology, X.L.; software, X.L. and D.H.; formal analysis, X.L.; validation, X.L., D.H. and D.L.; data curation, D.H.; writing—original draft preparation, D.H.; writing—review and editing, X.L. and C.F.; supervision, C.F. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

L	The length of a single storage tank chamber.
B	The width of a single storage tank chamber.
H	The height of a single storage tank chamber.
b_0	The width of the middle vertical slot.
b_1, b_2	The widths of the side vertical slots.
b_0/B	The relative width of the middle vertical slot.
R^2	The coefficient of determination.
GCI	The Grid Convergence Index.
Δy	The distance between the maximum flow velocity in the intermediate mainstream and the boundary line.
$u_{\max}$	The maximum flow velocity at the section.
$U_{\max}$	The maximum flow velocity throughout the process.
$u_{\max,i}/U_{\max}$	The dimensionless maximum flow velocity along the intermediate mainstream.
$1-\min(u_{\max,i}/U_{\max})$	The maximum longitudinal attenuation rate of the intermediate mainstream.
U_i	The local flow-velocity magnitude at the i -th point on the middle vertical-slot section.
U_0	The section-averaged flow velocity of the middle vertical-slot section used for normalization.
x_i	The distance from the starting point on the middle vertical joint section.
x_i/b_0	The dimensionless distance from the starting point on the middle vertical-slot section.
U_x	The transverse velocity component in the local x -direction at each point on the middle vertical-slot section.
U_y	The longitudinal velocity component in the local y -direction at each point on the middle vertical-slot section.
U_x/U_0	The dimensionless transverse velocity component at the middle vertical-slot section.
U_y/U_0	The dimensionless longitudinal velocity component at the middle vertical-slot section.
$\bar{u}_i, \bar{u}_j$	The time-averaged velocity components.
u_i', u_j'	The fluctuating velocity components.
$\overline{u_i' u_j'}$	The Reynolds stress term
p	The time-averaged pressure.
ρ	The fluid density.
ν	The molecular viscosity.
ν_t	The eddy viscosity.
k	The turbulent kinetic energy.
ε	The turbulent dissipation rate.
S_{ij}	The time-averaged strain-rate tensor.
R	The additional term in the ε equation of the RNG k - ε turbulence model.
δ_{ij}	The Kronecker delta function.
η	The ratio of the turbulence time scale to the mean flow time scale.
η_0	The typical value of η in uniform shear flow.
$\alpha k, \alpha \varepsilon$	The empirical constants in the RNG k - ε turbulence model.

c1, c2	The empirical constants in the ε equation.
VSDCF	The vertical-slot double-chamber fishway.
VSF	The vertical-slot fishway.
CFD	Computational fluid dynamics.

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