

Article

Hydraulic Performance of an Angled Oppermann Fine Screen with Guidance Wall

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Abstract

Fish protection and guidance are critical factors in the design and operation of water intakes at hydropower plants. In this study, the hydraulic performance of the angled Oppermann fine screen has been investigated in a hybrid model with and without a guidance wall. The experiments were conducted under two different angles of 30° and 45°, and a bar spacing of 10 mm at a large-scale flume with a width of 2 m. Just up- and downstream of the screen, three-dimensional velocities were measured with Acoustic Doppler Velocimetry (ADV). In the computational fluid dynamics (CFD) model, the Large Eddy Simulation (LES) coupled with the Darcy–Forchheimer law, in which screens were modeled as homogeneous porous media, was employed. The experimental results revealed that velocities less than 0.5 m/s just upstream of the Oppermann fine screen and tangential velocity gradients over the entire cross-section of the screen were found to be 0.04–0.338 m/s/m and 0.04–0.856 m/s/m for $\alpha = 30^\circ$ and $\alpha = 45^\circ$, respectively, creating favorable hydraulic conditions for effective downstream fish guidance. The CFD model was validated against the experimental data within an acceptable error range, both for the velocity and the turbulent kinetic energy. Numerical simulations showed that implementing a curved guidance wall creates a symmetrical and homogeneous downstream flow field without the formation of recirculation zones behind the angled screen.

Keywords: downstream fish guidance; Oppermann bar profile; angled fine screen; guidance wall; streamlines



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1. Introduction

Physical and behavioral barriers are frequently used at hydropower plants for fish downstream guidance [1]. Behavioral barriers rely on stimuli (such as turbulence, sound, and electric fields) to either attract or repel fish, while physical barriers are ones that the fish cannot physically pass through [2,3]. The first arrangement of physical barriers consists of vertically inclined bar racks. The plane screen is positioned at an angle β relative to the riverbed to direct fish towards one or several surface bypass inlets situated at the top of the rack. The second arrangement type involves angled bar racks. Angled bar racks are positioned at an angle relative to the flow direction in the plan view to guide fish into a bypass situated at the downstream end of the rack [4]. In the literature, various solutions have been thoroughly investigated and applied, including inclined, angled, vertical, or horizontal bars and various bar shapes and spacing.

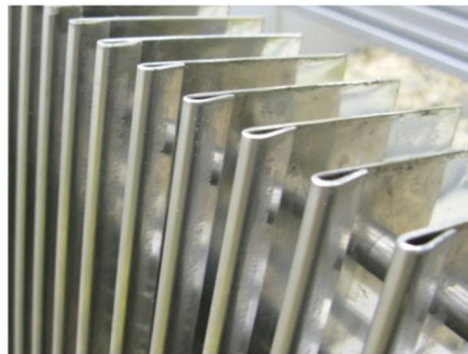
To achieve the effective guidance of fish species towards the bypass, which is located at the downstream end of the rack, it has been recommended to position the vertical bar racks with an angle of $\alpha \leq 45^\circ$, which are typically referred to as the angled vertical bar racks [5]. The flow fields around the angled vertical bar racks have been both experimentally and numerically investigated by recent studies where rectangular and various hydrodynamic bar profiles were tested under different rack angles [6–12]. In these studies, the Acoustic Doppler Velocimetry (ADV) and the Particle Image Velocimetry (PIV) measurements were carried out for the experimental methodology. Tsikata et al. [13] performed a PIV study to investigate the flow fields around a trash rack comprising three rectangular bars under four different horizontal angles. The main finding of those studies implied that, compared to rectangular bars, the downstream flow conditions were improved when rounded and curved bars were used. In the existing studies, mostly Reynolds-Averaged Navier–Stokes (RANS) turbulence models were employed for the numerical modeling. For instance, Leuch et al. [12] reported a moderately acceptable accuracy value of around 10–15% for their numerical simulation results. However, it should be noted that the RANS model reformulates the Navier–Stokes equations by time averaging and does not sufficiently represent the fluctuating flow field in the vicinity of screens. Hence, in the present study, LES was employed to simulate anisotropic turbulence flow fields around screens.

Knott et al. [14] observed that juvenile fish and small-bodied fish species cannot be protected from hydro-turbine entrainment by fine screens with 15 mm and 20 mm bar spacing. Also, the bar spacing of 20 mm does not provide sufficient protection for the fish, especially for the eels, whose populations have been greatly reduced [2]. Smaller fish, up to 40 cm long, can pass through the screen and enter the turbine. To effectively protect the fish, a narrower bar spacing of a maximum of 10 mm would be necessary. However, with conventional screens, the blockage ratio would be too high, and the turbines would no longer be economically viable due to increased head losses. Such an issue is a significant point of conflict between the economic operation of hydroelectric power plants and the protection of aquatic species. It should be noted that the upstream flow field influences fish downstream guidance efficiency, and the downstream flow field influences turbine efficiency.

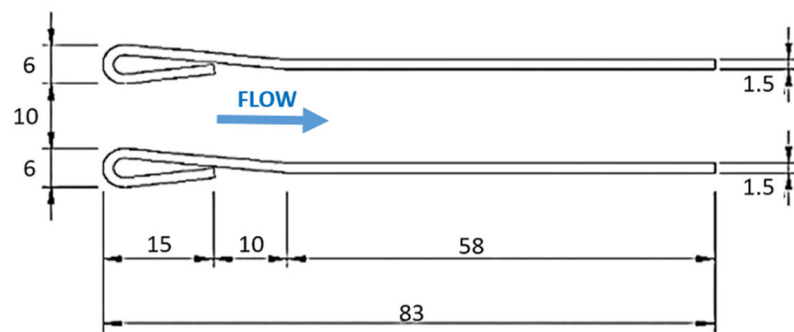
The present study focuses on a specific type of physical barrier that can be implemented at the intakes of run-of-river HPPs, which is referred to as the streamlined Oppermann fine screen. Figure 1 illustrates that the screen consists of vertical hydrodynamic bars featuring a rounded leading edge and a smooth surface. The Oppermann profile is made of folded stainless steel sheets, which results in a smoother surface and makes it easy to clean. This feature gives it a rounded profile head and prevents fish injuries. Furthermore, its outlet bar section is very thin compared to conventional screen profiles, which, due to a gradual expansion, results in less turbulence and thus lower head losses after the screen [15]. Based on field measurements, Ebel et al. [16] demonstrated that this fine screen system can provide high biological efficiencies as well as operational and economic benefits for an approach flow velocity of less than 0.50 m/s [17].

Figure 2 depicts the field of application of the angled fine screen. This type of downstream fish migration system was implemented at several run-of-river hydropower plants in Germany [17]. The water intake structures at run-of-river hydropower plants may have site-specific complex approach flow conditions (Figure 2), which can create vortices and recirculation zones even when the approach velocity is below 0.5 m/s and the flow is in the subcritical regime. The geometry of the approach flow system significantly influences fish guidance. If it is a large water body, the screens attract the streamlines from the whole area upstream, and then a part of the streamlines pass the screen at an angle close to 90 degrees. Then there exists a screen region without a guiding effect. There is not only a lack of

guidance, but in this critical region, the approach velocity is at a maximum (Figure 2). Accordingly, it is not possible to improve these unfavorable hydraulic conditions with smaller horizontal angles because the steep approaches at the bypass entrance persist.



(a)



(b)

Figure 1. Oppermann bar profile: (a) three-dimensional profile and (b) bar details in mm (top view).

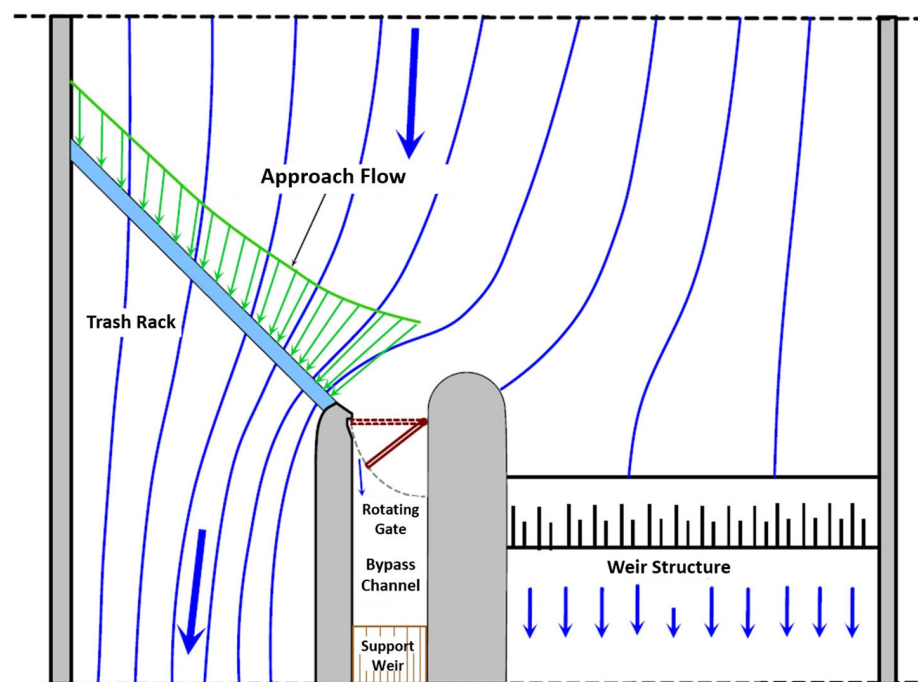


Figure 2. Poor approach flow conditions at the angled fine screen and bypass channel of a run-of-river hydropower plant. Blue Curved lines represent streamlines.

In the existing experimental and numerical studies, poor approach flow conditions were mostly ignored. To the author's best knowledge, no studies have examined the influence of the guidance wall on the hydraulic performances of angled vertical bars in a hybrid model. Also in the literature, studies on the hydrodynamic characteristics of streamlined vertical bar profiles used as physical barriers are scarce. The objective of this study is to investigate the impact of guidance walls on the hydraulic performance of angled Oppermann fine screens, both for upstream and downstream flow fields within experiments and in a CFD model. The study is expected to bring new insights into the hydrodynamic characteristics of angled Oppermann bar profiles used with curved guidance walls.

2. Methodology

2.1. Hydraulic Criteria

The local mean velocity magnitude, V_m (m/s), is calculated from the following equation:

$$V_m = \frac{\sum_{i=1}^n V_i}{n} \quad \text{in which} \quad V = \sqrt{V_x^2 + V_y^2 + V_z^2} \quad (1)$$

where n is the number of velocity samples, and V_x , V_y , and V_z show the velocity components in the x , y , and z directions. The turbulent kinetic energy per unit mass, TKE (m^2/s^2), is defined as

$$TKE = \frac{1}{2} (\overline{V_x'^2} + \overline{V_y'^2} + \overline{V_z'^2}) \quad (2)$$

where V_x' , V_y' , and V_z' are the turbulent fluctuation velocities in the streamwise, spanwise, and vertical directions, respectively. The vorticity vector in the z -direction, Ω_z (1/s), is defined as

$$\Omega_z = \left(\frac{\partial V_y}{\partial x} - \frac{\partial V_x}{\partial y} \right) \quad (3)$$

where x and y denote the coordinates in the longitudinal and lateral directions. Furthermore, the spatial velocity gradient in the longitudinal direction, SVG_x (1/s), is computed from

$$SVG_x = \frac{\Delta V_x}{\Delta x} \quad (4)$$

where ΔV_x and Δx refer to the change in velocity magnitude in the x direction and spatial position changes in the x direction, respectively. The spatial velocity gradient (SVG) is an important parameter related to flow convective acceleration or deceleration, which can trigger the avoidance or acceptance reaction of fish.

One of the key design criteria of downstream fish migration facilities is that the tangential component of the approach flow velocity, V_t , should be larger than the normal component, V_n to provide effective fish guidance toward the bypass channel [8,18]. Figure 3 illustrates the tangential and normal velocity components at the immediate upstream region of an angled screen. Here, the tangential velocity along the screen can be regarded as the main current that guides fish toward the bypass channel during downstream migration. From a biological point of view, it is important, among other things, that the orthogonal component of the approach velocity (V_n) does not exceed threshold values. These threshold values are derived from the sustained swimming speed of fish species, which refers to an endurance time of 200 min (anaerobic metabolism) and a certain water temperature and body length. The greater the approach velocity, the smaller the horizontal screen angle (α) must be [16].

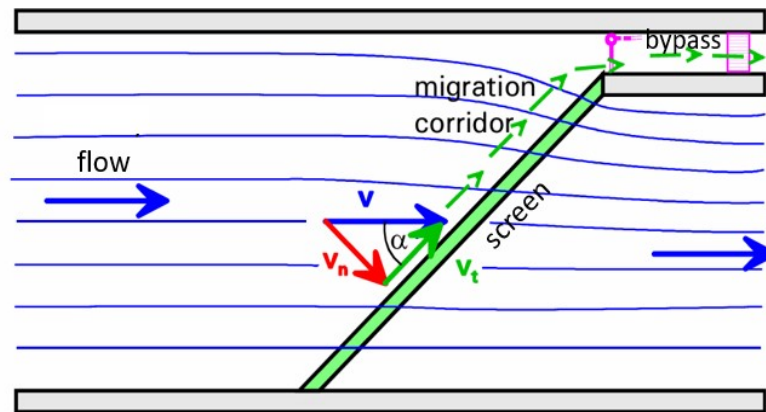


Figure 3. Definition sketch showing the tangential, V_t , and normal velocity components, V_n , in front of a screen having a horizontal angle of α .

Thus, for a proper design of an angled screen, the following design criterion should be met to maintain the guidance effect [18]:

$$\text{Approach velocity} \leq 0.5 \text{ m/s} \quad (5a)$$

$$V_t/V_n > 1 \quad (5b)$$

2.2. Experimental Setup

The experimental setup of the angled Oppermann fine screen, which was built in the hydraulics laboratory and testing facilities of the Kassel University Department of Civil and Environmental Engineering, is depicted in Figure 4. The angled Oppermann fine screen was tested in a recirculating 2 m wide and 30 m long horizontal rectangular laboratory flume without a bypass channel. In the experimental setup, there is a curved guidance wall at the left-hand side of the channel, which guides the flow towards the screen region (Figure 4a). The guidance wall is made up of a flexible plastic that is used to provide a smooth curvature. Accordingly, the arc length of the guidance wall is 2.4 m, and the radius of curvature is 1.85 m. The vertical height of the wall is 0.75 m, and it is supported by wooden frames. The leading and trailing edge positions are 2.55 m and 1 m upstream of the Oppermann fine screen (Figure 4b).

The hydraulic conditions of the experimental study are summarized in Table 1. In the experiments, the approach flow depth and the approach flow velocity were kept constant with a value of 0.6 m and 0.5 m/s, respectively. The 0.745 m of width shown in Figure 4b yields a discharge value of 0.225 m³/s, which was kept constant during the experiments. The approach flow Froude number was 0.21, and the Reynolds number (Re) was 1.1×10^5 , indicating that the viscous scale effects are negligible [19,20]. In the experiments, the clear bar spacing of $b = 10$ mm was tested for the Oppermann bar profile under two different horizontal angles of $\alpha = 30^\circ$ and $\alpha = 45^\circ$. The approaching hydraulic conditions, such as the flow depth and the total flow rate, in the two setups were kept constant throughout the experiments.

Table 1. Summary of the test conditions of the experiments.

Q (L/s)	U_0 (m/s)	y_1 (m)	B (m)	b (mm)	α (-)	Fr_1 (-)	Re_b (-)	ζ (-)
225	0.5	0.6	2	10	30°	0.21	3000	0.65
225	0.5	0.6	2	10	45°	0.21	3000	0.70

Note: Q = discharge, U_0 = approach flow velocity, y_1 = upstream flow depth, B = channel width, b = clear bar spacing, α = horizontal angle of the screen, Fr_1 = approach flow Froude number, Re_b = bar Reynolds number, and ζ = head loss coefficient.

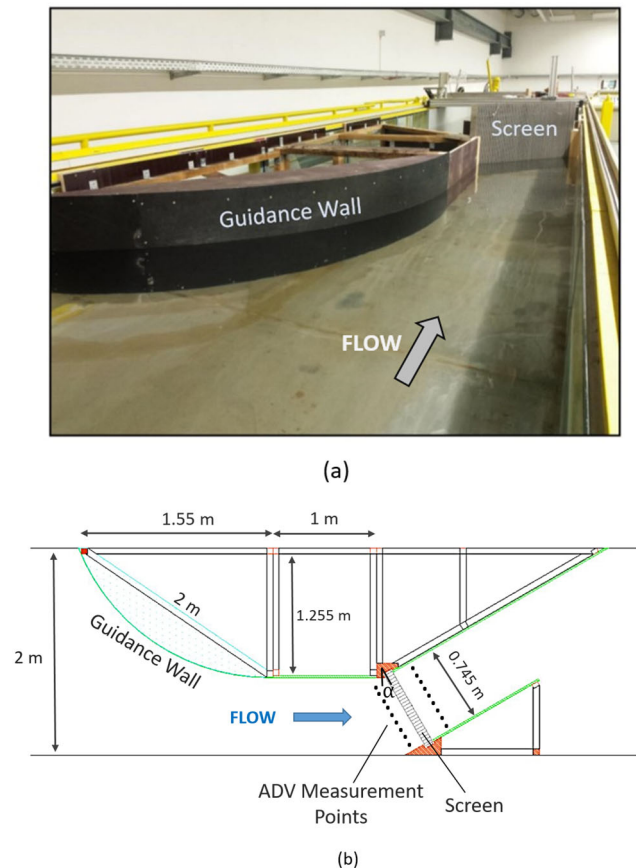


Figure 4. (a) Experimental setup showing the curved guidance wall and the Oppermann screen, (b) top view of the experimental setup and velocity measurement points. α denotes the screen horizontal angle. The guidance wall has an arc length of 2.4 m with a radius of 1.85 m. The orange parts represent the supporters to hold the screen in place.

The water surface elevation was measured by an ultrasonic distance sensor, Sonic Joker, which was mounted above the water surface and scanned downward the flow free surface [21]. The plan view of the experimental setup is shown in Figure 4b, where the locations of the screen and velocity measurement points, as well as the curved guidance wall, are shown. The instantaneous 3D velocities were measured at 90 different points at the vertical sections 0.1 m up- and 0.2 m downstream of the Oppermann fine screen (Figure 5). A 10 MHz Acoustic Doppler Velocimetry, ADV (Nortek Vectrino, Oslo, Norway) was used to gather the 3D velocity data, and the sampling duration was 30 s. ADV measures flow velocities ranging from around 0.001 m/s to 2.5 m/s with an accuracy of $\pm 1\%$.

2.3. CFD Modeling

The computational fluid dynamics (CFD) modeling of the present study was performed at Hacettepe University Civil Engineering Department with FLOW-3D v11.04 software. The CFD model was constructed by using the exact initial and boundary conditions of the physical model. Accordingly, the flow through the angled Oppermann fine screen was simulated by implementing a porous media model. This commercially available CFD software is based on the finite volume method (FVM), employing a rectangular orthogonal grid structure. Complex geometries are represented by using the Fractional Area/Volume Obstacle Representation (FAVOR) technique. Also, tracking the position and movement of the free surface is modeled by the Volume of Fluid (VOF) approach [22].

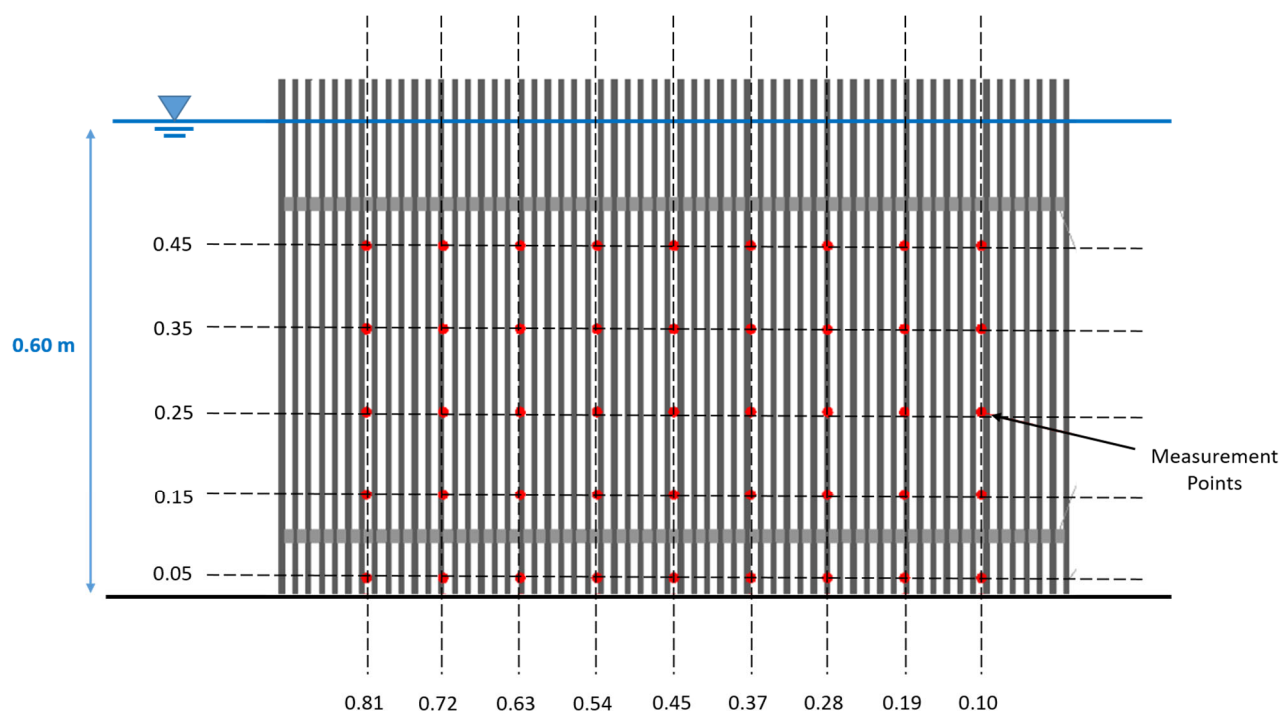


Figure 5. ADV measurement grid in the x - z vertical plane for $\alpha = 45^\circ$. Measurements were taken 0.01 m up- and 0.02 m downstream of the Oppermann fine screen. All dimensions are in meters. The bold, blue solid line represents the free surface.

The simulation results were compared to the experimental data under the same hydraulic conditions. For the validation of the CFD model, the numerical values of the velocity and turbulent quantities were compared to the measured data by using the following formula:

$$MAPE (\%) = \frac{1}{n} \sum \left| \frac{Measured - Simulated}{Measured} \right| \times 100 \quad (6)$$

where MAPE stands for the mean absolute percentage error and n is the total number of measurement points. The mean absolute percentage error (MAPE) values between physical and numerical model results were calculated based on Equation (6) at 90 different measurement points.

2.3.1. Flow Through a Porous Medium

When modeling the flows through a porous medium, a modified version of the Navier–Stokes equations is needed, which would result in the reduction of their original form. However, additional effects of the resistance that are triggered by the presence of the porous region should also be considered. The Darcy–Forchheimer model takes into account both viscous and inertial effects within a porous medium, leading to the following expression:

$$u_D = -\frac{K}{\mu}(\nabla p - \rho g) + K\nabla^2 u_D - \frac{F|u_D|u_D}{\nu} \quad (7)$$

where K and F stand for the Darcy (permeability) and Forchheimer (inertia) coefficients, respectively, u_D represents the Darcian (bulk) velocity, ∇p denotes the pressure drop, ρ is the fluid density, μ is the dynamic viscosity, ν is the kinematic viscosity, and g is the

gravitational acceleration. Further mathematical manipulation yields the following relation for the pressure drop within a porous medium:

$$-\nabla p = A|u_D|\mu \frac{(1-\phi)^2}{\phi^3} + B|u_D|^2\rho \frac{(1-\phi)}{\phi^3} \quad (8)$$

where A and B represent the Forchheimer drag coefficients, and ϕ is the porosity. Here, the drag coefficients A and B depend on the porous medium characteristics, where the values are determined empirically [23]. The so-called coefficients were calculated based on the measured head loss vs. velocity data, where a second-order polynomial fit was applied. The head losses were considered for a bar spacing of $b = 10$ mm, and the screen angles of $\alpha = 30^\circ$ and $\alpha = 45^\circ$, leading to the obtaining of separate drag coefficients for each case. The orientation of the bars is essential, and it is taken into account in the porous media model.

2.3.2. CFD Model Establishment

Figure 6 shows the CFD model of the experimental setup where the 45° -angled porous medium, velocity measurement points, and guidance wall are illustrated. Here, the streamwise direction is shown as the y axis, whereas the x and z axes represent the lateral and vertical directions. The velocity boundary condition was applied at the inlet by separately defining the x and y components of the approach flow velocity of 0.5 m/s. At the exit section, the pressure boundary condition coupled with the fluid elevation was set. Sidewalls and the channel bottom were defined as the symmetry and wall boundary conditions. The solid volume shown in violet (Figure 6) was defined as a complement in the CFD model, enabling fluid flow only within that region, while treating the other regions in the mesh block as solid material. The model region has a height of 0.65 m (Figure 4), and for the initial conditions, an approach flow depth of 0.60 m was defined within the entire domain where atmospheric pressure was satisfied at the free surface. Also, the initial time step was selected as 0.001 s, and the following time intervals were adaptively determined by the software. Thus, at sections 0.1 m upstream and 0.2 m downstream of the porous region, the three-dimensional instantaneous velocities were obtained at each probe point.

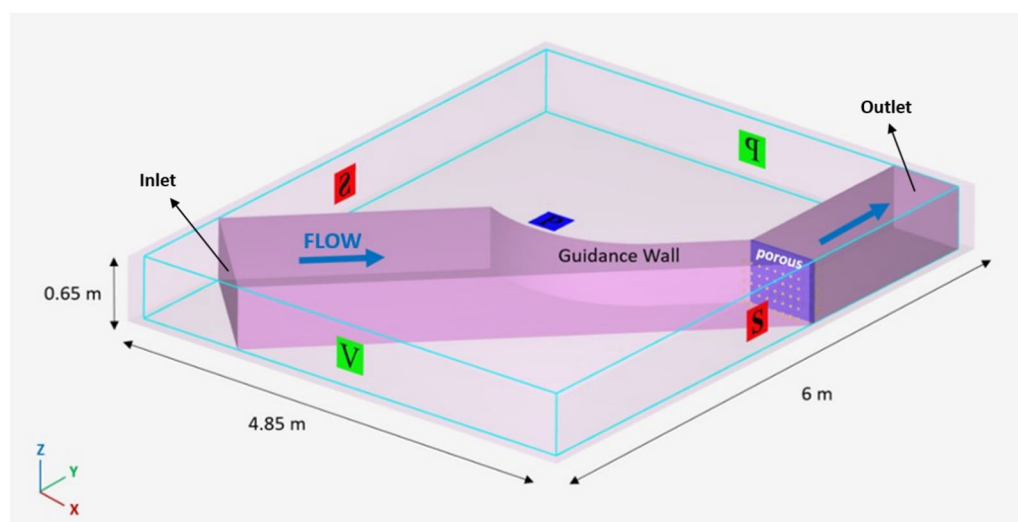


Figure 6. Computational domain of the CFD model in FLOW-3D including the curved guidance wall, porous medium (blue), and the probe points (yellow). The boundary conditions are as follows: P = pressure, S = symmetry, and V = velocity. The fluid flows only within the solid volume (violet), and the other regions in the mesh block are defined as solid material.

To evaluate the effect of the curved guidance wall on the hydraulic performance of the angled screens, the simulations were further performed for the same setup without the guidance wall under the same initial and boundary conditions. Figure 7 shows the three-dimensional domain of the CFD model without a guidance wall, where the setup was only numerically investigated. Also, the screen region was modeled as a porous medium.

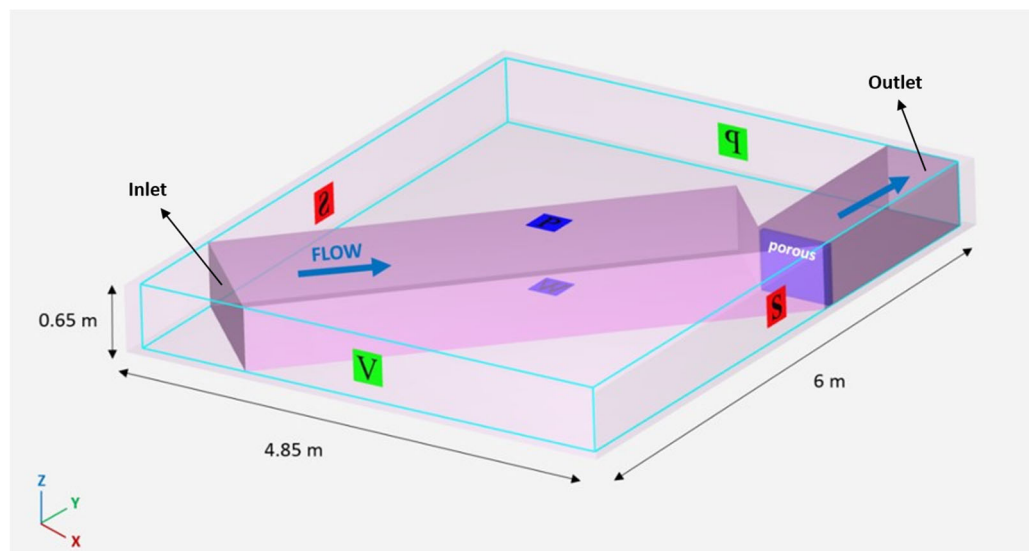


Figure 7. Computational domain of the CFD model setup without a guidance wall. Simulations were run in FLOW-3D while keeping all initial and boundary conditions identical to the previously constructed model shown in Figure 4. The fluid flows only within the solid volume (violet), and the other regions in the mesh block are defined as solid material.

The Large Eddy Simulation (LES) was selected for the turbulence model in this study. In comparison to the Reynolds-Averaged Navier–Stokes (RANS) turbulence closure models, the LES approach has been reported to resolve the 3D vortical structures with higher accuracy [24–26]. Within this context, the large-scale structures in the solution domain were directly resolved, whereas the structures that are smaller than the selected grid size were modeled by applying the Smagorinsky model as given in [27]:

$$\tau_{xy} = -2v_t \bar{S}_{xy} \quad (9)$$

$$\bar{S}_{xy} = \frac{1}{2} \left(\frac{\partial \bar{V}_x}{\partial y} + \frac{\partial \bar{V}_y}{\partial x} \right) \quad (10)$$

where τ_{xy} denotes the anisotropic stress tensor, $\bar{S}_{xy}$ represents the resolved rate of strain, v_t shows the eddy (turbulent) viscosity, and $\bar{V}_x$ and $\bar{V}_y$ are the resolved velocity fields.

A mesh sensitivity analysis was performed based on the velocity and turbulent kinetic energy errors between the physical and CFD model results (Table 2). It can be seen that, for both $\alpha = 30^\circ$ and $\alpha = 45^\circ$ screen angles, the relative errors of V_m and TKE parameters remain almost the same after the mesh size of 0.02 m, resulting in a mesh-independent solution.

Based on the mesh sensitivity analysis, for the meshing of the solution domain, at the channel bed, a uniform wall-normal grid spacing of 0.02 m was applied in the x and z-directions. However, the wall-normal grid spacing in the y-direction was gradually refined toward the porous region (Figure 8). Accordingly, a grid size of 0.005 m was employed in the first cell perpendicular to the porous zone. For all simulations, a structured rectangular mesh was used, yielding a total cell count of 0.42×10^6 within the entire computational domain.

Table 2. Mesh sensitivity analysis based on the mean absolute percentage error (MAPE) values at 90 data points.

Mesh Size (m)	$\alpha=30^\circ$		$\alpha=45^\circ$	
	V_m (m/s)	TKE (m^2/s^2)	V_m (m/s)	TKE (m^2/s^2)
0.05	MAPE = 7.8%	MAPE = 13.8%	MAPE = 10.8%	MAPE = 15.0%
0.04	MAPE = 7.2%	MAPE = 10.8%	MAPE = 10.5%	MAPE = 11.6%
0.03	MAPE = 5.3%	MAPE = 8.4%	MAPE = 9.3%	MAPE = 8.5%
0.02	MAPE = 4.6%	MAPE = 4.0%	MAPE = 9.1%	MAPE = 4.4%
0.01	MAPE = 4.5%	MAPE = 3.9%	MAPE = 9.1%	MAPE = 4.3%

Note: α = angle of the water intake, V_m = velocity magnitude, and TKE = turbulent kinetic energy.

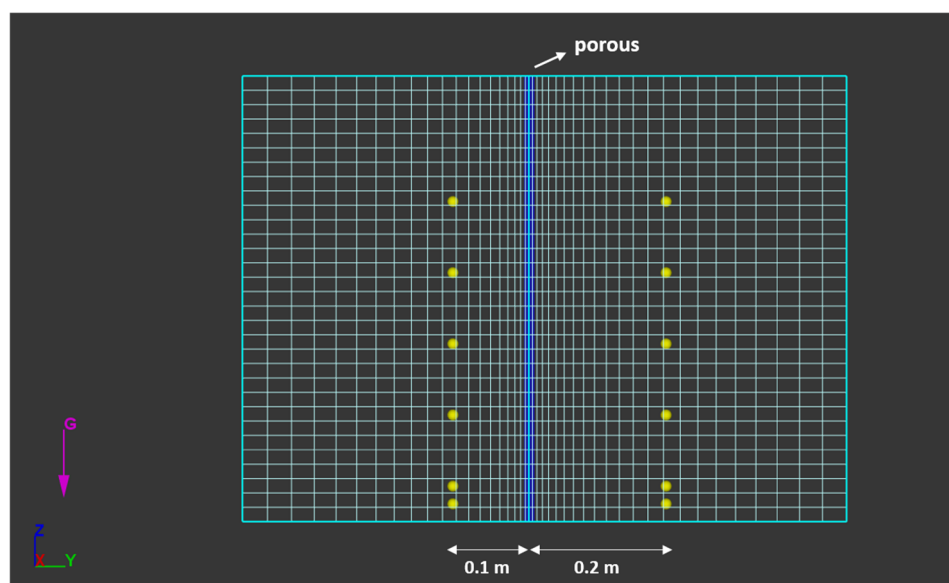


Figure 8. Gradual mesh refinement along the y -axis toward the porous region. The measurement points are denoted by yellow circles. Mesh resolution = 0.02 m in x - and z -axes. Total cells = 0.42×10^6 .

The CFD model used the LES with near-wall modeling, and the grid resolution distant from the wall was fine enough to resolve 80% of the turbulent energy [28]. For example, Hinterberger et al. [29] used 3D LES to simulate the flow field surrounding the groynes using a grid size equal to one-fifteenth of the flow depth. Thus, the chosen grid size of 0.02 m, which is equal to one-thirtieth of the flow depth, was thought to be sufficient in this study. The normalized wall distance for a wall-bounded flow, y^+ , is defined as follows:

$$y^+ = u_* y / \nu \quad (11)$$

where u_* refers to the friction (shear) velocity, y denotes the absolute distance to the nearest wall, and ν is the kinematic viscosity of the fluid. Hence, the CFD model's calculation of the y^+ value for the initial grid was 200, which is consistent with the numerical results of [30].

3. Results

3.1. Experimental Results

All experiments were conducted for an approach flow velocity of 0.5 m/s with the guidance wall condition. The sectional-average velocities before and after the screen were calculated as 0.5 m/s and 0.39 m/s, respectively. The head loss coefficients were computed from the measurements as 0.65 and 0.70 with a bar spacing of 10 mm for $\alpha = 30^\circ$ and $\alpha = 45^\circ$, respectively, indicating that the head loss coefficients did not change noticeably

under different screen angles. So, it was possible to keep the approach flow characteristics the same when the horizontal screen angle changed for the same discharge value.

Figure 9 displays the distributions of the measured mean local velocity magnitudes, V_m , on the x-z plane at the upstream region of the Oppermann fine screen with the bar spacing of $b = 10$ mm and the screen angles of $\alpha = 30^\circ$ and $\alpha = 45^\circ$ with a guidance wall. For both tested screen angles, the flow velocities are less than 0.6 m/s. The flow velocities in front of the screens exhibit a slight increase in the right flow direction. This variation is due to the curvature in the flow direction on the right at the beginning of the experimental setup. Moreover, a slight and gradual increase in the flow velocities upstream of the screen in the left-to-right flow direction can be observed (Figure 9).

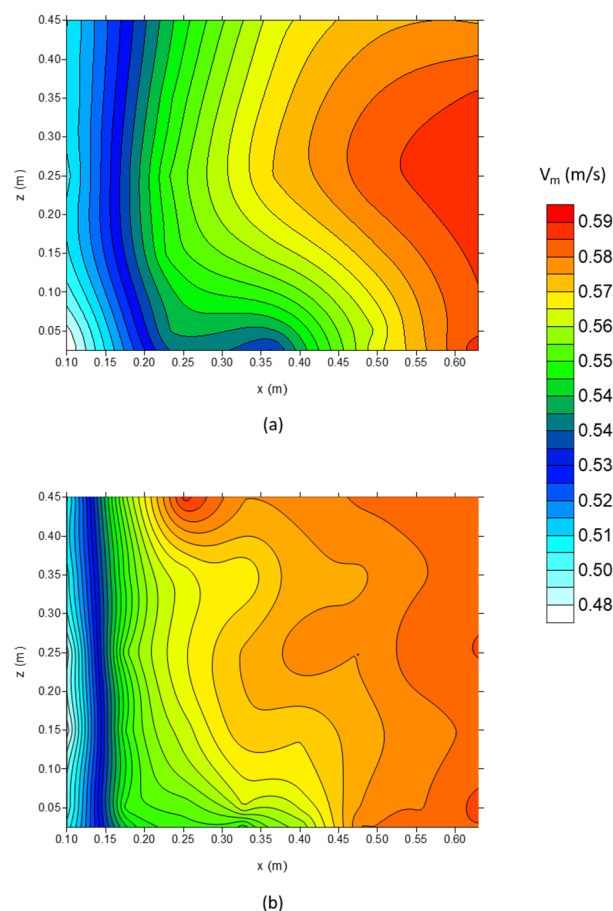


Figure 9. Experimentally measured velocity magnitude V_m contours in the x-z vertical plane located at 0.1 m upstream of the Oppermann fine screen having a bar spacing of $b = 10$ mm for the screen angles of (a) $\alpha = 30^\circ$, and (b) $\alpha = 45^\circ$.

Figure 10 shows the distributions of the turbulent kinetic energy, TKE, on the x-z plane at the up- and downstream regions of the Oppermann fine screen with the bar spacing of $b = 10$ mm and the screen angle of $\alpha = 30^\circ$ with a guidance wall. For both upstream and downstream of the screen, turbulent kinetic energy has low values in the range of 1.3×10^{-5} – 2.5×10^{-6} m²/s². Figure 10 indicates that the Oppermann fine screen does not significantly influence the turbulence compared to its prior state. However, when comparing the turbulence levels before and after the conventional bar screen (i.e., rectangular), it is noticeable that the values after the screen are not higher than those before. Thus, the turbulence levels also show that the Oppermann fine screen has a significantly better influence on the downstream flow field after the screen.

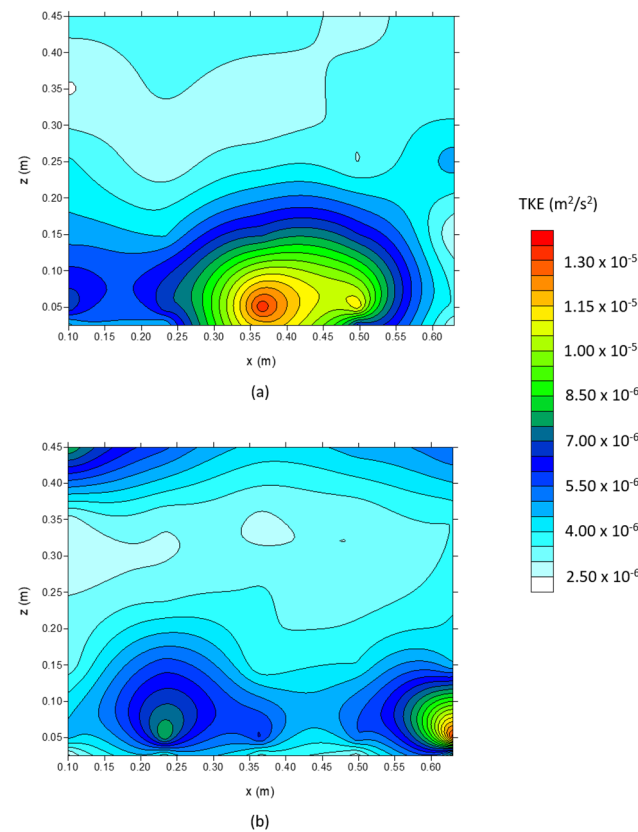


Figure 10. Experimentally measured turbulent kinetic energy (TKE) contours in the x-z vertical plane located (a) 0.1 m upstream, and (b) 0.2 m downstream of the Oppermann fine screen. $b = 10$ mm and $\alpha = 30^\circ$.

3.2. Numerical Model Results

The porous media approach results of the CFD model shown in Figure 6 were validated in terms of the velocity magnitude and turbulent kinetic energy (TKE) quantities as presented in Table 3. The MAPE values are shown under two different angles of the Oppermann fine screen. It can be seen that the error values are less than 10% for all tests, indicating the high prediction performance of the CFD model with a porous media approach. The velocity errors were much lower when $\alpha = 30^\circ$. The TKE errors remained within the range of 4–4.6%, indicating a high prediction accuracy of the turbulence. The absolute percentage error (APE) contours show the spatial distribution of the errors between the physical and CFD model results for $\alpha = 30^\circ$ (Figure 11). For both up- and downstream measurement points, errors of around 10% were observed at the left-hand side of the screen, where they gradually decreased in the x-direction. On the other hand, relatively more uniform errors were obtained along the vertical axis for $z > 0.05$ m. However, within the region of $0 < z < 0.05$ m, the highest errors of around 11% were observed, where the errors are highly non-uniform due to sharp velocity gradients near the channel bottom.

Table 3. The mean absolute percentage errors (MAPE) between the experiments and CFD model results at 90 different measurement points around the Oppermann fine screen.

Parameter	b=10 mm	
	$\alpha=30^\circ$	$\alpha=45^\circ$
V_m (m/s)	MAPE = 4.6%	MAPE = 9.1%
TKE (m^2/s^2)	MAPE = 4.0%	MAPE = 4.4%

Note: α = screen angle, b = bar spacing, V_m = velocity magnitude, and TKE = turbulent kinetic energy.

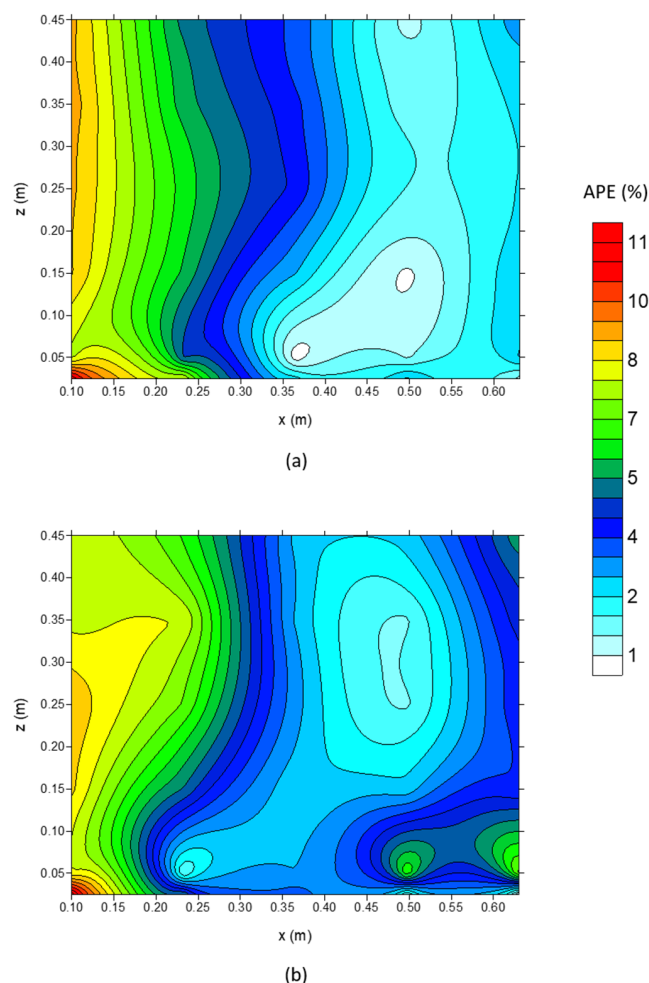


Figure 11. Absolute percentage error (APE) contours between the physical and CFD model results in the x-z vertical plane located (a) 0.1 m upstream, and (b) 0.2 m downstream of the Oppermann fine screen. Here, V_m errors are shown. $b = 10$ mm and $\alpha = 30^\circ$.

To compare the physical and CFD model results, the contour plots of the time-averaged local velocity distributions in the vertical plane located 0.1 m upstream of the Oppermann fine screen with the bar spacing of $b = 10$ mm and the screen angles of $\alpha = 30^\circ$ and $\alpha = 45^\circ$ are shown in Figure 12. Compared to the experimental measurements (Figure 9), although there are some deviations in the velocity distributions in the vertical direction, the CFD model captured the spatial velocity gradient towards the main flow direction well. It was observed that the regions of the highest and the lowest velocity magnitude values in the CFD model with the porous media approach are in good agreement with the physical model for both tested screen angles. The overall distribution patterns of the velocity magnitudes, particularly in the x-direction, were consistent with the experimental measurements.

3.3. Guidance Wall Effect

For downstream fish migration facilities, the distributions of streamlines are also important because fish align with the streamlines during their migration to benefit from an energy-optimized movement with the flow, which is consistent with the flow field when the guidance wall is implemented. Figure 13 shows the streamlines in the horizontal x-y plane for the CFD model setup with and without a guidance wall, where the Oppermann screen, having a bar spacing of $b = 10$ mm, is located at an angle of $\alpha = 45^\circ$. Here, the streamlines are colored with respect to the velocity magnitudes. It can be seen that, with the guidance wall, the streamlines at the wake region of the Oppermann screen are almost

parallel to each other, creating a symmetrical downstream flow field (Figure 13a). The guidance wall has a positive effect on the distribution of the streamlines by aligning the rotating streamlines perpendicular to the bars. When a guidance wall is implemented (Figure 13a), the skewed approaching flow on the horizontal plane is shown to be in a direction that is perpendicular to the screen in the downstream region without causing any flow separation. Figure 13a highlights that the streamlines leave the screen perpendicular to the screen plane. Furthermore, the flow-straightening effect of the bar profile leads to a homogeneous and symmetrical flow field downstream of the fine screen. The guidance wall also aligns the streamlines behind the screen, which has a positive impact on hydropower utilization. However, in the absence of the guidance wall (Figure 13b), a large recirculation zone of around 0.5 m wide and 2.5 m long was observed at the downstream region of the Oppermann screen. Also, without a guidance wall, it can be observed that the streamlines converge at the left side of the screen, indicating a rapidly accelerating flow region.

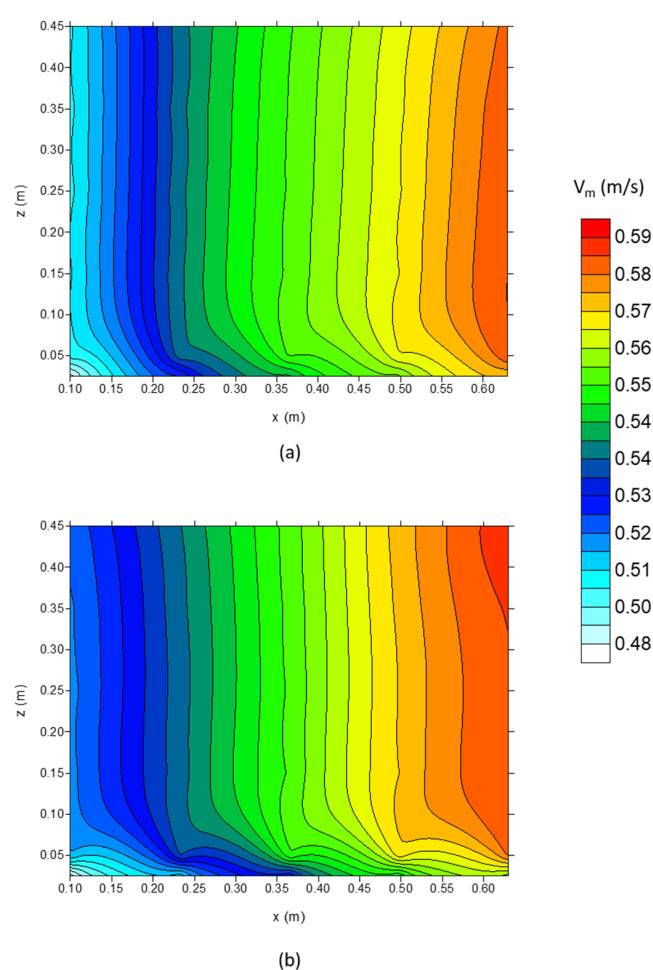


Figure 12. Time-averaged V_m contours in the x-z vertical plane located 0.1 m upstream of the Oppermann screen having a clear bar spacing of $b = 10$ mm with guidance wall: CFD data modeled by porous media approach in FLOW-3D. (a) $\alpha = 30^\circ$, and (b) $\alpha = 45^\circ$.

Figure 14 compares the effect of the guidance wall on the vorticity fields on the x-y plane for the 45° -angled Oppermann fine screen having the bar spacing of $b = 10$ mm. As can be seen from the figure, the vorticity around the z-axis is almost zero within the upstream flow field, creating a non-rotating approach flow for both cases. When a guidance wall was implemented at the upstream region of the screen, the vortex structures were dampened, leading to a downstream flow field with almost zero vorticity throughout the entire cross-section (Figure 14a). On the other hand, when there is no guidance wall

(Figure 14b), a large rotating flow covering more than half of the channel cross-section is observed. It is noticeable that the counterclockwise rotation almost disappeared behind the screen when the guidance wall was implemented (Figure 14a). The implementation of a guidance wall also reveals this pattern in the reduced TKE levels.

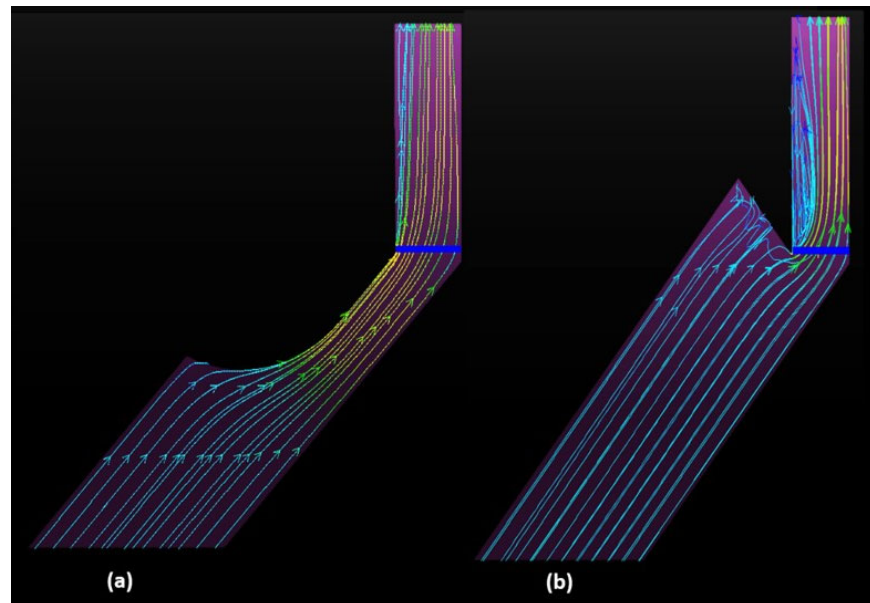


Figure 13. Colored streamlines in the horizontal x-y plane where the Oppermann screen is shown in dark blue (a) with a guidance wall, and (b) without a guidance wall. For both CFD model cases: $\alpha = 45^\circ$, mesh size = 0.02 m, and $b = 10$ mm. The velocity values increase from blue to green to yellow streamlines.

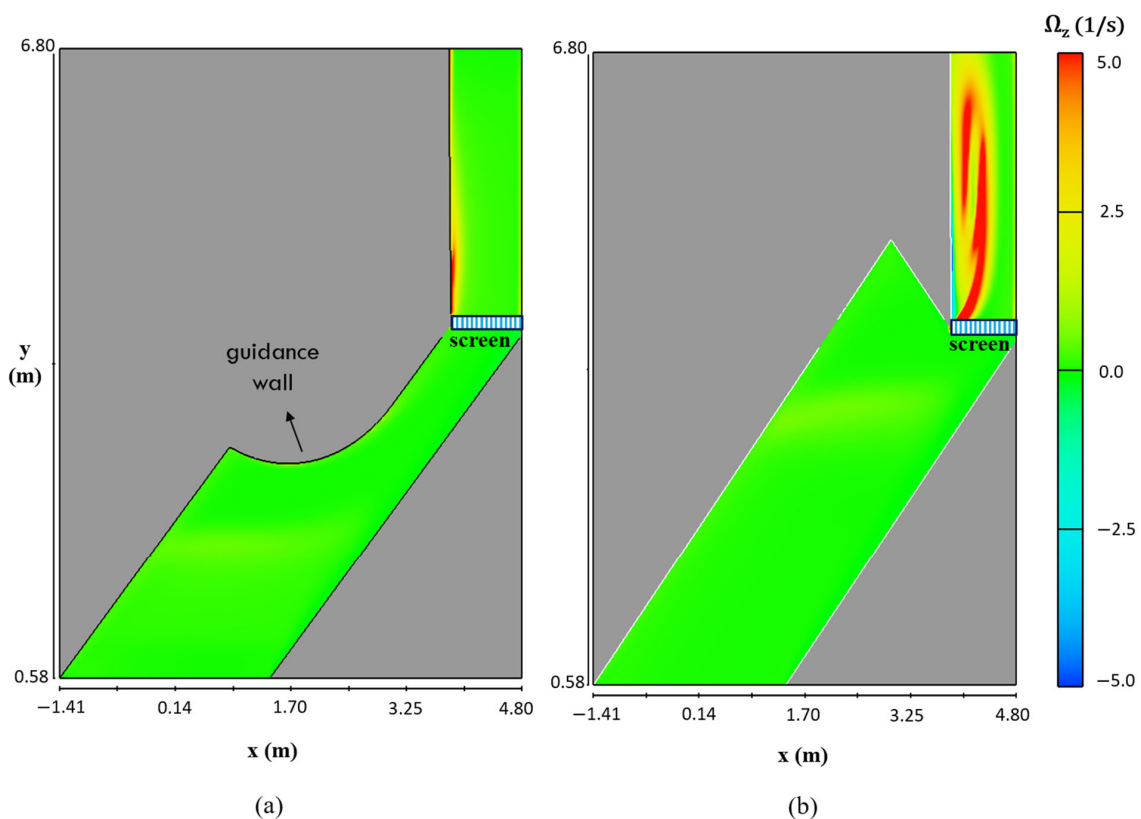


Figure 14. Instantaneous z-vorticity field on the horizontal x-y plane: (a) with a guidance wall, (b) without a guidance wall. For both CFD model cases: $\alpha = 45^\circ$, mesh size = 0.02 m, and $b = 10$ mm.

4. Discussion

The up- and downstream flow fields as well as the TKE distributions were experimentally and numerically investigated for the angled Oppermann fine screen. The local velocity magnitude and turbulent kinetic energy values of the CFD model were found to be in close agreement with the experimental data, yielding mean absolute percentage errors less than 10% (Table 3). This acceptable error limit of ~10% is also consistent with the numerical studies of [6,12].

Raynal et al. [7] and Chatellier et al. [31] reported that a large recirculation zone was formed behind the angled trash racks for $\alpha = 45^\circ$. Also, Albayrak et al. [32] experimentally observed the formation of such large recirculation zones downstream of the angled bar racks. In another experimental study, Beck et al. [10] also reported a smaller recirculation zone at the downstream region of the angled curved bar racks. Apart from those experimental studies, Raynal et al. [6] and Leuch et al. [12] numerically investigated the angled trash racks with different bar profiles under different turbulence models. The analyses of the flow fields also revealed relatively large recirculation zones downstream of the angled racks. The numerical results of Åkerstedt et al. [33] showed a large recirculation zone generated downstream of an angled rack for $\alpha = 40^\circ$. Differing from all the above-mentioned studies, almost no recirculation zone was observed in this present study at the downstream region of the angled Oppermann screen (Figure 14a). This result might be attributed to the combined effect of the presence of a guidance wall, which effectively deflects the inflow towards the screen and delays the flow separation, the streamlined bar profile of the Oppermann screen, and the thin bar length of 83 mm (see Figure 1b), leading to a flow-straightening effect at the downstream flow field. Tsikata et al. [13] observed a maximum TKE value of $0.3 \text{ m}^2/\text{s}^2$ behind the angled screen. However, in our experiments with a guidance wall where there is a smooth transition from the approach channel to the screen region, the maximum downstream TKE value was found to be $1.3 \times 10^{-5} \text{ m}^2/\text{s}^2$ (Figure 10b). David et al. [4] reported that the angled trash racks having vertical bars cause an asymmetric downstream flow field. However, in this present study, the downstream flow conditions were shown to be highly dependent on the presence of a guidance wall. It can be seen in Figure 13a that the usage of a guidance wall generated an almost symmetrical flow throughout the entire cross-section. On the other hand, without a guidance wall, the asymmetrical downstream flow field and recirculation zone were observed (Figure 14b).

Our experimental findings indicate that fish can approach the rounded smooth bar profile region with velocities in the order of 0.5 m/s without getting injured, and they cannot pass through the Oppermann screen due to the narrow bar spacing of 10 mm. Also, the fish should still be able to turn against the current and find the alternative descent route quickly and without unnecessary expenditure of energy. The fish can effectively be guided to a possible bypass channel at the end of the screen with continuous tangential velocity along the screen. The experimental measurements show that there is a range of 0.04–0.338 m/s/m tangential velocity gradient over the entire cross-section of the screen for $\alpha = 30^\circ$ (Figure 9a), which may effectively guide the fish to the possible bypass channel at the downstream end of the water intake. In our case, the screen positioned with an angle of $\alpha = 45^\circ$ has higher tangential velocities in the range of 0.04–0.856 m/s/m (Figure 9b). The spatial velocity gradient (SVG) is an important parameter related to the convective acceleration or deceleration, which can trigger the avoidance or acceptance reaction of fish [34,35]. Enders et al. [36] reported a threshold value of $\text{SVG} \leq 1.0\text{--}1.2 \text{ m/s/m}$ for Atlantic and Chinook salmon (*Oncorhynchus tshawytscha*) smolts, below which fish did not show an avoidance reaction. Accordingly, the observed SVG values are less than the species-specific threshold value of 1.0 m/s/m. Moreover, the water temperature was maintained approximately at 10.5 °C during the experiments, which may be regarded

as representative of typical natural river conditions for downstream migrating juvenile salmonids. As reported by Bellgraph et al. [37], juvenile salmonids were experimentally shown to respond dynamically to minor fluctuations in the water temperature, with impacts on their movement patterns. Thus, maintaining stable temperature conditions during the tests ensures relevance to ecological behavior during downstream migration and reinforces the biological significance of the enhanced hydraulic conditions due to the guidance wall.

The physical mechanisms behind the hydraulic improvements and hydrodynamic roles associated with the guidance wall should also be highlighted within the scope of this present study. The curved guidance wall positioned upstream of the Oppermann screen plays a crucial role in modifying the inflow conditions and thereby improving hydraulic performance. The implementation of a curved wall provides the necessary alignment of the streamlines and redirects the approach flow before the Oppermann screen. In the absence of the curved wall, the upcoming flow may approach the screen at varying angles, leading to an asymmetric flow field and regions of localized recirculation. Thus, the curved geometry also delays the flow separation, resulting in more uniform streamline curvature, especially in the near-wall region. Moreover, the guidance wall also acts as a passive deflector, causing the guided flow to adhere to the solid surface, which eventually generates a deflected wall jet that stabilizes the boundary layer and minimizes the flow separation. This is similar to and consistent with the flow control devices and strategies used to improve flow attachment, reduce turbulence, and suppress secondary vortices [38–40]. Consequently, the guidance wall functions as a structural and geometry-based modification that passively manipulates the streamline patterns, boundary layers, and hence the upstream flow field to optimize the hydraulic performance. It should also be noted that, rather than modeling the actual bar profile, the Oppermann fine screen was treated as a porous zone in the CFD model to reduce the computational cost. However, the individual bars of the screen might influence the flow field in the vicinity of the screen, and the velocity distributions may differ when the bar profile is fully represented in the computational domain. This fact is thought to be the limitation of this study. Future studies should consider full bar profile representation in the computational domain and integration of the guidance wall into the site-specific situation.

5. Conclusions

The effect of the guidance wall has been investigated in a hybrid model to evaluate the hydraulic performances of angled Oppermann fine screens. A porous media approach and the Large Eddy Simulation (LES) were used to model the fine screen, and simulations were run for two different angles of the screen. Our results indicate that the implementation of a curved guidance wall may lead to improvements in fish guidance efficiency. The main findings of this study can be summarized as follows:

- With the guidance wall configuration, the distributions of streamlines and tangential velocities in front of the screen are shown to be more suitable for effective downstream fish guidance.
- The implementation of a curved guidance wall considerably reduced the formation of recirculation zones, leading to a symmetrical and homogeneous downstream flow field, improving flow conditions behind the screen.
- The proposed guidance wall and numerical modeling technique can be used in the refurbishment of existing intake screens at run-of-river hydropower plants, considering the site-specific, poor approach flow conditions.

The results can be applicable to prototype conditions since the bar Reynolds number will be in the same order of magnitude (i.e., the bar thickness will be the same, and the approach velocity should be less than 0.5 m/s). Also, bar rack configurations are the same

in the laboratory and in the prototype. Hence, the findings of the study can be useful for guidelines and regulations on fish protection at water intakes.

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