AN EXPERIMENTAL STUDY OF TURBULENT FLOW IN VERTICAL SLOT FISHWAYS

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ABSTRACT

The vertical slot fishways are hydraulic structures that allow the upstream migration of fishes through engineering constructions or natural obstructions in rivers. 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 their characteristics might be modified in order to facilitate the passage of small species. The characteristics of mean flow and turbulence were studied by PIV and visualizations for several different slopes, flow discharges and pool widths. The results showed that the flow pattern always takes one of two topology models depending on the ratio length/width of the pool. 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 visualized.

1 INTRODUCTION

Fishways are hydraulic structures that enable fish to overcome obstructions in the passage to the spawning and other upstream migrations and are built when they are required for ecological, economical or legal considerations. The vertical slot fishway is the commonly used fish ladders because it allows variations in discharge and water levels [1]. It consists of a rectangular channel with a sloping floor which is divided into a number of pools. Water runs downstream in this channel through a series of vertical slots from one pool to the next one below. The water flow forms a jet as it goes through the slot and the energy is dissipated by jet mixing in the pool [2]. The baffles are so shaped that part of the flow is turned back upstream to create recirculation regions in the pools where the fish would rest to recover their swimming ability before ascending the fishway through the slots at any depth it chooses. The flow patterns are very important in order to guide the fish and make possible its way along the structure.

Several vertical slot fishways have been built in France over the last twenty years as part of the plan to restore or enhance migratory fish stocks. This may be considered to the best type of pool fish pass and is usually very effective in ensuring unhindered passage of the target species (generally salmon, sea trout, shad, marine lamprey...) as well as several riverine species such as trout, grayling, barbel, bream....However observations have shown that some small species seem to have difficulty in rapidly passing through very large pools. The recent 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 generally river fauna.

This experimental study was thus undertaken to characterize the turbulent flow for various configurations of vertical slot fishways and to determine how their characteristics may be modified in order to facilitate passage of the 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 visualized by laser tomography.

2 EXPERIMENTAL PROCEDURE

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 the Froudian similitude, of geometrical scale 1/4. The velocity scale is 1/2 and the discharge scale is 1/32. The width of the slot is b = 0.075 m. The vertical slot fishway model consists of five pools, L/b = 10 long and H/b = 7.33 deep. The width of each pool could be set to four values: B/b = 9, 7.66, 6.66 and 5.66. The channel slope could take three values: I = 5, 10 and 15 %. The crosswalls between pools are perfectly vertical for a channel slope I = 10 %. Three flow discharges are studied: Q = 18, 23 and 27 L/s. The discharge velocities in the slot are respectively V_d = 0.72, 0.94 and 1.09 m/s for the three channel slope I = 5, 10 and 15 %. The equivalent Reynolds numbers, calculated with the slot width b and the discharge velocities in the slot V_d, are respectively R_e = 60600, 79100 and 91800 according to the slope. The experimental measurements were taken in the third pool in order to ensure an established symmetrical flow. The X-axis is in the longitudinal direction and the Y-axis is in the transverse direction of the fishway. The XY plane is parallel with the channel bed. All the geometric dimensions are divided by the slot width b and the velocities are normalized by the discharge velocities in the slot V_d.

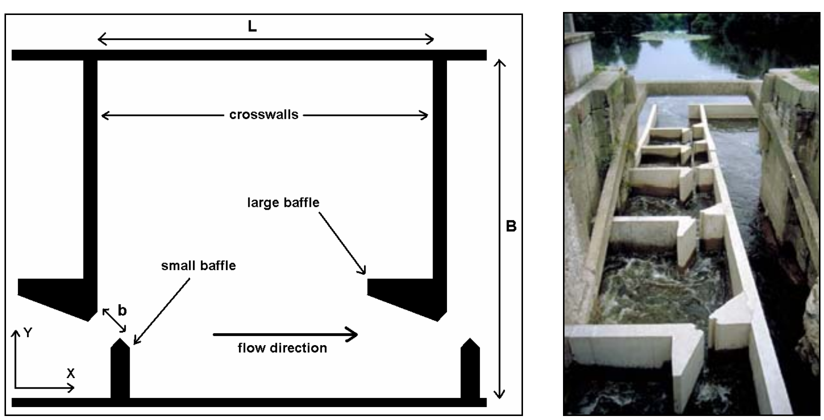

Fig. 1 - Pool configuration and example of vertical slot fishway

Velocity measurements were taken by means of Particle Image Velocimetry (PIV) in two planes parallel with the channel bed of the fishway (Z/b = 0.26 and 2) and in the vertical plane (Y/b = 1.82) passing by the slots. The acquisition and treatment PIV system is composed of a laser lighting a flow section, a camera system and a synchronization unit. The correlator Flowmap PIV 2000

Processor (Dantec) allows to synchronize the laser system and the cameras. A laser Nd-Yag double cavity Spectra-Physics (2x200 mJ) has been used to highlight a flow section seeded by particles 11 µm diameter. The frequency of each cavity is approximately 10 Hz and the wavelength is 532 nm. The beams coming from the two cavities are then conveyed, through a telescopic arm towards a system of double lens system making it possible to produce a narrow laser sheet which have a thickness of about 1.5 mm. In order to record the successive images of the flow, two cameras FlowIntense are used with objectives of 28 mm and placed in parallel to visualize the whole pool. The resolution of these cameras is 1376x1040 pixels², coded on 12 bits. The cameras make it possible to acquire two successive images of the flow separated by a very short time Δt (between 3000 and 4000 µs) which is generated between the two cavities of the laser. By means of a PC, the FlowManager software (Dantec) controls PIV system (i.e. to regulate the specific parameters to each measurement) and computes cross-correlation between the successive images and postprocessing on the calculated data. An initial interrogation area of 64x64 pixels², a final interrogation area of 32x32 pixels² with an overlap of 50 % and window deformation are used to compute the cross-correlation. For each camera, five bursts of 175 image acquisitions (separated by T = 200 ms) allow to obtain 875 instantaneous velocity fields which are then averaged. The two mean velocity fields calculated are combinated in order to have the complete mean velocity field of the pool.

Visualizations completed the study of the flow and were achieved by laser tomography (with a laser optic fibre) and recorded with a camera Panasonic NV-MX300EG (resolution:1568x1152 pixels², dynamic: 12 bits) at several depths within a pool, with and without cylinder.

3 RESULTS

3.1 Turbulent flow in vertical slot fishways

Fig. 2 shows the streamlines and velocities in the plane Z/b = 2 for four configurations of vertical slot fishways (slope I = 10 % and width B/b = 9, 7.66, 6.66 and 5.66) for a flow discharge Q = 23 L/s. For all the configurations, the flow in a pool is mainly composed of three important areas [6]: a principal jet caused by the slot, passing through the pool with decreasing velocity and two large recirculation zones generated on each side of this principal flow. The recirculations around an axis perpendicular to the channel bed allow for dissipation of the jet energy in each pool [5]. Swirling cells of variable sizes, created by the principal recirculations, occur in all the corners of the pool, due to the velocity differential between the recirculating flow and the zero velocities on the wall. Two different flow patterns occur according to the ratio length/width of the pool.

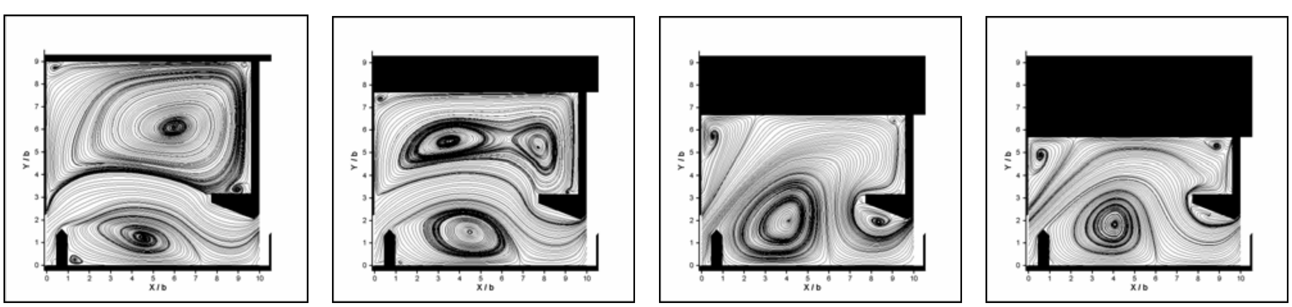

Fig. 2 - Streamlines and velocity in a vertical slot fishway: I = 10 %, B = 9, 7.66, 6.66 and 5.66, Q = 23 L/s at Z/b = 2

The first flow pattern is for the largest width (B/b = 9). 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 on a side, between the large baffles, an important recirculation area occupying roughly half of the pool surface. On the other side of the principal flow, a swirling zone of smaller size, rotating in the opposite sense to the preceding one, is generated between the small wall deflectors. The highest velocities 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 a high shear layer at the jet boundaries near the slot.

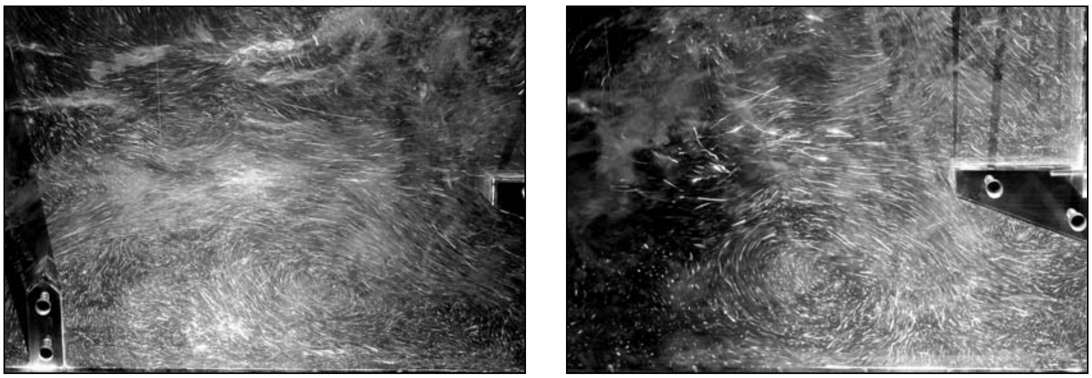

Fig. 3 - Flow visualizations in a vertical slot fishway: I = 10 %, B/b = 9, Q = 23 L/s at Z/b = 0.26

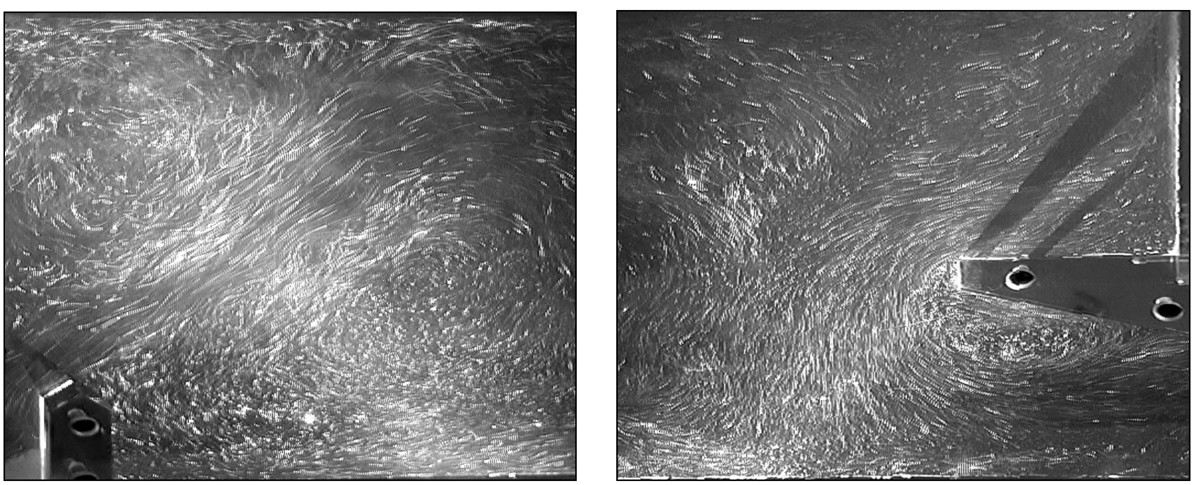

Fig. 4 - Flow visualizations in a vertical slot fishway: I = 10 %, B/b = 6.66, Q = 23 L/s at Z/b = 0.26

A second flow pattern occurs for the pools of low width (B/b = 6.66 and 5.66): the jet has a very curved form and directly hits the opposite side wall (Fig. 2 and 4). Two large contra-rotating swirls are then generated in the corner upstream of the pool and in the convex part of the jet and a smaller one occurs close to the large baffle. The reduction in width of the pool changes the dimensions and the 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 large 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 is stretched in the transverse direction. Its size relative to the pool surface area increases. The velocities 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. 4).

For all the fishway configurations studied, the slope variation does not generate different flow patterns: the two large countra-rotating cells are found on each side of the principal jet. Thus when the slope increases, the jet widens slightly whereas the sizes of the recirculation zones are reduced slightly.

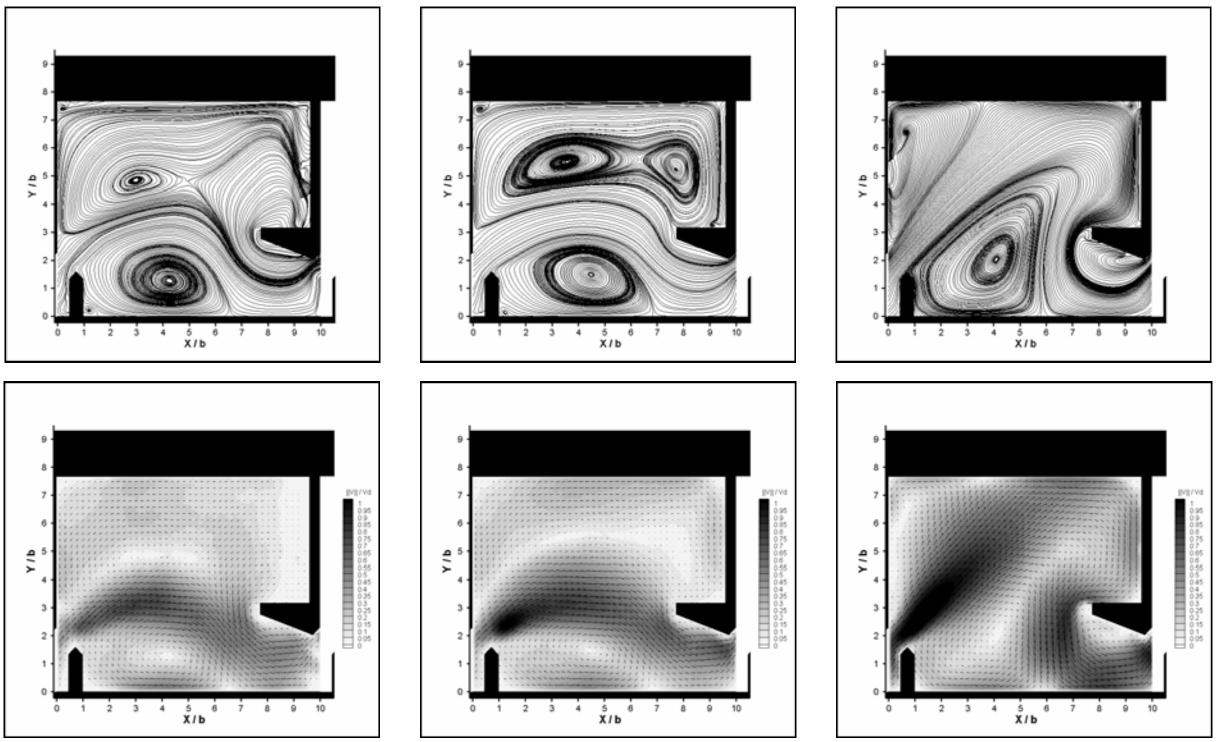

Fig. 5 - Streamlines and velocity in a vertical slot fishway: *I* = 5, 10 and 15 %, *B*/*b* = 7.66, *Q* = 23 L/s at *Z*/*b* = 2

For an intermediate pool width (*B*/*b* = 7.66), the flow topology varies according to the channel slope [7]. For the lower slopes (*I* = 5 and 10 %) the flow pattern looks like that observed for a pool of width *B*/*b* = 9: two great recirculation areas, one on each side of a jet, including one composed of two swirls separated by a singular point (Fig. 5). Whereas for the higher slope (*I* = 15 %) the flow pattern is similar to the topology obtained for widths *B*/*b* = 6.66 and 5.66 namely a curved jet, a considerable recirculation occupying the convex part of the principal flow, a swirl in the upstream corner and another along the large deflector.

For all pool widths tested and the two principal flow models, the velocities values undergo strong variations when the slope changed (Fig. 5). These values grow with the slope and are very more important for a slope of *I* = 15 % as compared to a slope of *I* = 5 %. The velocity gradients at the jet boundaries, mainly close to the slots, also increase with the slope.

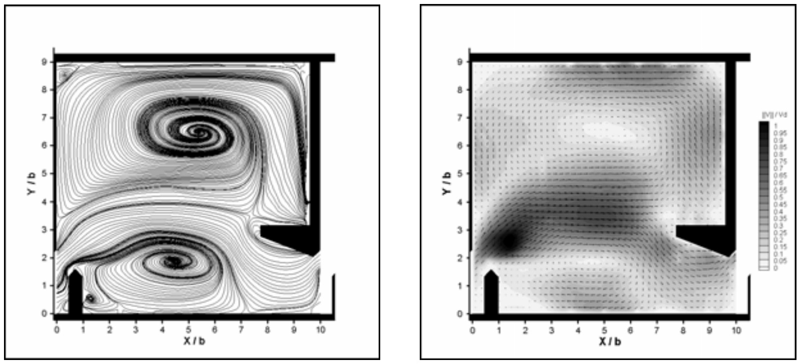

Fig. 6 - Streamlines and velocity in a vertical slot fishway: *I* = 10 %, *B*/*b* = 9, *Q* = 23 L/s at *Z*/*b* = 0.26

The flow topology is independent of the height of the measurement section [3] within the pool (Fig. 2 and 6). There are few variations of the recirculation shape and the location of their centres whatever the height, while velocities remain on the whole identical in the pool from the channel bed to the free surface. Except in the slot zone (Fig. 7), the vertical component of the velocity is less significant than the longitudinal and transverse velocities and the flow structure can thus generally be considered to be two-dimensional in the pool [4].

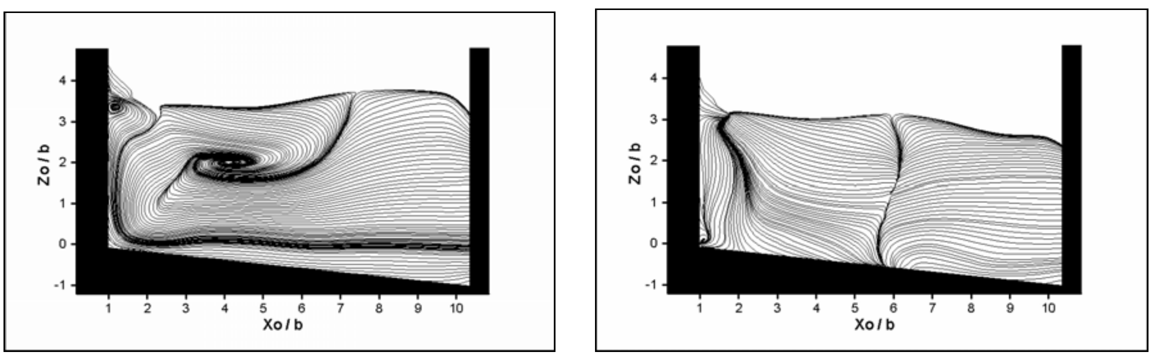

Fig. 7 - Streamlines in a vertical slot fishway: *I* = 10 %, *B*/*b* = 9 and 6.66, *Q* = 23 L/s at *Y*/*b* = 1.82

The discharge parameter has very little influence on the flow in vertical slot fishways. The flow topology as well as velocities remain similar for the three discharges. The main consequence of a flow increase is a rise in the water height, controlled by the slots, without velocity variation.

3.2 Flow control

Visual observations made in large vertical slot fish passes showed that certain small species can remain trapped a very long time in the large reciculation zones in the pools. All these areas, which in principle are designed to be resting areas, become in fact so many traps for small fish. The drastic increase of transit times in each pool can compromise the efficiency of the fish pass, particularly in the case of a facility composed of numerous pools. Such examples of disorientation of fish have been observed when the size of eddies becomes too large compared to that of the fish, then the fish will tend to orient themselves in relation to local components of the velocity and to bump into baffles. The disorientated fish seems to have difficulty in penetrating through the jet and rapidly finding the exit slot. This may have reduce the efficiency of the facility [1]. A first solution for small species, would consist in reducing both the drop between pools and the dimensions of the pools, so as to reduce the maximum velocities, the turbulence and the size of recirculation areas. 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 is to reduce the sizes of recirculating areas and to attenuate the obstacle of the strong shear layers at the jet boundaries.

First tests were carried out by inserting obstacles (of dimension equal to the slot width *b*) within the pools in order to break the large swirling structures. In order to check the effectiveness of such configuration on the shear layers and recirculation zones, flow visualizations were thus made for two geometric configurations (slope I = 10 % and width B/b = 9 and 6.66 for a discharge Q = 23 L/s) which represent the two flow models.

An obstacle of diameter equal to the slot width *b*, judiciously placed in the pool, modifies the flow topology. The obstacle must be insert in the jet near the slot. Indeed, the jet resulting from the slot widens 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, turns around the obstacle on each side. However the weak deviation does not make it possible to break or reduce notably the recirculations. The shear layers which are more intense at the slot exit are not affected by the obstacle. The insertion of obstacles within the recirculations does not modify the velocity gradients nor flow topology because the flow recirculates around the geometries which do not influence the jet and the swirls. It is thus necessary to establish the obstacles at the slot exit. In this zone, the jet has a minimal width of the same order as the slot. An obstacle of size identical to the jet has more effect on the flow in order to break or reduce the structures and to attenuate the velocity gradients at the jet boundaries.

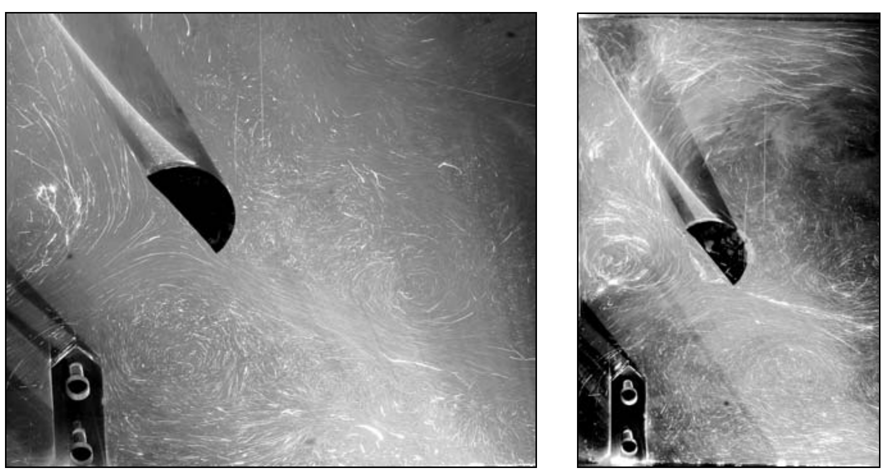

Fig. 8 - Flow visualizations in a fishway with a half-cylinder (plane face directed towards the flow): I = 10 %, B/b = 9 and 6.66, Q = 23 L/s at Z/b = 0.26

The insertion in the jet of a half-cylinder, whose plane face is directed towards the flow, changes basically the topology. The jet impacts the plane face of the half-cylinder and turns around it on the two sides with an important separation due to the presence of arrises (Fig. 8). For the two configurations, the same flow topology exists when the obstacle is placed at the slot exit. A part of the jet impacting the plane face of the half-cylinder is directly conveyed along the small deflectors towards the following slot, creating a recirculation behind the small baffle. The other part of the jet is directed towards the opposite wall between the large deflectors and then joined the direct flow in the slot entry. The recirculating flows which exist in the case of pools without obstacles are removed but an important recirculation zone is created downstream from the obstacle between the two principal flows resulting from the slot and getting around the half-cylinder. The fluid separation on the edges of the half-cylinder generates intense shear zones which amplify the problem of the velocity gradients at the jet boundaries when the fish penetrates the jet. This solution of breakable structure is not satisfactory since the number and the site of the recirculations are modified but a more important recirculation is created in the central part of the pool, which increases the trap risk and disorientation for fish.

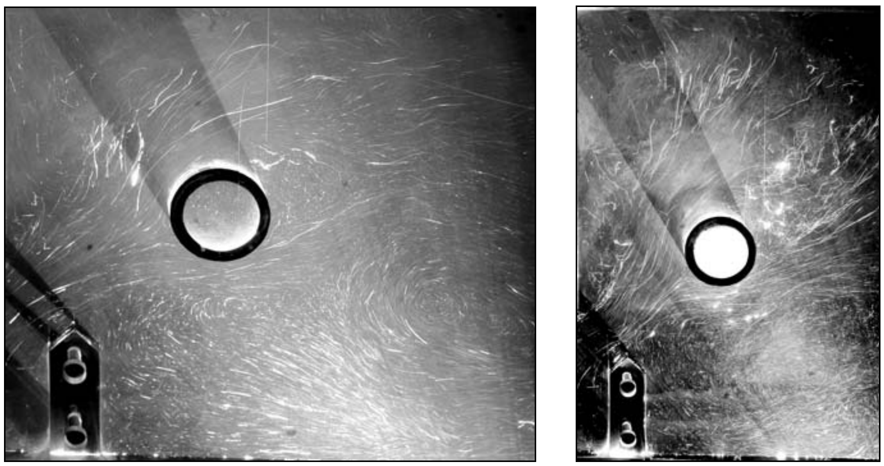

Fig. 9 - Flow visualizations in a fishway with a cylinder: I = 10 %, B/b = 9 and 6.66, Q = 23 L/s at Z/b = 0.26

The insertion of cylinder was thus tested in order to modify the flow without changing it radically. The presence of a cylinder in the jet at the slot exit makes it possible to obtain some aspects of a half-cylinder while mitigating its effects. The flow resulting from the slot turns around the cylinder on the two sides of the obstacle by generating a less important separation due to the absence of arrises on the obstacle. Nevertheless separation is sufficient to widen the jet significantly what reduces by the same occasion the two contrarotating cells located on both sides (Fig. 9). For the two configurations, a recirculation is generated downstream from the cylinder between the two principal flows resulting from the slot. The two direct flows reattach behind the cylinder. The dimension of the recirculation and the localization of the reattachment point depend on the configuration and the site of the cylinder. The more the cylinder is placed close to the slot, the more the two principal flows are diverted far from the cylinder near the walls with very curved trajectories. In this case the reattachment point takes place far downstream from the cylinder and the recirculation behind the cylinder is more important. On the contrary when the cylinder is far from the slot, the principal flows are less curved, the recirculation is smaller and the reattachment point is closer to the cylinder. The absence of arrises decreases the intensity of the velocity gradients and makes it possible to have 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 makes it possible to place the cylinder approximately at *X/b* = 2.1 and *Y/b* = 3.1 (variable according to the configuration). Such a location of the cylinder influences significantly the flow topology (deviation of the jet, shear layer, reduction of the recirculations) while allowing the passage of the large fishes.

The test with a half-cylinder whose round face is placed in the flow direction does not improve the flow topology for the fish because the profit obtained on the reduction of the principal swirls on both sides of the jet is compensated by the separation on the arrises which increases the recirculation behind the obstacle (Fig. 10).

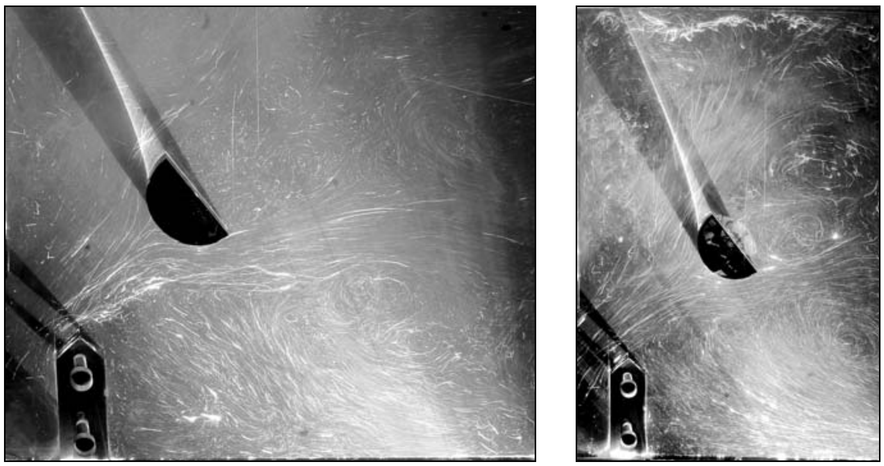

Fig. 10 - Flow visualizations in a fishway with a half-cylinder (round face directed towards the flow): *I* = 10 %, *B*/*b* = 9 and 6.66, *Q* = 23 L/s at *Z*/*b* = 0.26

Fig. 11 - Flow visualizations in a fishway with 2 cylinders: *I* = 10 %, *B*/*b* = 9 and 6.66, *Q* = 23 L/s at *Z*/*b* = 0.26

A last configuration with two cylinders was tested for the two configurations (Fig. 11). The first is placed at the slot exit in order to widen the jet and to reduce the two contrarotating cells on both sides. The second cylinder is 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 makes it possible to reduce the recirculation located between the small deflectors. But this reciculation becomes more intense and the rotation rate is stronger than for the configuration with only one cylinder. The second cylinder creates downstream a small swirling zone which could be an additional rest area for fish.

Finally two solutions were obtained to optimize the flow pattern and to facilitate the fish passage. The insertion of a vertical cylinder at the slot exit allows to reduce the recirculations dimensions and to attenuate the shear layers at the jet boundaries. It provides rest area for fish when they ascend the fishway. The insertion of a second cylinder reduces the swirl located near the small baffle which becomes more intense.

CONCLUSION

The flow for various configurations of vertical slot fishways was finally limited to two principal topology models according to the ratio length/width of the pool. The first which occurred for L/B = 10/9 was composed of two great recirculation areas located on each side of the jet leaving the slot. The second occurred when the ratio L/B 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 large 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 rather two-dimensional so 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 increased with the channel slope. The insertion of vertical obstacles judiciuously placed at the slot exit allows to reduce the recirculations and to attenuate the shear layers at the jet boundaries. The velocities in the principal flow are within the swim capacities of the small fish and the swirl created downstream from the cylinders provides rest area.

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