Assessment of head loss coefficients for water turbine intake trash-racks by numerical modeling

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HIGHLIGHTS

• Numerical modeling can be used to evaluate head losses for different trash-racks.
• Rectangular bar cross section mostly generates greatest head-losses.
• Change in bar cross sections can lead to considerable head-loss reduction.
• Optimization can be conducted to provide innovative trash-rack design.

ABSTRACT

In this work, numerical simulations of fluid flow around trash-rack for different bar cross sections are conducted to investigate cross section influence on head losses. Comparison with experimental data is conducted to validate the usage of numerical simulations which enable investigation of great number of trash-rack configurations. In previous experimental studies researchers mostly focused on trash-rack parameters (bar spacing, bar length, inclinations etc.) where bar cross section was mainly rectangular or streamlined shape. Therefore, 2D simulations for different cross sections are carried out for a range of trash-rack configurations in order to provide better insight how it affects energy losses. It is shown that head loss reduction due to change in cross section is greatly dependent on trash-rack configuration, therefore optimization of simplified real water turbine trash-rack is also conducted to produce the cross section that generates smallest head losses for given configuration.

Introduction

Trash-racks are installed in the intake system of hydroelectric power plants to prevent entrance of large debris which can damage turbine parts and cause serious problems in power plant operation. Installation of trash-rack causes disturbance in fluid flow with
inevitable energy losses which should be minimized. To reduce these losses and to keep the design simple for manufacturing and cleaning, trash-racks, oriented perpendicular to fluid flow, usually consist of many rectangular bars directed parallel to fluid flow. Another main purpose of trash-rack is to prevent fish species from entering the intake system [1]. With growing ecological concern [2], influence of trash-rack design on fish migration and fish mortality is increasingly taken into consideration [3,4]. Trash-rack is not a suitable obstacle for some fish species, especially for juvenile fish, which could be entrapped in turbine parts. Furthermore, in case of large approaching velocities, some fish species are incapable of avoiding trash-rack which can cause fatal injuries when colliding with bars. Increased awareness of these problems prompted a change in the design of hydroelectric power plants intake system. Inclined trash-racks in combination with angled bars are increasingly considered to provide better fish guidance toward fishways which are being installed to provide safe passage way for upstream or downstream migration considering fish behaviour [5,6]. Due to site specifications and fish species characteristics, great number of case studies regarding fishway efficiency are being conducted [7,8]. Multidisciplinary approach is also considered to improve current knowledge and practice of fishways [9].

To determine energy losses, a number of experimental investigations on trash-racks were conducted. Idel'chik [10] proposed empirical relationship regarding different bar cross sections, bar spacing and rack angles that estimates head loss for bars parallel to fluid flow. The United States Army Corps of Engineers [11] proposed head loss coefficient values based on summarized open channel tests with racks perpendicular to fluid flow for different bar designs and spacings. Tsikata et al. [12] experimentally investigated influence of bar spacing and bar length on head losses where it was shown that bar length reduction and increase in bar spacing reduce head losses. Furthermore, fluid flow around angled bar racks and influence of different cross sections (rectangular, bar with rounded leading edge and streamlined bar) were analysed in [13]. Significant reduction in head losses was observed when rectangular cross section edges were rounded or cross section was replaced with streamlined shape. Bar inclination to the approaching flow was investigated only for rectangular cross section while for other cross sections bars remained parallel to the fluid flow, where head loss value increased when bar inclination increased. Asymmetric flow behind inclined bars was also reported. Vortex shedding behind trash-rack bars induce vibrations which can interfere with natural frequency of the trash-rack and cause damage to bars. Therefore, structural aspect of trash-rack exploitation must be also taken into consideration [14]. Since design of trash-rack varies greatly and trash-racks are used in wide range of operating conditions, number of experimental and numerical studies investigated this problem [15–17]. Clark et al. [18] analysed head losses for six different cross sections (rectangular, rounded, commercially available bar and variants of NACA airfoil) for bars parallel to fluid flow and reported increase in head loss when channel inclination before trash-rack i.e. approach flow inclination increases. In Raynal et al. [19] different trash-rack inclinations with regards to channel flume bottom were investigated where new head loss equation considering blockage ratio, bar shape and rack inclination was proposed. Additionally [20], rectangular and hydrodynamic bar shapes were analyzed for various trash-rack to flume wall angles (while bars were kept perpendicular to the trash-rack). In more recent research, Albayrak et al. [21] investigated a wide range of angled trash-rack configurations for rectangular and rounded bars and other geometry parameters and proposed new head loss equation which included relation between bar spacing, rack and bar angles (primary parameters) and bar length, relative rack submergence and bar shape (secondary parameters). Szabo-Meszaros et al. [4] examined six different configurations of streamlined and rectangular bar profiles for different bar-setups; in four configurations trash-rack was inclined against the channel wall for various bar angles while two configurations had horizontally oriented bars. Horizontal trash-racks and vertical with streamlined bars were suggested as the best candidates for fish-friendly trash-racks. Zayed et al. investigated influence of screen angle from the trapezoidal open channel wall for angled trash-racks [22] and V-shaped trash-rack [23], both with circular bars where new head loss equations were proposed. In Beck et al. [24] a new innovative curved bar design was investigated. Böttcher et al. [25] compared trash-rack with circular bars and new fish protection and guidance system – flexible fish fence where common head loss equations were adapted for new proposed design.

Few numerical studies investigated flow around trash-racks. Raynal et al. [26] validated two-dimensional fluid flow analysis for bars angled at 45° using their previous experimental results, under-estimating head loss experimental results. In work by Paul et al. [27], 3D analysis of fluid flow around 3 and 7 submerged bar-racks was conducted, where numerical analysis overestimated experimental head loss coefficient. Åkerstedt et al. [28] conducted an investigation for rectangular and biconvex bars for different inclinations of fully submerged trash-rack, where simplification was made with periodic boundary conditions and two-dimensional fluid flow domain.

It can be noticed that most experiments from previous studies considered two bar cross section shapes at most, whereas the proposition of different cross sections could provide more favourable hydraulic conditions, especially considering configurations with angled trash-racks and angled bars. The main problem with innovative designs (e.g. V shape trash-rack in [23] and curved bar shapes in [24]) is that researchers usually define trash-rack geometry a priori, hence optimal solution could be overlooked. The uniqueness of power plant intake geometry must also be taken into consideration since channel geometry after trash-rack is usually not regular as in experimental setups. Geometry changes in the intake channel, inclination or narrowing, are important since they affect head losses, especially if analyzing bars with greater angle of inclination. In those cases, recirculating zones are longer with the possibility of geometry interference in the wake zone which may also lead to turbine efficiency reduction. Numerical studies provide a solution for a number of presented problems. In the numerical approach, the whole turbine geometry can be modelled in full scale, the influence of all geometry parameters can be evaluated and fluid flow can be investigated in more detail [29]. Furthermore, an optimization procedure can be conducted to provide optimal trash-rack configuration for specific turbine that is investigated.

In this work, numerical simulations are conducted for four different cross sections with different configurations of trash-rack and bar inclinations. To validate the numerical results, trash-rack configurations are chosen according to experiments conducted by Albayrak et al. [21]. Following the numerical model validation, cross section influence on head loss reduction for different configurations is further investigated. Finally, optimization of simplified trash-rack geometry for a 50 years old hydroelectric power plant HE Senj (Senj, Croatia) is conducted in order to provide optimal cross-section regarding the head losses.

Materials and methods

Geometry definition

Numerical simulations are conducted for trash-rack inserted in 1 m wide, 12 m long and 0.1 m deep flume with constant rectang-
lar cross section (Fig. 1). Flume and bar dimensions are chosen to validate numerical simulation with full scale trash-rack model investigated in Albayrak et al. [21], for the trash-rack inclination of 45° and rectangular bars with inclinations of 45°, 67.5° and 90°. Bars are considered completely submerged. Flow velocity ranges from 0.13 to 0.43 m/s, in accordance to experiment. Trash-rack bars are 0.1 m long with the greatest cross section width of 0.01 m and with bar spacing 0.05 m. Reynolds bar number $Rs = Us/v$ where $U$ is approaching velocity and $s$ bar width ranges from 1295 to 4285. After validation, further investigation is conducted for trash-rack inclinations of ($\alpha$ angle) 15°, 30° and 45° with bar inclinations of ($\beta$ angle) 45°, 67.5° and 90° for different cross sections. Influence of bar spacing on head losses for different bar and trash-rack inclinations is investigated in Albayrak et al. [21] so this parameter is kept constant for all conducted simulations and only influence of cross section change was considered.

Four different cross section geometries are considered – rectangular, rhombus, rounded front edge with inclined back in the lower half and rounded front edge with inclination starting right after rounded edge (Fig. 1). Hereinafter considered cross sections will be referred to as cross section A, B, C and D, respectively. In cross sections B, C and D, sharp edges are avoided due to production reasons. Consequently, 2 mm straight segments can be seen in cross section profiles.

Geometry and trash-rack placement in the channel can be seen in Fig. 1. The trash-rack origin for all geometries is set at 3 m downstream from the inlet. Cross sections considered for head loss measurements for numerical model validation are defined 3 m upstream (inlet) and 3 m downstream from the trash-rack origin. For all other configurations, head loss measurements were conducted on inlet and outlet cross sections.

Number of bars on trash-rack depends on $\alpha$ and $\beta$ angles, which leads to different blockage of fluid flow on flume sides for different configurations, e.g. for configuration $\beta = 90°$ and $\alpha = 45°$ bars can be spaced on trash-rack in a way there is no clearance on flume sides or with clearance on both flume sides if one bar is removed. Numerical investigation of both configurations shows around 15% difference in head loss coefficient. Considering this information is usually not mentioned when the experiment is described to avoid influence of side clearance, outer bars were extended to completely block the fluid flow. A similar method can be seen in Raynal [26] where sides of the trash-rack domain were cut off.

For the configuration with greatest fluid flow blockage ($\alpha = 45°; \beta = 90°$), 3D multiphase, 3D single phase and 2D simulations are conducted. 3D multiphase fluid flow simulation best describes the open channel nature of the experiment but requires considerable computational resources, thus simplification is made to reduce computational time. A 3D geometry is created where domain height is set as an estimation of free surface level which was constant throughout the whole domain. This simplification allowed usage of a single phase fluid flow model which significantly reduced computational time. Since cross section along the vertical axis remained constant, 2D simulations are also considered. All three simulations provide similar results - both 3D models underestimate the head loss coefficient for around 14% while 2D single phase model underestimation is around 15%. Consequently, for all configurations, 2D simulation is chosen in order to reduce computational time.
Numerical model

Simulations are conducted in ANSYS-Fluent for an unstructured mesh with local refinement around trash-rack and channel walls. Considering that changes in trash-rack configuration greatly influence fluid flow field (e.g. width and length of recirculation zone) and keeping in mind that optimization should be conducted with automated meshing, i.e. cannot be further refined according to simulation results, meshing parameters are kept the same for all considered configurations. First layer height is defined to maintain $y^+ > 30$ and scalable wall functions are used. Global element edge size is defined to be within 0.016 m and 0.0001 m with prescribed value of 0.004 m. Maximum size of the element edge for bar edges is defined as 0.003 m and for channel wall 0.005 m. Mesh independence study is conducted for configuration $\alpha = 45^\circ$, $\beta = 90^\circ$ with numerical meshes sizing 230 000, 413 000, 723 000 and 920 000 elements (Table 1). Values of head loss coefficient became constant for numerical mesh consisting of 723 000 elements, which prompted the choice of the grid with around 800 000 elements (depending on trash-rack configuration) for all simulations. Detailed investigation of turbulent models for numerical simulations of fluid flow around trash-rack was conducted in previous study [30], where it was observed that $k-$e standard turbulence model generates greatest head loss values showing the best agreement with experimental results at the same time. In general, when greater recirculation zone is present behind trash-rack, $k-$e standard turbulence model shows stability in results, while other models tend to oscillate. Due to these observations, $k-$e standard turbulence model is chosen for all simulations in this study. Overview of boundary conditions can be seen in Table 2.

Numerical simulation is done by solving the steady-state incompressible isothermal Navier–Stokes (NS) equations which describe the fluid flow:

$$\nabla \cdot \textbf{u} = 0$$  \hspace{1cm} (1)

$$\left( \textbf{u} \cdot \nabla \right) \textbf{u} = -\frac{1}{\rho} \nabla p + \nu \nabla^2 \textbf{u} + \textbf{f}$$  \hspace{1cm} (2)

where $\textbf{u}$ is the velocity vector, $p$ represents the pressure, $\rho$ is the fluid density, $\nu$ is the fluid kinematic viscosity and $\textbf{f}$ represents the external forces acting upon the fluid (e.g. gravity). Eq. (1) represents the conservation of mass while Eq. (2) defines the conservation of momentum of fluid flow. Reynolds averaging is additionally applied to the NS equations for turbulence modeling.

Chosen fluid is water with properties for temperature of 20°C. Pressure-velocity coupling SIMPLE algorithm is used and discretization scheme for the convection terms of governing equations is second order upwind. Convergence criteria is assumed if all residuals drop below $10^{-5}$ and additionally no change of head loss coefficient is observed with further iterations.

Results and discussion

Validation of simulation

Validation is conducted for rectangular bars with $\alpha$ angle $45^\circ$ and $\beta$ angles $45^\circ$, $67.5^\circ$ and $90^\circ$ for four different velocities, 0.13, 0.23, 0.33 and 0.43 m/s. Head loss coefficient is calculated as (to match the head loss coefficient in Albayrak [21]):

$$k = \frac{\Delta p}{U_0^2}$$  \hspace{1cm} (3)

In Eq. (3) $U_0$ is inlet velocity and $\Delta p$ is the pressure difference between upstream and downstream cross sections. Pressure difference represents an approximation of water level difference (Ah) present in experiments. This assumption is validated with aforementioned comparison with multiphase simulation results where small variation was present for both considered models.

A greater recirculation zone for trash-racks with greater bar inclination is noticed in the simulations (Fig. 2). Highly turbulent flow behind trash-rack was also observed in experiments [21]. For $\beta$ angle $45^\circ$ recirculation zone accounts for around one third of channel cross section, which is in agreement with Raynal [26]. For $\beta$ angle $67.5^\circ$ recirculation zone is present in around half of the channel, while for $\beta$ angle $90^\circ$ recirculation zone increases even more and with that suppresses fluid flow and increases head losses (pressure drop). For the same inlet velocities, with the change in trash-rack configuration, greater recirculation zone leads to higher magnitudes of velocities due to the reduced cross sectional area available for fluid flow. This produces a greater variance in downstream velocity profiles.

Measurement locations must be placed at an adequate distance where fluid flow is undisturbed in order to obtain precise data. That is often a problem, due to the space limitation of the experiment. Mean velocities at observed cross-sections, that are needed to determine head loss coefficient in the experiment, are calculated with water height measurements at a given number of points or combined with flow rate measurements - depending on available instruments. For example, in Albayrak [21] three points in the measurement cross section were considered. This is especially a problem if measurements are made in a recirculation zone where great velocity variation in the cross section is present. Therefore, the average of measurements with a smaller number of points and measurements with a greater number of points can produce significantly different results.

With the increase in $\beta$ angle, a greater deviation in results is observed, where simulation underestimates head loss coefficient with maximum deviation of 15%. Geometry simplifications must be taken into consideration regarding this deviation since the trash-rack structure is simplified, e.g. spacers are omitted from the geometry. Design of trash-rack sides is not defined in the

| Table 1 | Head loss coefficient relative error for different mesh sizes with different global element edge size. |
|------------------------|---------------------------------------------|
| number of elements     | 230 000 | 413 000 | 723 000 | 920 000 |
| element size           | $\varepsilon (k_e)$                           |
| 0.007 m                | 2.02%   | 0.07%   | 0%      | 0%      |

| Table 2 | Boundary conditions used for fluid flow simulation. |
|------------------------|---------------------------------------------|
| boundary               | inlet | outlet | channel walls | bar walls | top | bottom |
| type                   | velocity inlet | pressure outlet | wall | wall | symmetry | symmetry |
| value                  | 0.13–0.43 m/s | atmospheric pressure | no slip | no slip | —     | —     |
experiment description and is thus chosen arbitrarily for simulation, as mentioned previously in Section b. Albayrak [21] reported a head loss difference of 15% for some configurations due to scale effects. Free surface measurement can also generate errors, with a deviation of around 5% as reported in Raynal [20]. Also, when considering experiments which have low water heights, the bottom has a greater influence on head loss coefficient due to friction, while in real turbine intakes, these water heights are always greater. Water depth to channel width ratio in the experiment is always considerably smaller than 1, while in real intakes it is greater, making the influence of bottom surface negligible, thus resulting in an overestimation of head loss coefficient measurements in experimental studies. To avoid uncertainty regarding aforementioned issues, head loss coefficient is normalized as:

$$k_n = \frac{k_e}{k_{max}} \quad (4)$$

In Eq. (4) $k_e$ represents experimental head loss coefficients for given trash-rack configuration and $k_{max}$ represents maximum head loss coefficient observed in all considered experiments. Normalization of head loss coefficients will be used in the course of this study.

Validation of numerical results can be seen in Fig. 3. Normalized values of head loss coefficient obtained from simulations show good agreement with normalized values of experiment results. Greatest discrepancy is 4% for $\beta=90^\circ$ where for other configurations it is under 2%. Numerical analysis shows very small variation in head loss coefficient due to change in inlet velocity, contrary to the experiment which is subjected to measurement errors. This behaviour is expected, because head loss coefficient equation is chosen to be invariant of the inlet velocity.

Numerical shape investigation

Numerical investigations are conducted for 4 different cross sections with 9 different combinations of $\alpha$ and $\beta$ angles for inlet velocity 0.43 m/s. Measurement locations for verification are set at inlet and 6 m downstream from inlet. At these measurement locations for some configurations, large recirculation zone is observed and for configurations with $\alpha = 15^\circ$ if trash-rack starts 3 m downstream, measurement location at 6 m is not behind the trash-rack (in experiment trash-rack location varied due to space limitation where in this study it is set 3 m downstream from the inlet). Therefore, numerical shape investigation measurements are conducted at inlet and outlet cross sections. Trash-rack position for different $\alpha$ angles and influence on fluid flow field can be seen in Fig. 4.

Investigations conducted for different cross sections with different ranges of bar and trash-rack inclinations showed that for most configurations, cross section A provides the greatest head loss coefficient (since the A area is the largest when compared to other bar types) with the exception of configuration $\alpha = 45^\circ, \beta = 90^\circ$ and $\alpha = 30^\circ, \beta = 90^\circ$ where cross section B generates the greatest head loss coefficient. This could be explained with cross section A creating better fluid flow guidance (smaller turbulence zones) when fluid flow is perpendicular to bar orientation. The smallest head loss coefficient was observed mostly for cross section C, with the exception of configuration $\alpha = 45^\circ, \beta = 45^\circ$ where cross section B generated the smallest head loss. For greater $\alpha$ and $\beta$ angles, selection of cross section is more relevant, whereas for smaller angles, the value of head loss coefficient is similar for all cross sections. These results are presented in Fig. 5 where values of normalized head loss coefficient (normalized with value of greatest head loss,

| Fluid | Water |
|-------|-------|
| Temperature [°C] | 20 |
| Density [kg/m³] | 998.2 |
| Viscosity [kg/m-s] | 0.001 |

Fig. 2. Velocity magnitude (in m/s) for trash-rack configuration $\alpha = 45^\circ$ and for $\beta$ angles 45°, 67.5° and 90° (top to bottom) and pathlines coloured by velocity magnitude for trash-rack configuration $\alpha = 45^\circ$ and $\beta = 90^\circ$. |
i.e. cross section B for configuration $\alpha = 45^\circ, \beta = 90^\circ$), for cross sections that generate greatest and smallest head loss, are presented for all configurations.

It can be observed that trash-rack configuration (inclinations of trash-rack and bars) has the greatest influence on head loss. Simulation results show that for greatest bar inclination ($\beta = 90^\circ$) reduction of trash-rack inclination ($\alpha$) leads to a reduction of head loss greater than 40%. For greatest considered trash-rack inclination ($\alpha = 45^\circ$), reduction of bar inclination leads up to head loss reduction of around 80%. For smaller inclinations (for example $\beta = 45^\circ$ where $\alpha$ is changed or $\alpha = 15^\circ$ where $\beta$ is changed) lesser reductions in head loss can be observed, which is expected due
to the fact that values of head loss coefficient are generally smaller for these configurations. Configurations that provide better fish avoidance are increasingly being installed, but since they cause more losses, influence of cross section becomes more prominent.

In Fig. 6 normalized head loss values are presented for all considered configurations and for all cross sections. Reduction of head losses due to change in cross section accounts mostly for around 10%. Results for configuration $a = 15^\circ, b = 45^\circ$ are not aligned with the trend of other configurations which could be explained due to small head loss coefficients for configurations with $b = 45^\circ$ (seen in Fig. 5). For these configurations, a reduction of $a$ angle or change in cross section geometry generates a very small reduction of head loss. For some configurations, different cross sections provide very similar results, where if the configuration is changed, the head loss coefficient difference becomes greater i.e. cross section selection is more prominent. For example, for trash-rack configuration $a = 45^\circ, b = 90^\circ$ both cross section A and D generate similar head loss coefficient, where if $a$ angle is decreased to $15^\circ$ cross section A generates the greatest head loss coefficient. This shows that generalization of the optimal cross section cannot be made, hence it must be optimized for every trash-rack configuration, especially when new designs such as V-shaped trash-rack [23] start being implemented.

Cross section optimization

Optimization of bar cross section is conducted for turbine intake system of 50 years old hydroelectric power plant HE Senj (Senj, Croatia) (Fig. 7a). Since the power plant is in the need of reconstruction, a new trash-rack design is being considered also.

In the time of power plant construction there was no concern for fish species so trash-rack consisted of rectangular bars installed parallel and trash-rack perpendicular to fluid flow.

The optimization process is conducted for simplified geometry; trash-rack remained perpendicular and bars parallel to fluid flow. Distance between bars and their length is kept the same and only cross sections are changed. Validation of numerical simulation was conducted for rectangular cross section. Results showed good agreement with available empirical results [10] and with in situ measurements with error around 4%. Three different cross sections, which are chosen due to easy machining, are considered: cross section with front and back inclinations, cross section with curvature at front and back and cross section with front curvature and back inclination. For the first cross section, four optimization variables defining width and length of inclination are considered. The second cross section has three optimization variables which define the radius of front curvature and inclination width and length in the back. For the last cross section, two optimization variables which define the front and back curvature are considered (Fig. 7b). There are no limitations imposed on optimization variables due to construction reasons, thus considered shapes present theoretical solution. Overview of optimization variables for each optimization case is presented in Table 4.

Optimization is done using Particle Swarm Optimization (PSO) which is a population based search algorithm that is inspired by swarm intelligence, such as birds flock or fish school movements [31]. The starting point of PSO is to initially randomly generate, within certain bounds, a set of solutions (swarm) to a problem and iteratively evaluate the quality (fitness) of every candidate solution (particle). After every evaluation, the position of every particle is adjusted towards the local or global optimal position.
Movement of every particle through the problem space is influenced both by its own best solution and swarm’s best solution. This process continues until values converge into a satisfactory and/or steady set of solutions. Factors such as particle cognitive rate, social rate, and problem space movement inertia greatly influence the optimal position convergence. The PSO algorithm implemented in the python optimization package inspyred is used with swarm size of 10 particles, inertia factor 0.75, cognitive rate 1 and social rate 1.

Goal functions for all considered optimization cases are defined as:

\[
\text{min} f_a(x_a) = \Delta p(x_a) \\
\text{min} f_b(x_b) = \Delta p(x_b) \\
\text{min} f_c(x_c) = \Delta p(x_c)
\]  \hspace{1cm} (5)

In Eq. (5) \( \Delta p \) represents result of numerical simulation conducted for optimization variables \( x_a, x_b \) or \( x_c \), which denotes vectors of optimization variables dependent on the case:

\[
x_a = [a_1, a_2, a_3, a_4] \\
x_b = [b_1, b_2, b_3] \\
x_c = [c_1, c_2]
\]

Fig. 6. Normalized head loss coefficients for (a) \( \beta = 45^\circ \), (b) \( \beta = 67.5^\circ \) and (c) \( \beta = 90^\circ \).
Details of optimization variables in Eq. (6) can be seen in Table 4. Optimization is conducted several times to verify results. Results converged to identical solutions for every cross section separately. Particle swarm optimization is used where for all three cross sections optimization variables converged in their upper limits. For case (a) optimization generated a cross section with maximum front and back inclinations which generated rhombus shaped cross section. For case (b) front edge has maximum curvature with maximum inclination in the back, which generated streamlined shaped bar and for case (c) optimization generated cross section with front and back edges with maximum curvature. These results are expected since all considered profiles converged in cross section with minimal cross section area; they generated the smallest head loss which validated this optimization process. Initial and optimized cross sections with indicated optimization parameters can be seen in Fig. 7b.

Fig. 7. (a) Intake structure of HE Senj with detail of current bar design. (b) Cross sections considered for optimization cases with optimization parameters (left) and their optimized shape (right).

Table 4
List of optimization parameters for optimization cases with parameter constraints (L denotes bar length and s bar width).

| Optimization variables | Constraints [lower limit, upper limit] |
|------------------------|---------------------------------------|
| Case a                 |                                       |
| front inclination length | $a_1$ [0, L/2]                      |
| front inclination width | $a_2$ [0, s/2]                      |
| back inclination length | $a_3$ [0, L/2]                      |
| back inclination width | $a_4$ [0, s/2]                      |
| Case b                 |                                       |
| front curvature radius | $b_1$ [0, s/2]                      |
| back inclination length | $b_2$ [0, L - s/2]                  |
| back inclination width | $b_3$ [0, s/2]                      |
| Case c                 |                                       |
| front curvature radius | $c_1$ [0, s/2]                      |
| back curvature radius  | $c_2$ [0, s/2]                      |

Sharp edges in cross sections must be carefully considered due to production, exploitation and safety reasons. During the process of trash rack cleaning considerable forces can be induced on bars, especially when removing debris stuck between bars, which if trash rack cleaning system is in direct contact with the trash-rack, forces induced during interaction can cause structural damage. Also, depending on the hydroelectric power plant location, different intakes are subjected to different type of debris. Considered HE Senj mainly deals with smaller debris (weed or branches) so rhombus shaped bars that have thinner front edge can be considered for
installation. However, if greater debris (logs) is frequently present at intake it can cause damage to construction if that type of cross section is chosen. Also, depending on configuration, sharp edges can cause fish injuries when interacting with trash-rack. This problem is also present with rectangular cross section, where for some bar inclinations (e.g. 90°) rhombus shape provides a safer solution. Considering these problems are problem specific, edge thickness constraints must be defined in accordance.

For different intake geometries, shape optimization of the bar cross section can be conducted to provide the optimal solution. Hence, cross sections that are usually not used, can be derived as an optimal result for specific intake (e.g. innovative design considered in [24]). In this study, only parameters defining cross section are included as optimization parameters, however, other geometry parameters such as bar spacing, bar length, bar inclination etc. can also be included. Cross section optimization for HE Senj was done to reduce the losses without changing the bar spacing (which was proved to be valid during exploitation). As it was mentioned in [19,20] head loss reduction due to cross section change enables reduction in bar spacing, but that must be carefully evaluated due to its influence on other criteria such as structural aspect, debris accumulation, vibrations and velocity filed that can influence the fish movement. With new innovative designs, such as V-shaped trash-rack [23] optimization value becomes more prominent because it can reduce the time necessary for conducting experiments that vary different geometry parameters. Also, since vortex shedding that influences vibrations and can cause damages to trash-rack structure is known for standard trash-rack design, when considering new innovative designs this aspect must also be taken into consideration. More detailed numerical analysis (LES) of unsteady fluid behaviour should be conducted [16] with encompassing structural (FEM) numerical analysis [17].

Conclusion

In this study, the influence of trash-rack and bar geometry on head losses is examined. Validation of numerical results is conducted with experimental results from previous studies. A numerical investigation of four bar cross sections for nine different trash-rack configurations, where trash-rack and bar inclinations are varied, is performed. Additionally, optimization of trash-rack bar cross section is conducted using the PSO algorithm.

For a given experiment, where the channel cross section is constant along the vertical axis, similar results are obtained with 3D multiphase, 3D single phase and 2D simulations. Since difference in 2D and 3D results were around 1%, 2D simulations are conducted for all considered cases to save computational time. For greatest bar (90°) and trash-rack (45°) inclinations greatest variation in the result is observed with numerical simulation underestimating head loss coefficient by 15%. Rectangular cross section, which is mainly present in turbine intakes, causes the greatest head loss for almost all configurations which suggests there is an area for improvement in current designs. For greater bar and trash-rack inclinations greater turbulence zones can be observed which cause greater head loss coefficient. Also, in case of low-head turbines where the turbine is positioned rather close to the trash-rack, the non-uniformity of flow may cause a reduction of turbine efficiency. For these configurations influence of cross section is greater than for configurations with smaller inclinations. Optimization conducted for trash-rack perpendicular and bars parallel to fluid flow, generated geometry with minimal bar cross section area.

In future work, possibilities of optimization should be explored and validated with the experiment. Optimization can be conducted for real intake geometries where the influence of channel before and after trash-rack should also be also included. To decide on the optimal cross section, apart from head losses, other flow field parameters which influence the fish behaviour near trash-rack can be included in the optimization goal function to encompass both ecological and engineering approach. Construction and stability aspect must also be taken into consideration, where constraints or penalties for designs that induce vibrations that could lead to construction failure should be included. Currently this optimization procedure would include expensive goal function evaluation since it would include both LES simulation and structural (FEM) numerical analysis, but with growing computational power it would provide comprehensive study of trash-rack design.

Declaration of Competing Interest

The authors have declared no conflict of interest.

Compliance with Ethics Requirements

This article does not contain any studies with human or animal subjects.

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