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Flow and Turbulence Measurements in a Diagonal Brush Fish Pass: A Field Study

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Abstract: *This study aims to investigate flow and turbulence structure of a diagonal brush fish passage which has been constructed at the existing Small Hydropower Plant (SHP) on İyidere River on the East Black Sea Coast of Turkey. The flow and turbulence characteristics of diagonal brush fish pass were investigated in a 1.1 m wide rectangular flume with a bed slope of 10% for Reynolds and Froude numbers ranging between $3.45x10^4$-$2.4x10^5$ and 0.15-0.16, respectively. By taking into account dynamic upstream water levels (H=101.20 m to H=102.05 m) of fish pass structure throughout the year, the vertical velocity profiles of different flow regions have been obtained by using Nivus instrument, whereas the turbulence quantities were gathered by measuring the three-dimensional instantaneous velocity fields using Micro acoustic Doppler velocimeter. The flow data was grouped for four different relative submergence of bristles. Thus, the analysis is done based on a physical basis and focus on the most important hydraulic parameters of velocity field, turbulence, and flow depth for fish passage design. The main findings of this study can be summarized as follows: (i) a significant proportion of energy dissipation (>50%) takes place in the brush plates with the vibration and bending of bristles, (ii) turbulent kinetic energy seems to be considerably lower for a same dissipated power in brush fish pass than other conventional fish passes (vertical slot and nature type), (iii) the turbulence intensities in the lateral velocity component were an important contributor to turbulence, and (iv) when the bristles are submerged, the maximum turbulent kinetic energy value is tripled. The flow is quasi-uniform and in subcritical regime which provides different migration corridors with typical hydraulic conditions and, very important for the fish, these corridors continue through the complete fish pass. The results from this study would be useful to fish-pass designers.*

Keywords: *Brush fish pass, diagonal arrangement, turbulent kinetic energy, energy dissipation, flow-induced vibrations.*

1. Introduction

The brush-type fishways consist of a sloping channel into which brushes are fixed which provide reduced velocities for easing the upstream migration of fish. They are known to provide low velocities, a variety of structures inside the water body, and ample resting room for small and juvenile or weak fish. The brush elements do not totally block the flow in which hydraulic elements have permeability, and a quasi-uniform flow condition occurs so flow regime is subcritical (Kucukali and Hassinger 2015). In brush fish pass, the energy dissipation is rather effective because the large number of flow-induced vibrating bristles initiate strong energy dissipation. Rahn (2011) conducted experiments with grouped brush-blocks to investigate the distribution of the energy dissipation, and Rahn (2011) found that a significant proportion of energy conversion (>50%) takes place in the bristle plates. However, without the bristle field, the flow velocity would be excessively high and the flow regime will be supercritical. Although the flow pattern is three-dimensional (3D) in fish pass structures, most of the standards take into account only streamwise velocity as the relevant criterion and turbulence quantities are not considered (DWA, 2014; Environmental Agency, 2010). The energy dissipation rate per unit volume is taken into account as a relevant parameter for turbulence indicator (Table 1). Moreover, in the literature, there are several studies about the flow and turbulence characteristics of the conventional fish pass structures such as: vertical-slot, pool-weir, and natural-like. The common characteristic of those fish pass structures is that the hydraulic energy is mostly dissipated when the turbulent jets plunge into pools. Moreover, in the previous studies, the migrations of smaller and weaker fish are mostly neglected (Kucukali and Hassinger 2018). Accordingly, the proposed brush fish pass differs from the conventional fish passage types by providing a nearly optimal migration corridor under uniform and subcritical flow regime for smaller and weaker fish without any obstructions. Thus, favorable hydraulic conditions are created with the porous structure of the brush blocks (shown in Figure 1 below) and the oscillation of the bristles which dissipate the hydraulic energy. In the literature there is a lack of knowledge concerning the turbulence structure of diagonal brush fish pass. Accordingly, the flow patterns and turbulence characteristics of a brush type fish pass will be presented at prototype scale (~$Re=10^5$). This study focuses more on the turbulence and velocity pathways for fish passage.

Table 1. Maximum allowable energy dissipation per unit volume at different fish zones of rivers. Data source: DWA (2014).

Biological zone of river	Allowable maximum energy dissipation per unit volume
upper trout zone	250 W/m^3
lower trout zone	225 W/m^3
grayling zone	200 W/m^3
barbel zone	150 W/m^3
bream zone	125 W/m^3
estuarine zone	100 W/m^3

2. Field Study: Prototype Flow and Turbulence Measurements

This study aims to investigate the flow and turbulence structure of brush fish passage which has been established at the existing Incirli Small Hydropower Plant (SHP) on İyidere River on the East Black Sea Coast of Turkey. İyidere River Basin is rich in biodiversity and 13 fish species have been identified in the river. The İyidere River Basin has a drainage area of 835 km^2 and the annual average discharge of the river is 28 m^3/s. In the river basin, a cascade type hydropower system has been developed and the Incirli SHP is situated at the first downstream of the basin which is in the barbell zone. Incirli SHP is diversion type (tunnel length= 4 km) with a head of 27.5 m and installed capacity of 25 MW.

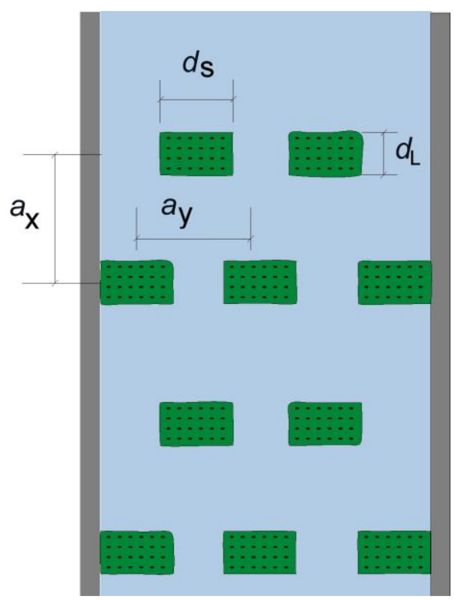


Figure 1. Drawing of a brush fish pass. Adopted from DWA (2014).

Figure 2 shows the general view of the brush fish pass which was constructed in 2017. By grouping brush blocks, pools can be formed between the groups of brush bars. The reason for the diagonal arrangement is that in this kind of street the flow is cross-exchanged constantly. The density of the brushes is selected according to the result of a designing process which is based on an equilibrium of forces. The density is a function of slope, discharge, water depth, bristle diameter, bristle length and grouping pattern of the brush modules. This design-tool is developed by

Hassinger (2002) and it is widely used to design brush-type fish ways. Rounded river stones (maximum 0.16 m diameter) have been placed on the bed of the channel to create a reduced velocity and low turbulence microhabitat. This benefits species with low swimming performance. An acoustic Doppler velocimeter (Sontek 50-MHz ADV) was used to measure the three-dimensional instantaneous velocity fields. The employed ADV had three sensors and measured the flow velocity in a control volume of 0.05 m in front of its sensors. The turbulence quantities were collected at 55 Hz frequency during a sampling time of 30 seconds. The primary tests showed that 30 s of sampling was enough and yielded stationary results for all measuring points. ADV measures flow velocities from about 1mm/s to 2.5 m/s with an accuracy of $\pm 1\%$. The velocity measurements were taken at each grid point. The lateral and vertical distribution of velocity measurement points for the given cross-section are shown in Figure 3. In the figure, circles show the velocity measurement points taken by the acoustic doppler. Moreover, additional vertical velocity profiles were obtained by using an acoustic correlation principle in a device of type Nivus PCM Pro, which was installed on the channel bed behind the brush block.

Figure 2. General view of the diagonal brush fish pass from downstream view at Incirli Small Hydropower Plant. The channel has a bed slope of 10% and width of 1.1 m.

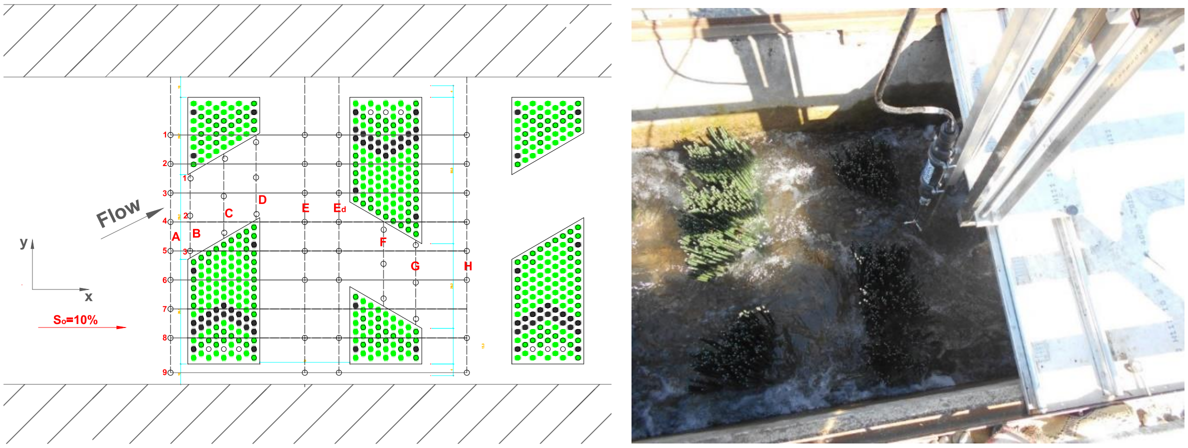


Figure 3. Top view of the brush fishway and the velocity measurement grid.

From those point velocity measurements, instantaneous local velocity components of u, v, and w in streamwise, lateral, and vertical directions, respectively, were obtained. Then, the resultant horizontal local velocity V can be calculated by using Eq. (1)

$$V = \sqrt{u^2 + v^2} \tag{1}$$

From the time-series of the velocity measurements, the root-mean-square of the turbulent fluctuation velocities $\sqrt{\overline{u'^2}}, \sqrt{\overline{v'^2}}, \sqrt{\overline{w'^2}}$ in the longitudinal, lateral, and vertical directions, respectively, were calculated at each measurement point. Then, the turbulent intensities in three directions were computed from

$$TI_x = \frac{\sqrt{\overline{u'^2}}}{U} \tag{2a}$$

$$TI_y = \frac{\sqrt{\overline{v'^2}}}{U} \tag{2b}$$

$$TI_z = \frac{\sqrt{\overline{w'^2}}}{U} \tag{2c}$$

where U is the cross-sectional average flow velocity. Also, the turbulent kinetic energy per unit mass k is calculated using Eq. (3)

$$k = \frac{1}{2}(\overline{u'^2} + \overline{v'^2} + \overline{w'^2}) \tag{3}$$

The distribution of the turbulent kinetic energy in the flow field is important because the energy dissipation is resulted from the turbulence generation. Hence, *Prandtl-Kolmogorov* formula (Schlichting and Gersten 2000) related the local energy dissipation rate with the 1.5 power of the turbulence kinetic energy as follows:

$$\varepsilon = 0.168 \times \frac{k^{3/2}}{L} \tag{4}$$

where ε *(*m^2/s^3*)* is the energy dissipation rate per unit mass, L *(m)* is the macro-scale turbulent length scale, and k *(*m^2/s^2*) is* the turbulent kinetic energy per unit mass. Accordingly, in this study turbulence intensity components at three directions and turbulent kinetic energy (TKE) are selected as the relevant parameters for the turbulence analysis rather than the two-dimensional Reynolds shear stress. The reason for the selection TKE as the relevant turbulence quantity in the analysis is that in fish passage structures flow is mostly three-dimensional due to the sudden changes in hydraulic geometry (i.e. sudden expansions and contractions).

3. Results and Discussion

The flow is quasi-uniform in brush fish pass. Hydraulic conditions are repeating in each following basin (Kucukali and Hassinger, 2018). Accordingly, a representative basin is selected for the hydraulic measurements and the analysis. The flow conditions in the brush fish pass are summarized in Table 2 where Q is the discharge, d is the uniform flow depth (it is measured in the fish pass), h is the height of the bristles, R_h is the hydraulic radius (ratio of the cross-sectional area to the wetted perimeter), f is the Darcy-Weisbach friction factor (Eq. (5))

$$f = \frac{8 S_0 R_h g}{U^2} \tag{5}$$

in which g is the acceleration due to gravity and S_o is the channel bed slope. Therein, Reynolds Re and Froude number Fr are defined as:

$$\mathrm{Re} = \frac{q}{\nu} \tag{6a}$$

$$Fr = \frac{U}{\sqrt{gd}} \tag{6b}$$

Moreover, the energy dissipation per unit volume ΔP is calculated from:

$$\Delta P = \frac{\gamma Q S_o}{Bd} \tag{7}$$

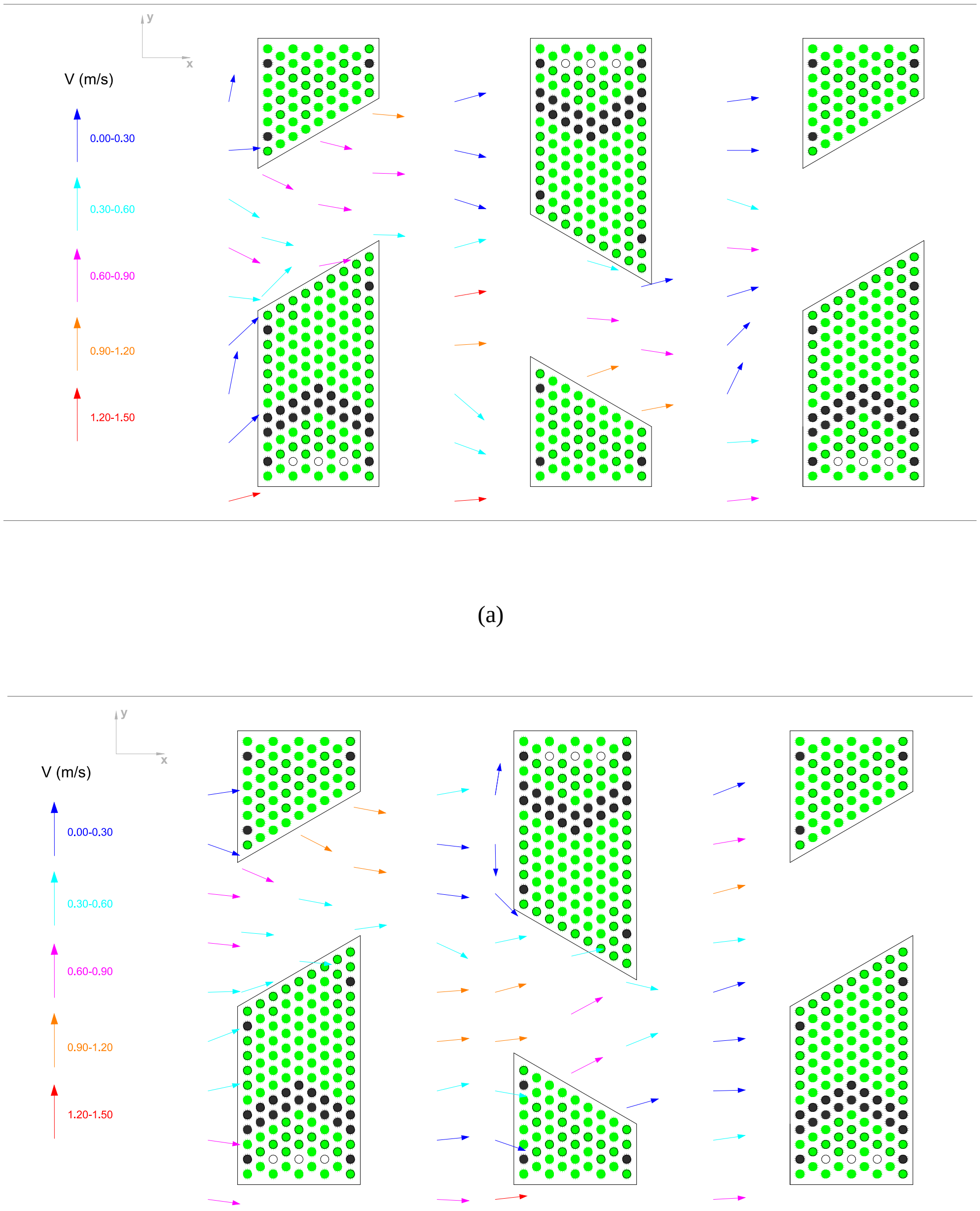
in which γ is the specific weight of the water and B is the channel width. The results are also presented in Table 2. In all hydraulic conditions, quasi-uniform and subcritical flow conditions were achieved. The flow depths and the depth-averaged velocities in Table 2 show values in the range of 0.15-0.40 m and 0.23-0.60 m/s, respectively, for the tested discharges. The energy dissipation per unit volume tends to increase with the discharge and it has values in the range of 220-590 W/m^3 (Table 2). In the brush zone the energy dissipation takes place in the oscillation and bending of bristles resulting from the flow separation at each bristle element. Also, the flow induced vibrations were clearly observed within the brushes during the field measurements.

Table 2. Flow conditions in brush fish pass for different inlet water levels.

H [m]	**d** [m]	**Q** [L/s]	**d/h**	**U** [m/s]	**f** [-]	**U*** [m/s]	**Re**	**Fr**	**ΔP (W/m^3)**
101.70	0.15	38	0.41	0.23	6.98	0.023	3.45E+04	0.16	226
101.85	0.2	66	0.54	0.30	5.12	0.029	6.00E+04	0.15	294
102	0.34	187	0.92	0.50	2.64	0.041	1.70E+05	0.15	491
102.05	0.40	264	1.08	0.60	2.02	0.045	2.40E+05	0.15	589

Note: H: fish pass inlet water level, d: flow depth in fish pass, Q: discharge, h: bristle height, U: Uniform flow velocity in fish pass, f: friction factor, U: shear velocity, Re: Reynolds number, Fr: Froude number, ΔP: energy dissipation per unit volume*

Figure 4 shows the velocity field in x-y plane. This horizontal velocity field in the vicinity of brush blocks is consistent with the Rahn (2011) laboratory measurements. In the brush fish pass, the friction process is dominated by the sum of the drag forces of all bristles. On one side flow with low velocities comes out the neighboring brush field and has to be accelerated. On the other side, quick flow disappears in the brushes and thus losses its kinetic energy. This mechanism prevents excessive acceleration and high velocities in the alley despite the fact that the gap runs through the brushes in a straight line. Small and big fish can favor this flow structure because fish can detect acceleration zones with their lateral lines and they response to this. Figure 5 highlights that in the brush fish pass the vertical velocity profile exhibits a quaisi-uniform distribution and vertical turbulent shear region is absent at the outside of the brush-blocks. The logarithmic velocity distribution is not valid behind the brush blocks related with the flow-bristle interaction. The maximum flow velocity, V_{max}, is measured near the channel bottom and there is a deceleration towards the free-surface. This velocity profile is in agreement with the Kucukali and Hassinger's (2015) physical model measurements. The result of higher flow velocities in lower layers of the water body in the brush zone is contrary to the results in different papers (Maier and Lehmann 2006; Kubrak et al., 2008) which point out that the flow velocity is constant over the water depth if the water level does not exceed the brush tips. The reason for this is that the new and clean brushes in the test present larger gaps for the flow in lower parts because the bristles are bundled closely to each other and spread to a bunch only in upper layers. So, the process of energy dissipation by a large number of small eddies is concentrated on upper portions and there are larger gaps between the bundles in lower parts. In real operation conditions, the gaps will be partly filled with organic debris and the velocity will be uniform over the water column.



(b)

Figure 4. Flow field in the horizontal plane for *d/h*=0.92 at (a) channel bottom and (b) central flow depth.

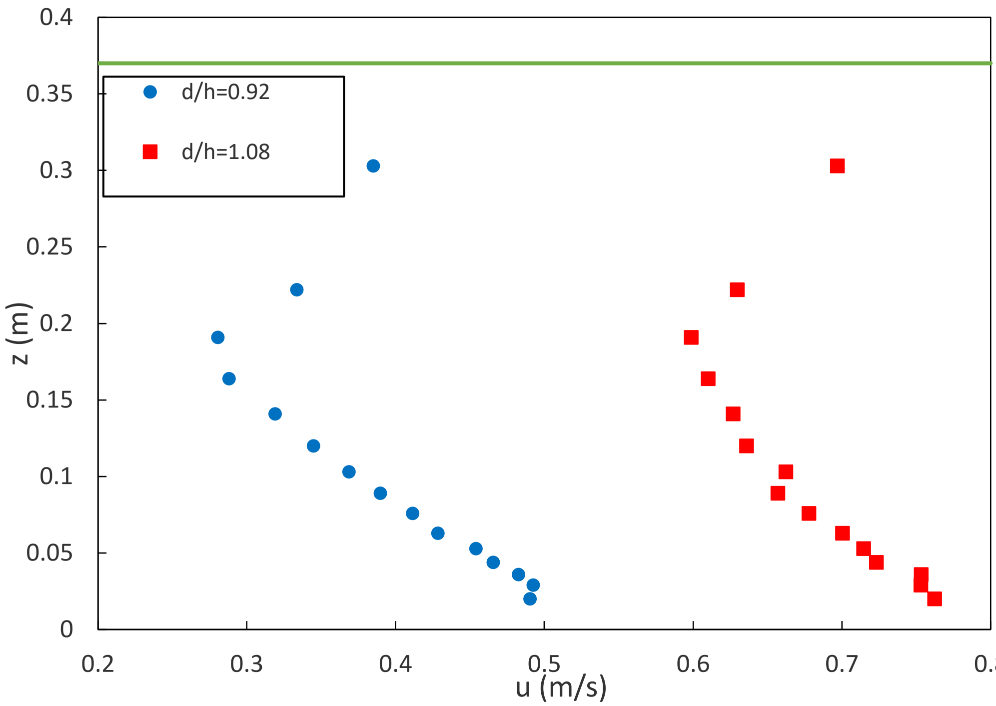
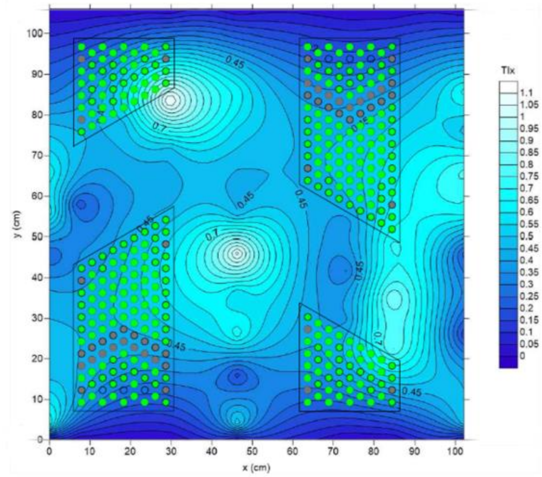
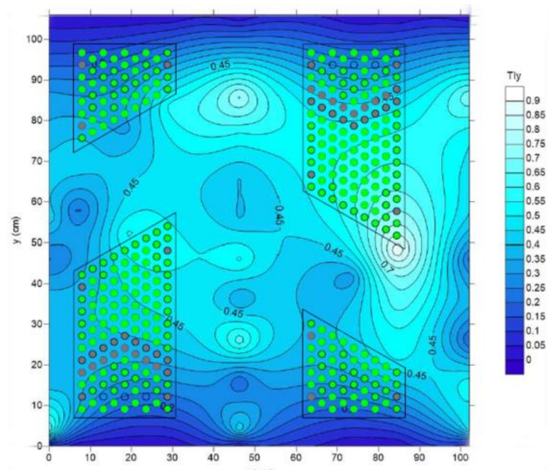


Figure 5. Vertical velocity profiles for different bristle relative submergences.

Turbulence intensities were also examined to better understand the components of the turbulence intensity in streamwise (TI_x), lateral (TI_y), and vertical (TI_z) directions. It is found that the turbulence is non-isotropic and the values of TI_x are higher compared to other directions. Also, the authors found that the turbulence intensities in the lateral velocity component were an important contributor to turbulence (Figure 6).



(a)



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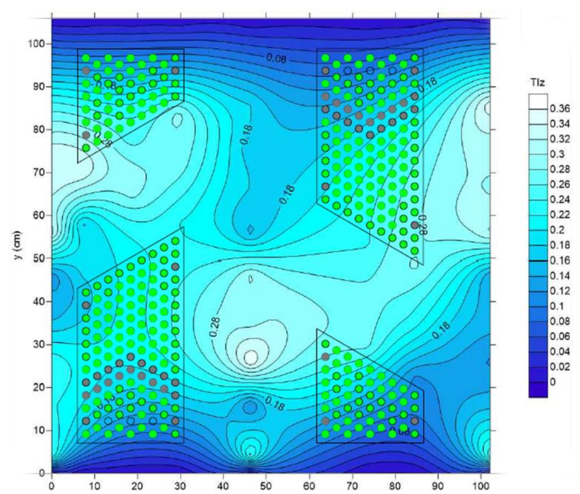


(c)

Figure 6. Turbulence intensity contours at streamwise, TI_x, lateral, TI_y lateral, and vertical TI_z directions at the central flow depth for *d/h*=0.92.

Figure 7 shows the turbulent kinetic energy distribution in the vicinity of brush blocks. The turbulent kinetic energy takes its maximum value of 0.21 m^2/s^2 in the outer region of the diagonal; *k* seems to be lower (for a same dissipated power) in brush fish than in pool-type fish passes. Compared to technical pool-type fish pass, average TKE in the basin reduced by 35% from 0.13 m^2/s^2 (Larinier, 2007) to 0.084 m^2/s^2 for the same dissipated power of ΔP=490 W/m^3. Also, maximum velocity is reduced by about 30%. This can be explained due to the fact that in the brush zone energy dissipation is related to the flow-induced vibrations of the bristles and the main energy dissipation takes place due to the oscillation and bending of bristles rather than by the viscosity of the water in an energy cascade process. In most of the international standards (DWA, 2014), it is recommended that ΔP should not exceed 200 W/m^3, but it is argued that it is not suitable to use energy dissipation density as a relevant parameter for brush fish passes because in this case, it is demonstrated that for brush fish pass the energy dissipation rate per unit volume cannot be an indicator of turbulence. Consequently, the low turbulent kinetic energy regions in the brush zone would be good for fish passage because fish normally avoid entering areas of high turbulence at sustained swimming levels and there is no need to build resting pools. It is evident in Figure 8 that when the brushes are submerged, flow resistance is dominated by the wave resistance and the maximum turbulent kinetic energy is tripled compared to unsubmerged conditions. This result is consistent with the Ballu et al. (2017) experimental findings.

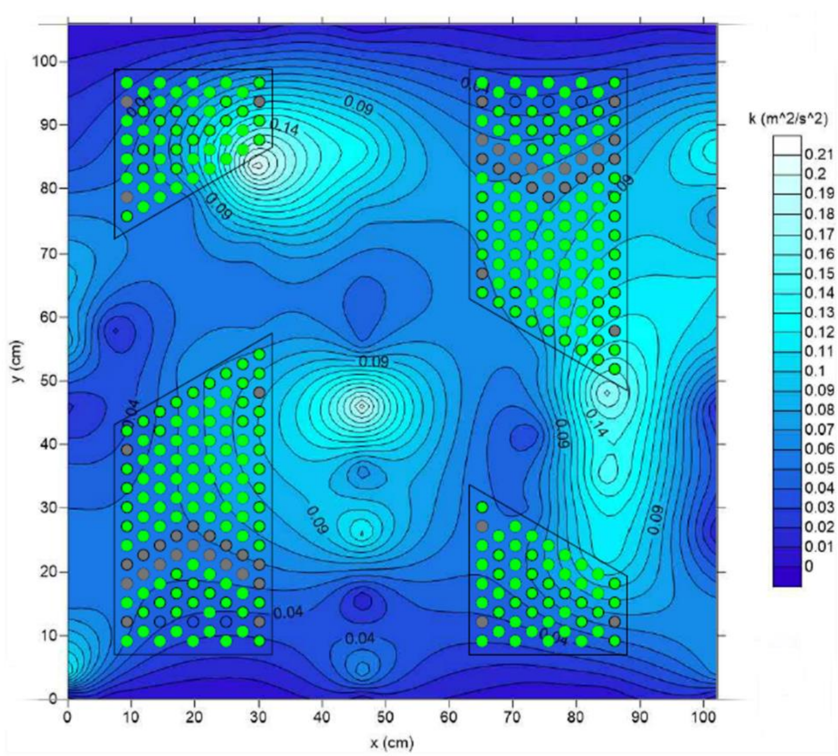
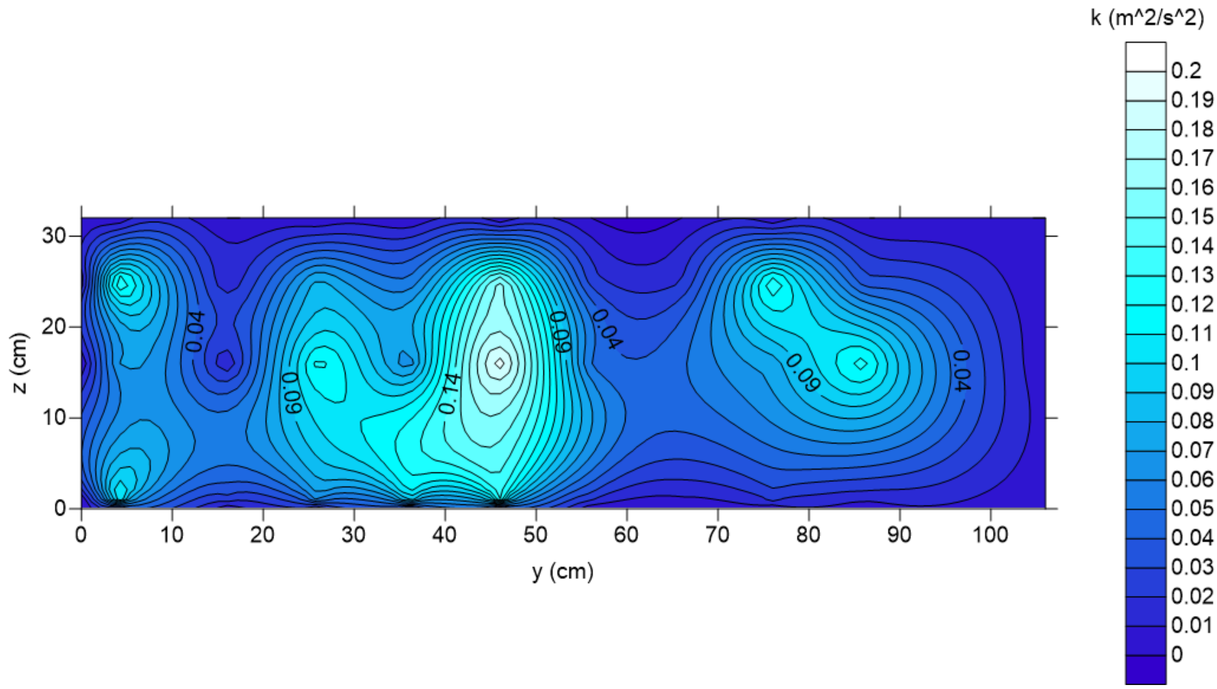
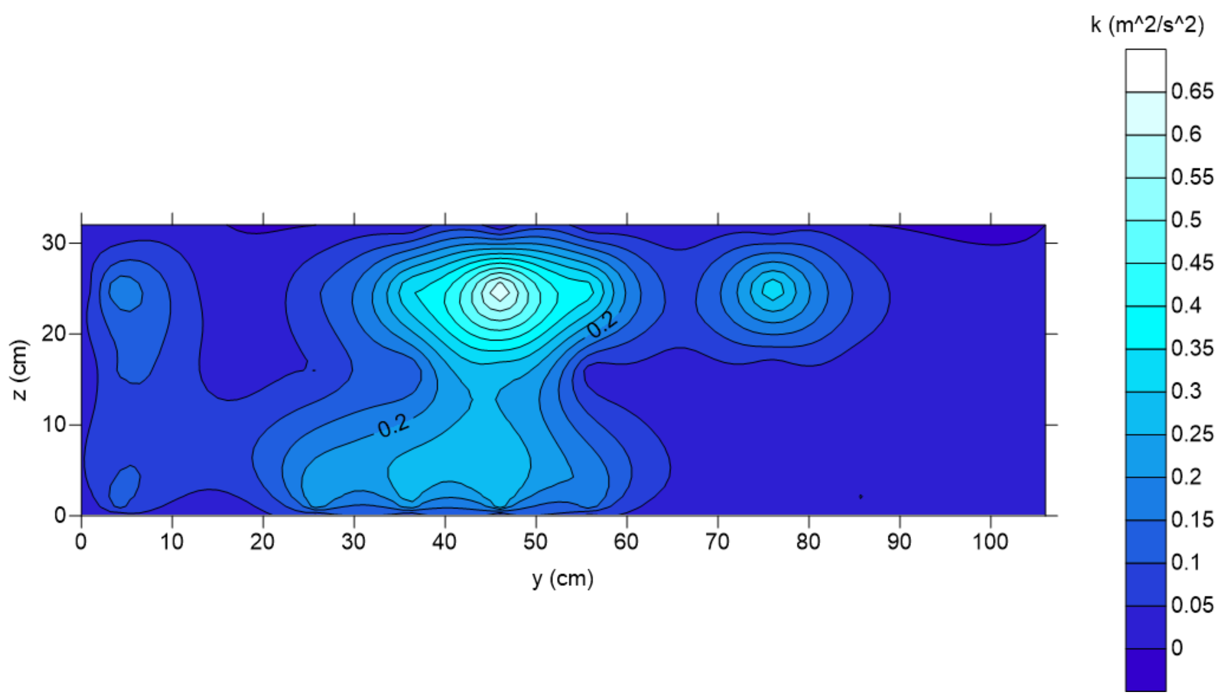


Figure 7. Turbulent kinetic energy, *k*, distribution in x-y plane at the central flow depth for *d/h*=0.92.



(a)



(b)

Figure 8. Turbulence kinetic intensity distribution in x-z plane for (a) unsubmerged and (b) submerged flow conditions.

A fish monitoring was carried out on site. The efficiency of the fish passage was assessed by the PIT telemetry method. The fish were caught by electro shocker at the downstream of the fish passage and they were anaesthetized with 2-phenoxy ethanol and then their body length was measured. A total of 200 fish were tagged with the passive integrated transponder (PIT) tags by a tag gun and the tagged fish were released downstream of the fish passage. All the PIT tags were HPT 12 model tags and they were 12 mm in length. Square antennas (100x80 cm in dimension) were installed at the entrance and exit of the fish passage. 54 of the tagged fish were detected in the fish pass entrance and 39 of them passed successfully through the brush fish way. The passage efficiency of five fish species was calculated as 72.2%. The body lengths of fish species that ascended the fish way varied between 9.5 and 21.5 cm. It is evident that brush fish way provides passage for small-bodied fish (L<15 cm) which is a problem for vertical-slot and natural type fish ways (Peter et al., 2017).

4. Conclusions

The field measurements reveal that a wide spectrum of different flow characteristics is provided in diagonal brush fish pass. There are several migration corridors with different hydraulic conditions, and they continue through the complete fish pass. The cleverness of the fish is used to seek the convenient corridors and to avoid zones not suitable for their migration preferences. In the flow velocity distribution in the cross sections between the rows of bristle block shows that the maximum velocities occur in the outer regions of diagonal. The results also illustrate that the velocity distribution in cross-section is not homogeneous. In each measured cross section, there are areas with velocities below 0.3 m/s which makes the ascent lane easier to swim through for less efficient fish. The maximum measured velocity 1.5 m/s is well below that set for fish passages maximum velocity of 2.0 m/s. Bristle element mounted vertically in the middle of the wall alters and deflects the flow in the basin that a flow deflection in the direction of the street entrance of the next multiple row of bars takes place and no backflow forms in the middle of the basin. Turbulent kinetic energy was found to be lower (for a same dissipated power) in brush fish than in pool-type fish passes. This situation can be described in terms of a dynamic instability of the bristle which gives rise to energy transfer from the main flow to the bristles. This energy transfer is dependent on the drag force and body (bristle) displacement. The results from this study would be useful to fish-pass designers.

5. Acknowledgements

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