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To cite this version:

Laurent Tarrade, Alain Texier, Laurent David, Michel Larinier. Topologies and measurements of turbulent flow in vertical slot fishways. Hydrobiologia, 2008, vol. 609, pp. 177-188. 10.1007/s10750-008-9416-y . hal-00967167

HAL Id: hal-00967167

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To link to this article : doi:10.1007/s10750-008-9416-y
URL : http://dx.doi.org/10.1051/kmae/2010022

To cite this version : Tarrade, Laurent and Texier, Alain and David, Laurent and Larinier, Michel Topologies and measurements of turbulent flow in vertical slot fishways. (2008) Hydrobiologia, vol. 609 (n° 1). pp. 177-188. ISSN 0018-8158

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DOI 10.1007/s10750-008-9416-y

Topologies and measurements of turbulent flow in vertical slot fishways

Laurent Tarrade · Alain Texier · Laurent David · Michel Larinier

Abstract Several vertical slot fishways have been built in France over the last 20 years. This type of pool fish pass is generally very effective in ensuring passage of the target species, particularly diadromous species. However, visual observations have shown that certain small species may be trapped in the large recirculation zones and seem to have difficulty in rapidly passing through very large pools. An experimental study was undertaken to characterize the turbulent flow for various configurations of vertical slot fishways and to determine how they might be modified to facilitate the passage of small species. The characteristics of mean flow and turbulence were studied by particle image velocimetry (PIV) for three slopes ($I = 5\%$, 10%, 15%), three flow discharges ($Q = 576$, 736, 864 L/s) and four pool widths ($B = 1.7$, 2, 2.3, 2.7 m). The results showed that the flow pattern always follows one of two topological models depending on the length/width ratio of the pool. A strong link was found between the calculated volumetric dissipated power and the mean kinetic energy of velocity fluctuations measured in the pools. In order to study the extent to which the dimensions of recirculation zones can be reduced, the effect of the insertion of vertical cylinders within the pools was displayed by laser tomography.

Keywords Fishway · Turbulent flow · Recirculation zone · Turbulent kinetic energy · Shear layer

Guest editors: R. L. Welcomme & G. Marmulla
Hydropower, Flood Control and Water Abstraction: Implications for Fish and Fisheries

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Notations

b	Width of the slot (m)
B	Width of the pool (m)
g	Gravitational acceleration (m s^{-2})
h	Water height (m)
I	Slope of the channel (%)
k	Turbulent kinetic energy (m^2 s^{-2})
L	Length of the pool (m)
ρ	Water density (kg m^{-3})
P_v	Volumetric dissipated power (W m^{-3})
Q	Flow discharge (L s^{-1})
u,v	Longitudinal and transverse instantaneous velocities (m s^{-1})
u',v'	Longitudinal and transverse RMS fluctuating velocities (m s^{-1})
U,V	Longitudinal and transverse mean velocities (m s^{-1})
$\|V\|$	Velocity module (m s^{-1})

X,Y,Z	Longitudinal, transverse and vertical distance (m s^{-1})
Δh	Water level difference between two adjacent pools (m)
Δt	Time between two PIV image acquisitions (μs)

Introduction and context of study

Several vertical slot fishways have been built in France over the last 20 years as part of the plan to restore or enhance migratory fish stocks. This type of pool fish pass is usually very effective in ensuring unhindered passage of the target species (generally salmon, sea trout, shad and marine lamprey) as well as several riverine species such as trout, grayling, barbel and bream. However, observations have shown that some small species appear to find it difficult to pass quickly through very large pools.

In 2000, the European Water Framework Directive confirmed the importance of ecological continuity in rivers, not only for migratory species but also for all fish species, including small species and more general river fauna.

This experimental study was undertaken to characterize turbulent flow for various configurations of vertical slot fishways and to determine how they might be modified in order to facilitate passage of small species. The characteristics of mean flow and turbulence were studied by PIV for several different slopes, flow discharges and pool widths. In order to study the extent to which the dimensions of recirculation zones can be reduced, the effect of the insertion of vertical cylinders within the pools was displayed by laser tomography.

Material and methods

The prototype of the vertical slot fishway considered in this study consisted of five pools with a length of $L = 3$ m. The width of the slot was $b = 0.3$ m. The width of each pool could be set to four values: $B = 2.7$, 2.3, 2 and 1.7 m (Fig. 1). The channel slope could take three values: $I = 5\%$, 10% and 15%. The crosswalls between pools were perfectly vertical for a channel slope of $I = 10\%$. Three flow discharges

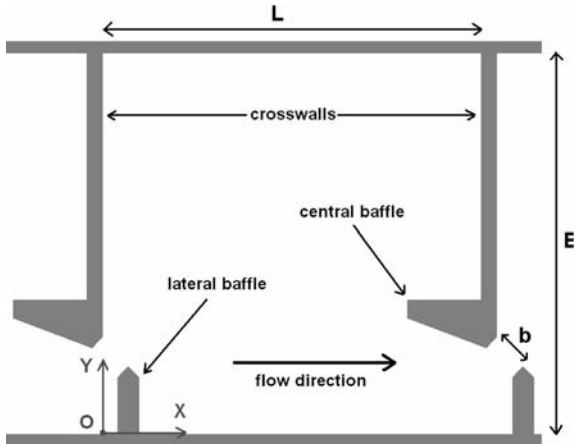

Fig. 1 Geometric characteristics of a pool

were studied: $Q = 576$, 736 and 864 L/s. The experimental work was undertaken in the Laboratoire d'Etudes Aérodynamiques (LEA) of the University of Poitiers (France) on a physical model, related to the prototype by Froudian similitude, on a geometrical scale of 1/4. The velocity and energy scales were 1/2 and the discharge scale was 1/32. The experimental measurements were taken in the third pool to ensure an established symmetrical flow. The X-axis was in the longitudinal direction and the Y-axis was in the transverse direction of the fishway. The XY plane was parallel to the channel bed.

Velocity measurements were taken by means of particle image velocimetry (PIV) in two planes parallel to the channel bed of the fishway ($Z = 0.08$ and 0.6 m) and in the vertical plane ($Y = 0.55$ m) passing through the slots (Table 1). The technique consisted of lighting a flow section seeded with particles 5 μm in diameter using a laser sheet (Fig. 2). Two FlowMaster CCD cameras were placed in parallel to display the whole pool. Each camera recorded two successive images of the flow at intervals of time Δt and the recordings were then divided into interrogation areas. The interrogation areas of these two successive images were then cross-correlated to determine the displacement of the particles and the image time interval Δt (between 3,500 and 4,900 μs) in order to calculate the velocity field. For each camera, 875 instantaneous velocity fields were obtained and averaged. The two mean velocity fields calculated were then combined to obtain the complete mean velocity field of the pool.

Flow displays were achieved by laser tomography in various planes of pools with and without cylinders. A laser sheet illuminated a section of the flow seeded with particles and successive images of the instantaneous flow were recorded with a camera. Cylinders (with the same dimension as slot width b) were inserted within the pools to disrupt the large swirling structures. In order to check the effectiveness of such a configuration on the shear layers and recirculation zones and to study the resulting flow modification, flow was displayed for two geometric configurations (slope $I = 10\%$ and width $B = 2.7$ and 2 m for a flow discharge $Q = 736$ L/s), which represent the two flow models.

Table 1 Summary of the experimental conditions

Slot width B (m)	Pool length L (m)	Channel slope I (%)	Measurement section X *or* Y (m)	Pool width B (m)	Flow discharge Q (L/s)
0.3	3	5	$X = 0.08$	2.7	576, 736
				2.3	576, 736, 864
				2	576, 736, 864
				1.7	576, 736, 864
			$X = 0.6$	2.7	576, 736
				2.3	576, 736, 864
				2	576, 736, 864
				1.7	576, 736, 864
			$Y = 0.55$	2.7	736
				2.3	736
				2	736
				1.7	736
		10	$X = 0.08$	2.7	576, 736, 864
				2.3	576, 736, 864
				2	576, 736, 864
				1.7	576, 736, 864
			$X = 0.6$	2.7	576, 736, 864
				2.3	576, 736, 864
				2	576, 736, 864
				1.7	576, 736, 864
			$Y = 0.55$	2.7	736
				2.3	736
				2	736
				1.7	736
		15	$X = 0.08$	2.7	576, 736, 864
				2.3	576, 736, 864
				2	576, 736, 864
				1.7	576, 736, 864
			$X = 0.6$	2.7	576, 736, 864
				2.3	576, 736, 864
				2	576, 736, 864
				1.7	576, 736, 864
			$Y = 0.55$	2.7	736
				2.3	736
				2	736
				1.7	736

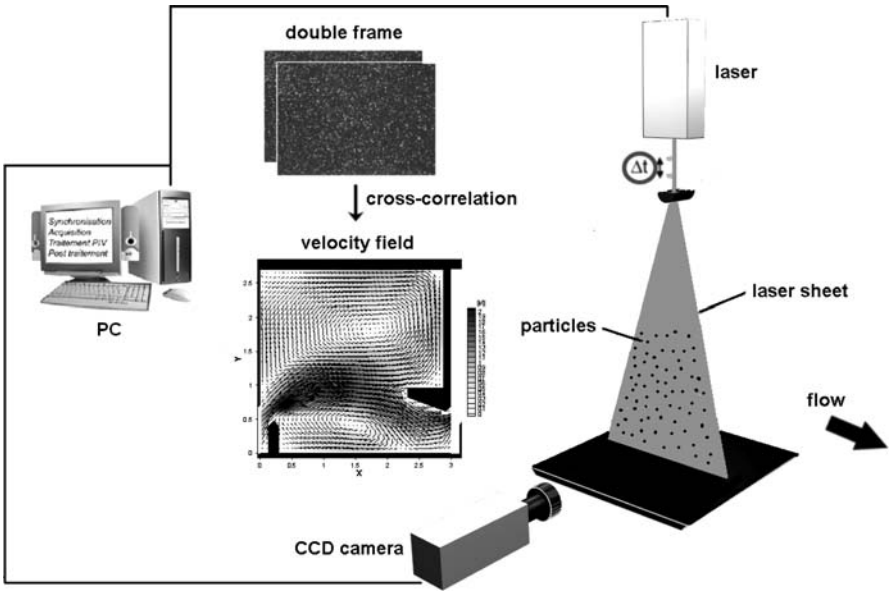

Fig. 2 Principle of the PIV measurements

Results

Figure 3 shows the streamlines, velocities and turbulent energies in the plane $Z = 0.6$ m for four configurations of vertical slot fishways (slope $I = 10\%$ and width $B = 2.7$, 2.3, 2 and 1.7 m) for a flow discharge $Q = 736$ L/s. For all configurations, the flow in a pool is composed of three significant areas (Rajaratnam et al., 1992): a principal jet caused by the slot that passes through the pool with decreasing velocity and two large recirculation zones generated on each side of this principal flow. Recirculation around an axis perpendicular to the channel bed allows for dissipation of the jet energy in each pool (Rajaratnam et al., 1986). Swirling cells of variable sizes, created by the principal recirculation currents, occur in all the corners of the pool, due to velocity differential between the recirculating flow and the velocities close to zero at the wall. Two different flow patterns occur according to the length/width ratio of the pool.

The first flow pattern is for the widest pool ($B = 2.7$ m). The principal flow leaving the slot enters the pool as a curved jet, which opens out before converging towards the following slot. The jet creates an important recirculation area, occupying roughly half of the pool surface on one side, between the crosswalls. On the other side of the principal flow, a smaller swirling zone, rotating in opposite direction to the preceding one, is generated between the small lateral deflectors. The highest velocities and turbulent energies are found in the jet at a maximum when leaving the slot and decreasing progressively as the flow enters the pool, while the lowest values are found in the recirculation areas (Fig. 3). The great difference between the velocities of the principal flow and those of the recirculation areas creates an intense shear layer at the jet boundaries near the slot.

A different flow pattern occurs for narrower pools with width $B = 2$ and 1.7 m: the jet has a very curved form and directly hits the opposite side wall. Two large counter-rotating swirls are then generated in the corner upstream of the pool and in the convex part of the jet, while a smaller one occurs close to the central baffle. The reduction in the width of the pool changes the dimensions and shapes of the swirling cells: the area of principal recirculation occurring for the first flow pattern is divided into two small swirls. The first is moved towards the upstream corner of the pool with a reduction in its surface area compared to the first pattern and the second is pushed back along the central deflector. On the other side of the flow, the vortex tends to occupy the open space left in the convex part of the curved jet. It contracts in the longitudinal direction and stretches in the transverse direction. Its size relative to the pool surface area increases (Fig. 3) for these narrower pools. The velocities and turbulent energies are high in the principal flow, at a maximum in the slot, while the values are low in the centre of the large swirls, creating zones of strong velocity gradients on the edges of the jet.

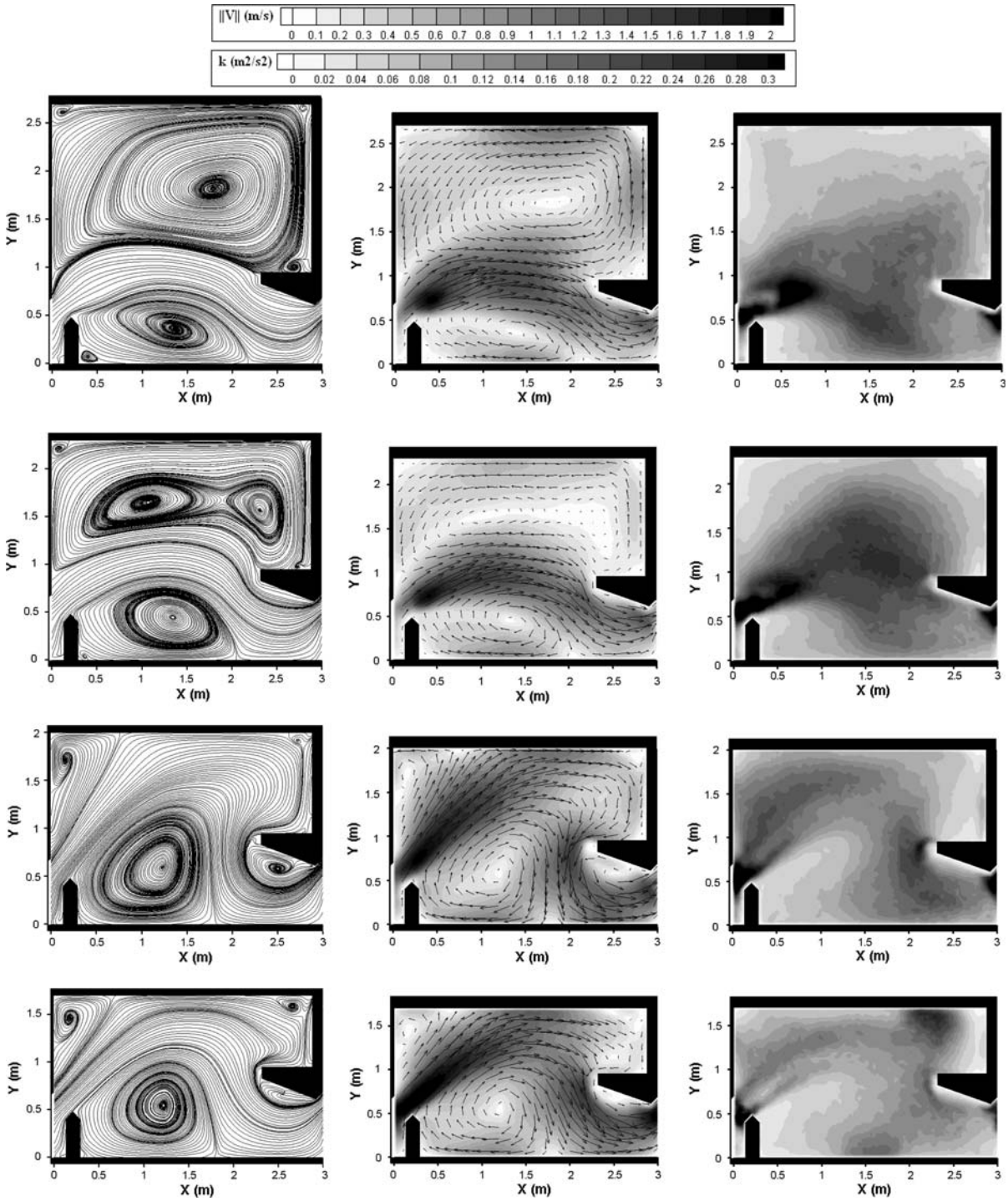

Fig. 3 Streamlines, velocity and turbulent energy in a vertical slot fishway: $I = 10\%$, $B = 2.7, 2.3, 2$ and 1.7 m, $Q = 736$ L/s at $Z = 0.6$ m

For an intermediate pool width ($B = 2.3$ m), the flow pattern varies according to the channel slope (Wu et al., 1999). For the lower slopes ($I = 5\%$ and 10%), the flow pattern looked like the one observed for a pool of width $B = 2.7$ m: two large recirculation areas, one on each side of a jet, including one

composed of two swirls separated by a singular point (Figs. 3 and 4). On the other hand, for the higher slope ($I = 15\%$), the flow pattern was similar to the topology obtained for widths $B = 2$ and 1.7 m, namely a curved jet, considerable recirculation occupying the convex part of the principal flow, a swirl in the upstream corner and another along the central deflector (Fig. 4).

Except for the intermediate pool width, which generated one of the two flow patterns according to the channel slope, a variation in slope did not generate different flow patterns for any other fishway widths tested: the two large counter-rotating cells were found on each side of the principal jet. Thus, when the slope increased, the jet widened slightly, whereas the sizes of the recirculation zones were reduced slightly. However, for all pool widths studied and the two principal flow models, the velocities and turbulent energies values varied greatly when the slope was changed (Figs. 3 and 4). These values increased in proportion to the slope and almost doubled for a slope of $I = 15\%$ as compared to a slope of $I = 5\%$ (Fig. 4). The velocity gradients at the jet boundaries, mainly close to the slots, also increased with the slope.

The flow pattern is independent of the height of the measurement section (Peña Mosquera et al., 2004) within the pool (Figs. 3 and 5). The recirculation shapes and the location of their centres did not vary much, irrespective of the height, while velocities and turbulent energies remained identical on the whole in the pool, from the channel bed to the free surface. Except in the slot zone, the vertical component of the velocity was less significant than the longitudinal and transverse velocities (Fig. 6) and the flow structure can thus generally be considered to be two dimensional in the pool (Puertas et al., 2004).

The discharge parameter had very little effect on the flow in vertical slot fishways. The flow pattern as well as velocities and turbulent energies remained similar for the three discharges. The principal consequence of a flow increase was a rise in the water height, controlled by the slots, without velocity variation.

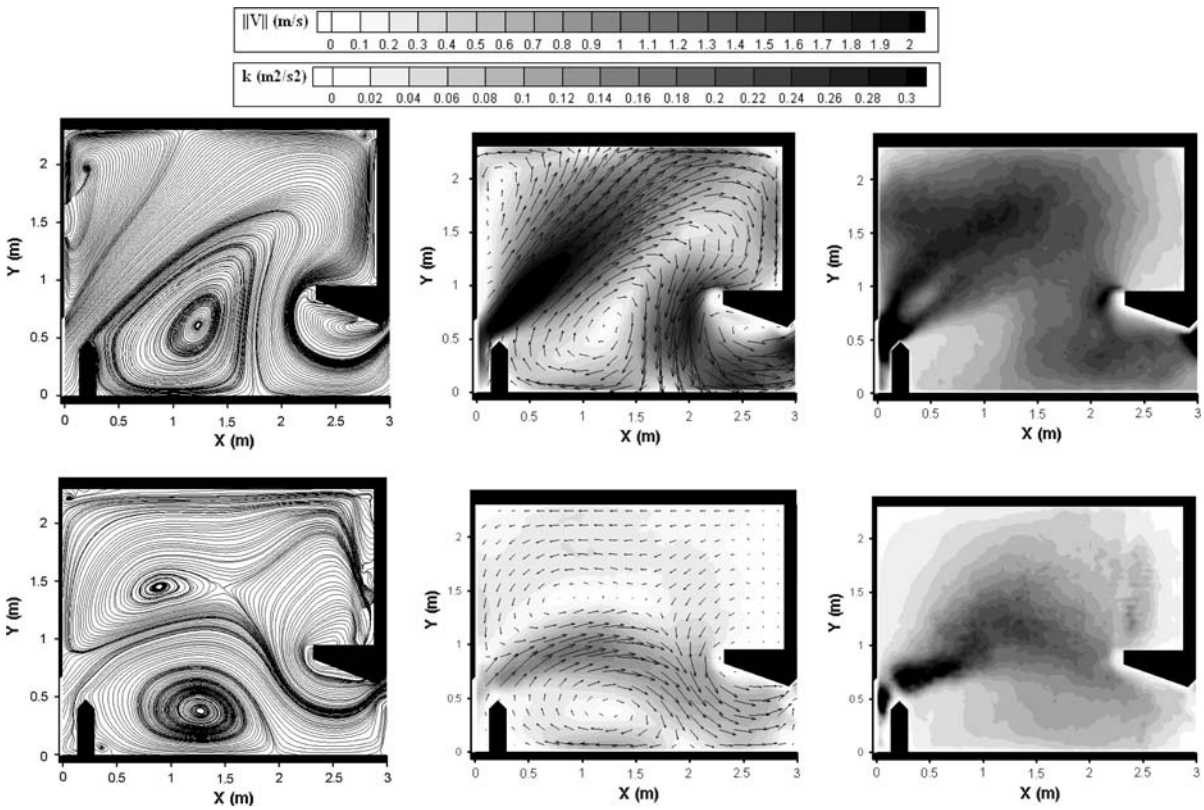

Fig. 4 Streamlines and velocity in a vertical slot fishway: $I = 5\%$ and 15%, $B = 2.3$ m, $Q = 736$ L/s at $Z = 0.6$ m

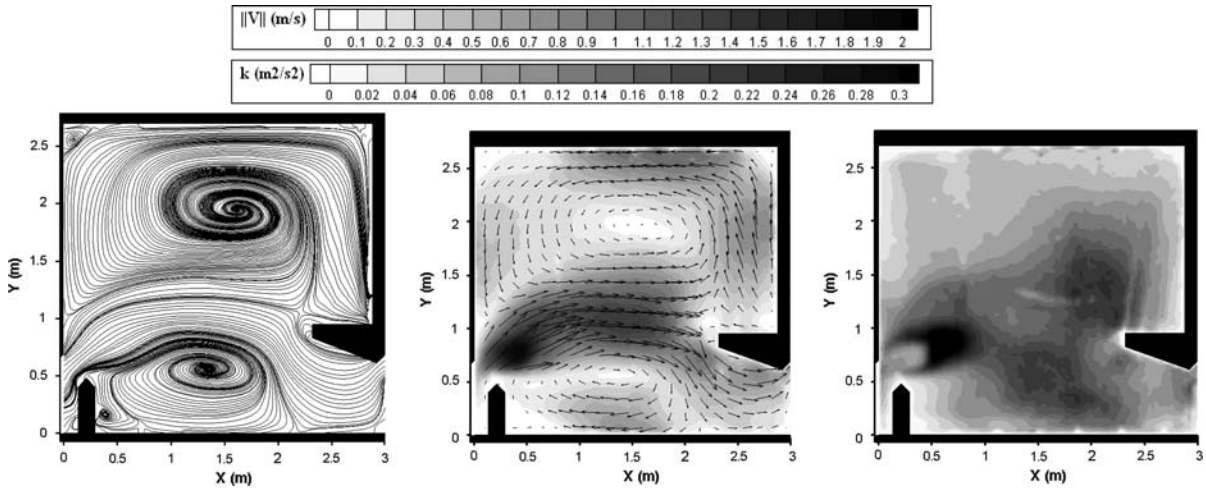

Fig. 5 Streamlines, velocity and turbulent energy in a vertical slot fishway: $I = 10\%$, $B = 2.7$ m, $Q = 736$ L/s at $Z = 0.08$ m

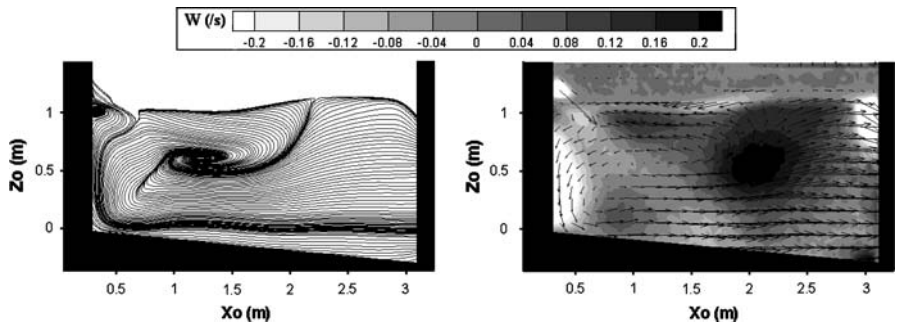

Fig. 6 Streamlines and vertical velocity in a vertical slot fishway: $I = 10\%$, $B = 2.7$ m, $Q = 736$ L/s at $Y = 0.55$ m

Turbulent energy represents the kinetic energy of the velocity fluctuations. It has the advantage of being a local indicator of turbulence and flow instationnarities and, unlike the dissipated power, which is a global parameter of the flow, it allows us to determine the intensity of the turbulence in particular local zones. The turbulent kinetic energy k in a plane and the volumetric dissipated power P_v are defined as:

$$k = \frac{1}{2}\left(\overline{u'}^2 + \overline{v'}^2\right) \quad \text{and} \quad P_v = \frac{\rho g Q \Delta h}{LBh}$$

Figure 7 shows the relationship between volumetric dissipated power and turbulent kinetic energy averaged on the pool surface for all configurations. There was a good correlation between k (m^2/s^2) and P_v (W/m^3), which are related by:

$$k = 0.000159 P_v + 0.0557 \quad \left(R^2 = 0.75\right)$$

The channel slope and pool width (i.e. the pool volume) parameters influence both volumetric dissipated power and turbulent kinetic energy, whereas the flow discharge has little or no influence (Wu et al., 1999).

An obstacle of diameter equal to the slot width b, judiciously placed in the pool, modified the flow pattern (the obstacle should be inserted in the jet core near the slot). Indeed, the jet resulting from the slot, widened in the pool before converging towards the following slot. For an obstacle located in the jet in the middle of the pool, the principal flow, of width higher than the geometry diameter, turned around the obstacle on each side. However the weak deviation neither broke nor notably reduced the recirculation currents. The shear layers, which were more intense at the slot exit, were not affected by the obstacle. The insertion of obstacles within the recirculation zones did not modify the velocity gradients or the flow pattern because the flow recirculated around the obstacles, which did not affect the jet and the swirls. It was thus necessary to position the obstacles at the slot exit. In this zone, the jet had a minimal width similar to that of the slot. An obstacle, identical in

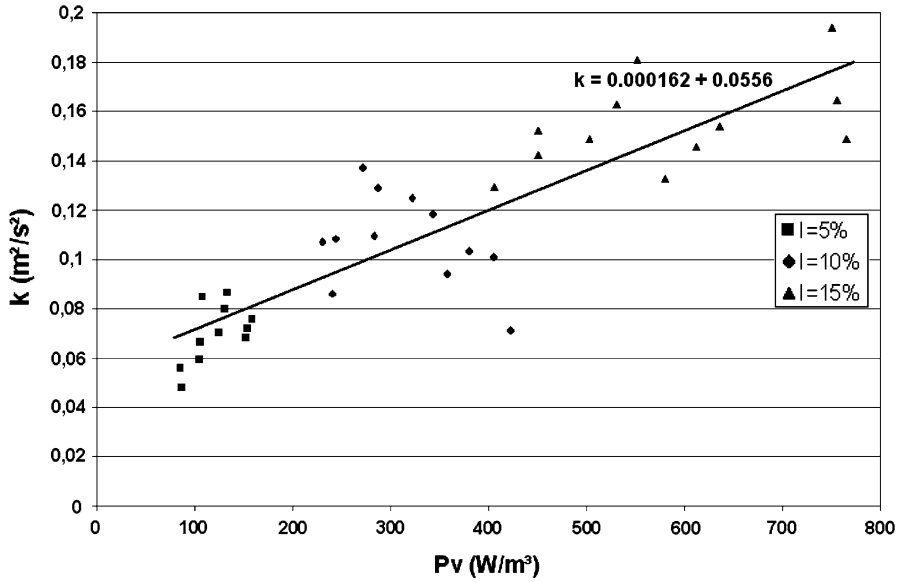

Fig. 7 Relation between k averaged on the pool surface and P_v at $Z = 0.6$ m

size to the jet, had sufficient effect on the flow to break or reduce the structures and to attenuate the velocity gradients at the jet boundaries.

The insertion of a half-cylinder in the jet, whose plane face was directed towards the flow, changed the basic topology. The jet impacted the plane face of the half-cylinder and turned around it on each side with an important separation due to the presence of edges. For the two configurations, the same flow pattern existed when the obstacle was placed at the slot exit (Fig. 8). Part of the jet impacting the plane face of the half-cylinder was directly conveyed along the lateral deflectors towards the following slot, creating a recirculation behind the lateral baffle. The other part of the jet was directed towards the opposite wall between the crosswalls and then joined the direct flow in the slot entry. The recirculating flows, which existed in the case of pools without obstacles, were eliminated, but an important recirculation zone (generating instantaneous, alternating swirls) was created downstream from the obstacle between the two principal flows resulting from the slot and flowing round the half-cylinder. Fluid separation on the edges of the half-cylinder generated intense shear zones, which amplified the problem of the velocity gradients at the jet boundaries when the fish penetrated the jet. This solution of a breakable structure is not satisfactory, since the number and location of recirculations were modified, but a more important recirculation was created in the central part of the pool, which increased the risk of fish being trapped or disoriented.

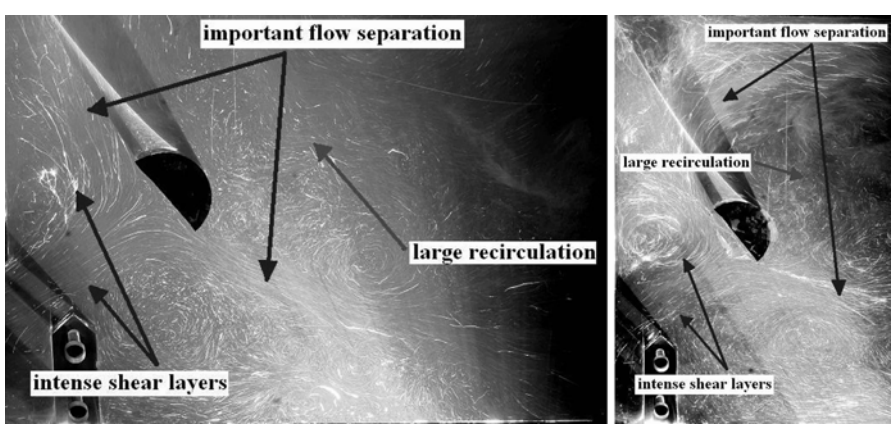

Fig. 8 Flow displays in a fishway with 1/2 cylinder (round face towards the flow): $I = 10\%$, $B = 2.7$ and 2 m, $Q = 736$ L/s at $Z = 0.08$ m

The configuration with a half-cylinder, whose round side was placed in the flow direction, did not improve the flow pattern for the fish, because the principal swirls on both sides of the jet were reduced, but the separation on the edges of the obstacle, which increases recirculation behind the obstacle, was still strong.

The inserted cylinder was thus tested to see whether it would modify the flow without changing it radically. The cylinder placed in the jet at the slot exit made it possible to obtain some effects of a half-cylinder while mitigating them. The flow resulting from the slot rounded the cylinder on each side of the obstacle, thus generating less separation due to the absence of arrises on the obstacle (Fig. 9). Nevertheless, the separation was sufficient to widen the jet significantly, which at the same time reduced the two counter-rotating cells located on each side. For the two configurations, a recirculation composed of two instantaneous alternated swirls was generated downstream from the cylinder between the two principal flows resulting from the slot (Fig. 10). The two direct flows merged behind the cylinder. The dimension of the recirculation and the localization of the reattachment point depended on the configuration and location of the cylinder. The closer the cylinder was placed to the slot, the more the two principal flows were diverted from the cylinder, near the walls with very curved trajectories. In this case, the reattachment point took place far downstream from the cylinder and the recirculation behind the cylinder was greater. On the contrary, when the cylinder was far from the slot, the principal flows were less curved, the recirculation was smaller and the reattachment point was closer to the cylinder. The absence of arrises on the cylinder decreased the intensity of the velocity gradients at the jet boundaries and made it possible to obtain shear layers that the fish could penetrate. An acceptable compromise between the recirculation dimension downstream from the cylinder, the fish passage in the slot and the reduction of the two principal swirls made it possible to place the cylinder approximately at $X = 2.1b$ and $Y = 3.1b$ (variable according to the configuration). Such a location of the

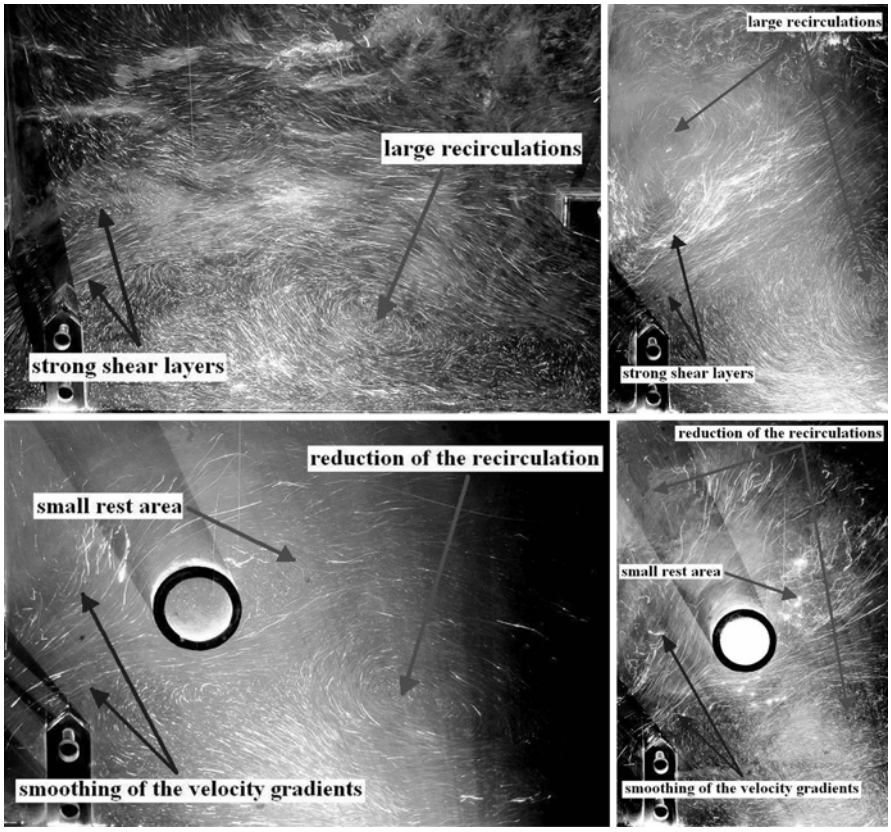

Fig. 9 Flow displays in a fishway with and without 1 cylinder: $I = 10\%$, $B = 2.7$ and 2 m, $Q = 736$ L/s at $Z = 0.08$ m

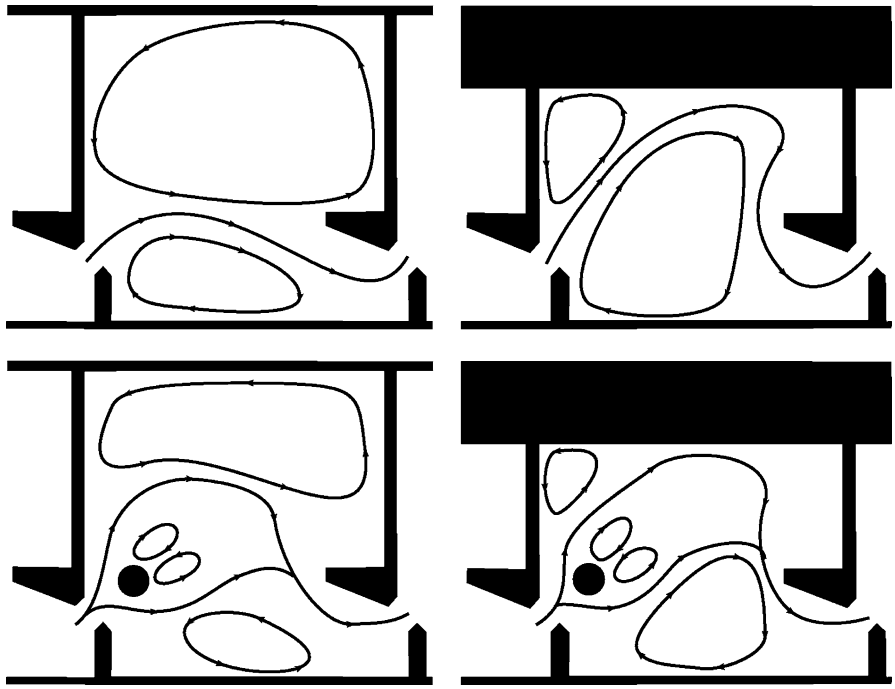

Fig. 10 Flow patterns in a fishway with and without 1 cylinder: $I = 10\%$, $B = 2.7$ and 2 m, $Q = 736$ L/s

cylinder significantly influenced the flow pattern (by deviating the jet and shear layer and reducing the recirculation currents) while allowing passage of the large fish.

A last test with two cylinders was achieved for the two configurations (Fig. 11). The first was placed at the slot exit in order to widen the jet and to reduce the two counter-rotating contra-rotating cells on each side. The second cylinder was placed downstream from the first, slightly shifted in the pool according to the configuration, in order to break the direct flow resulting from the deviation of the first cylinder. This configuration made it possible to reduce the recirculation located between the lateral deflectors. However, this recirculation became more intense and the rotation rate was stronger than for the configuration with only one cylinder.

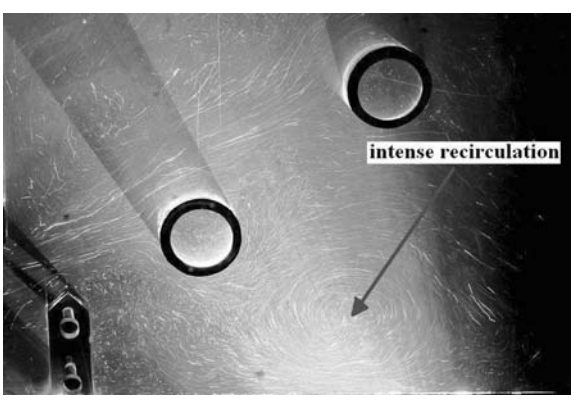

Fig. 11 Flow displays in a fishway with 2 cylinders: $I = 10\%$, $B = 2.7$ m, $Q = 736$ L/s at $Z = 0.08$ m

Discussion and conclusion

The flow for various configurations of vertical slot fishways was finally limited to two principal topological models according to the length/width ratio of the pool. The first, which occurred for $L/B = 10/9$, was composed of two large recirculation areas located on each side of the jet leaving the slot. The second occurred when the L/B ratio was lower than 3/2. The large recirculation area was then divided, by the jet hitting the side wall, into two swirling cells, one of which was located at the upstream corner of the pool and the other along the central baffle. A third swirl then occupied the convex part of the jet. Depending on the channel slope, the intermediate pool widths generated one or other of the models. For these two topologies, the flow within the pool was fairly two dimensional as the fish, which swim up the vertical slot, encounter the same characteristics at any

depth of the flow from the bottom to the water surface. Moreover, a discharge variation caused a variation of the water depth in the fishway without modifying the flow patterns. Velocities and turbulent energies increased with the channel slope.

A strong link was found between the calculated, volumetric dissipated power and the mean kinetic energy of velocity fluctuations measured in the pools. They both increased when the fishway slope increased, while remained independent of the flow discharge in the pools. This overall finding was completed by a spatial analysis of the turbulent energy. The places where the high energy was measured are the sites of the largest velocity fluctuations in the fishway. A more refined analysis of turbulent kinetic energy will be made to distinguish between the values in high-velocity areas, where fish have to pass, and values in low-mean velocity areas, which are necessary to allow small species to rest.

Visual observations made in large vertical slot fish passes equipped with viewing windows showed that certain small species can remain trapped for a very long time in the large recirculation zones in the pools. All these areas, which in principle are designed to be resting areas, become in fact traps for small fish.The drastic increase of transit times in each pool can delay the clearing of the fish pass, particularly in the case of a facility composed of numerous pools. Such delays in pools were observed during a recent study of the behaviour of percid species (*Zingel asper L.*) in model fish passes (Gomes et al., 2005). Such examples of fish being disoriented have been observed in Denil fish passes. An increase in the sizes of the baffles results in an increase in the size of the helicoidal currents; if the eddies become too large in relation to the fish, then the fish will tend to orient themselves in relation to the local components of the velocity and bump into baffles. This may diminish the efficiency of the facility (Larinier et al., 2002).

A first solution for small species would consist of reducing both the drop between pools and the dimensions of the pools, so as to reduce the maximum velocities, turbulence and size of recirculation areas. The main drawback is that the width of slots and length of pools can become inadequate for large species and it would thus be advisable to install two fish passes (one for small and one for large fish) on the same obstruction. On existing facilities, the most realistic and economical solution is to adapt the internal flow in the pools. Considering that it is not easy to reduce the drop between pools, the only way this can be done is to reduce the sizes of recirculating areas and to attenuate the obstacle of the strong shear layers at the jet boundaries.

An obstacle placed in specific zones of the flow can control the flow and might be a way of facilitating the migration of small species by limiting the number and size of trap zones and decreasing the turbulence. A cylinder of dimension equal to the slot width b, judiciously inserted at the slot exit, modified the flow and limited obstacle zones within the pools of vertical slot fishways. Indeed, the flow resulting from the slot turned around the cylinder on each side of the obstacle. The separation was sufficient to widen the jet significantly, which in turn reduced the two counter-rotating cells located on each side. A small recirculation zone, composed of two instantaneous alternated swirls, was generated downstream from the cylinder between the two principal flows leaving the slot and reattaching behind the obstacle. Because of the risk of disorientation if the eddies become too large in relation to the fish, the reduction of the two large recirculating structures by the insertion of a cylinder made it possible to decrease the trap zones, where the fish could remain blocked for a very long time. The recirculating cell generated behind the obstacle did not create any problems for the fish because it was small and provided a rest area when they ascend the fishway. The cylinder decreased both the velocities near the slot and attenuated the velocity gradients at the jet boundaries. The smoothing of these intense shear layers made it possible to limit the obstacle zones and to facilitate the penetration of fish, which had been trapped in the large recirculation currents in the jet. The passage through the slots by the small species became easier due to reduction in velocity gradients, which were better suited to their swimming abilities.

A study with various fish species (migrating species such as brown trout and riverine species such as gudgeon, roach, club, bleak and common bitterling) has been undertaken to validate this type of adaptation of vertical slot fishway and to check its effectiveness on fish behaviour. The first results, which still have to be confirmed and expanded by other experiments, tend to verify the contribution of a cylinder in the pool for small fish and to demonstrate the potential of changing the geometry in this way.

Acknowledgements This work was undertaken in the Laboratoire d'Etudes Aérodynmiques (LEA) at the University of Poitiers. Financial support was provided by the Voies Navigables de France[1] and the Direction Régionale de l'Environnement. Our thanks as well to all laboratory technicians for their help in installing the facility and during the experiments.

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[1] NdT Navigable French waterways