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Influence of Macro-Roughnesses on Vertical Slot Fishways

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Abstract: *To restore the ecological continuity of European rivers and streams, and, more specifically, the unrestricted movement of aquatic species vertical slot fishways (VSF) are built and offer the possibility for fish to cross dams or weirs. Initially, such devices were constructed to allow the migration of fish species with high swimming capacity like salmonids. Currently, more and more VSFs are equipped with macro-roughnesses fixed to the bed to help small or benthic species to cross obstructions. Macro-roughnesses are most often stones or concrete cylinders and have been introduced to decrease the velocity and the turbulent kinetic energy of the flow inside pools. In this paper, unsteady 3D flow simulations are carried out to study the effects of such macro-roughnesses on the flows. LES simulations, validated in a previous paper with experimental results, provide valuable information of the flow characteristics.*

Keywords: *Upstream migration, flow topology, roughnesses, vertical slot fishway, numerical simulation.*

1. Introduction

The European Water Framework Directive (adopted in October 2000) aims to restore the ecological continuity along rivers and streams. Thus, devices such as Vertical Slot Fishways (VSFs) are used to allow fish migrations by offering them the possibility to cross permanent obstructions like dams or weirs. VSFs are fish passage devices that are commonly used in France because they are well adapted to the discharges commonly observed in rivers in this region and are quite insensitive to the variations of upstream and downstream water levels. Nevertheless, the flow conditions inside VSFs are not always in accordance with the swimming capacity of some small or benthic fish species that swim near the river's bed. In an attempt to adapt the flow characteristics to those species, macro-roughnesses, which are most often stones or concrete cylinders, are fixed on the bed of a VSF. These element insertions will be helpful for the velocity and turbulent kinetic energy (TKE) reduction locally and could increase migration efficiency. Many studies have been conducted in recent years to characterize the flow inside classical VSF with a smooth floor configuration both experimentally (Wu et al. 1999, Puertas et al. 2004, Liu et al. 2006, Tarrade et al. 2008, Wang et al. 2010) and numerically (Khan 2006, Tarrade 2007, Cea et al. 2007, Chorda et al. 2010, Heimerl et al. 2008, Barton et al. 2009, Musall et al. 2014; An et al. 2016, Klein et al. 2016, Fuentes-Perez et al. 2017). The different studies show that the flows are influenced by main parameters of a VSF which are the dimensions of the pools, the geometrical characteristics of the wall separating two slots, as well as the drop between the pools. These geometrical parameters determine (considering the upstream and downstream water levels) the hydraulic conditions in the pools, i.e. the flow pattern, the velocities, as well as the flow passing through the slot. In the literature, Branco et al. (2015) studied the influence of bottom rugosity on the performance of upstream fish movements through a pool-type fishway and there are also experimental and numerical results for the natural-pass fishways (Baki et al. (2014, 2015), Cassan et al. (2014, 2016)). The macro-roughnesses used for this specific device are composed with larger blocks that are partially or fully immersed in the turbulent waters in the fishway. In the case of the presence of macro-roughnesses inside a vertical slot fishway, the flow will be different. However, the effects of macro-roughnesses on the characteristics of the flow have never been studied. Ballu et al. (2016, 2017) presented first results about the topology of the flows and the influence of the macro-roughnesses on the discharge coefficient. The present paper proposes to investigate the influence of macro-roughnesses on both the mean and the turbulence features of the flow inside a VSF using Large Eddy Simulation (LES). At first, the simulation of the LES will be detailed with the meshes, the numerical model used, and the boundary conditions. In a second part, the results will be analyzed from the topology description inside the pool. Finally, velocity and turbulent characteristics will be compared between vertical slot fishway with and without macro-roughnesses.

2. Geometry and Numerical Setup

The design of the baffles used in this numerical investigation of the flow inside a five pool VSF with macro-roughnesses is based on the mean geometry characteristics of VSFs constructed in France. To be consistent with the experimental model used for the validation of the LES, the length of the pools is $L=0.75$ m and the width of the vertical slots is $b=0.075$ m, giving the ratio L/b equal to 10. The width of the pools that have been investigated is $B=0.675$ m, i.e. $B/b=9$. The model and the prototype were related by Froude similitude on a geometrical scale between 1/2.5 (for a small trout fish pass) and approximately 1/6 (for a large fish pass for shad and large diadromous species) depending on the dimensions of the prototype pools. The geometrical dimensions could be easily modified to be adapted at different scales. For the study presented here, the slope of the VSF is set to $s=7.5\%$ and the discharge to $Q=0.023$ m³/s. The macro-roughnesses arranged on the bottom of the VSF model are equally spaced cylindrical studs with a diameter of 0.035 m and a height $h_r=0.05$ m.

The density (d_r) is defined as the ratio of the elementary surface covered by the elements of macro-roughnesses (S_r) to the total bed surface of the pool (S_p) (Figure 1).

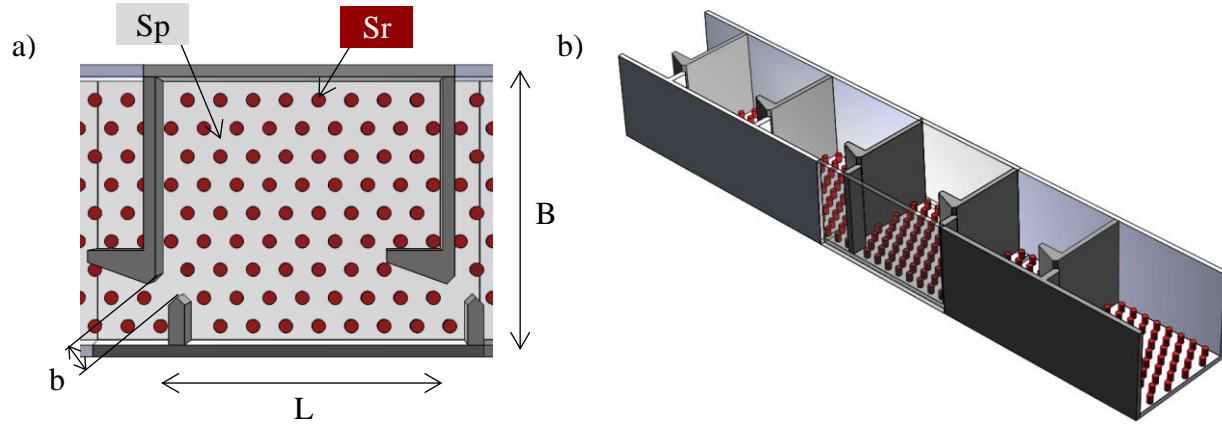


Figure 1. a) Dimensions of a pool and characteristics of the density of macro-roughnesses; b) Design of the VSF that is investigated numerically.

In the studied configuration, a density is set to $d_r=15\%$ which is one of the densities applied today in France for the design of VSF.

Simulations of the flow were conducted in Large Eddy Simulation (LES) with Star-CCM+ software for a configuration that is identical to that used for the experimental measurements (5 pools, $B/b=9$, $Q=0,023$ m³/s and $s=7.5\%$) with a smooth floor configuration and with macro-roughnesses. The Large Eddy Simulation method (LES) consists of solving large flow structures that are highly dependent on geometry and models only small ones that are supposed to be more universal thanks to a subgrid-scale model. The Wall Adapting Local Eddy-viscosity (WALE) model was used for simulations and it is particularly suitable for complex geometries and has, therefore, been used in this study. To simulate free surface flow, the Volume of Fluid (VOF) method was used. This method is based on a function which makes it possible to define the volume fraction of one of the two fluids present in a control volume. An implicit temporal discretization scheme is used and consists of two nested loops: a loop in physical time which allows the description of the unsteady evolution and a loop in dual time which seeks to reach a quasi-stationary state. For spatial discretization, a third order scheme (MUSCL) was used for LES.

Hydrostatic pressure conditions and volume fraction of each phase (water and air) are set at the input and output of the calculation domain. Water levels are derived from experimental measurements of water heights on the VSF of the laboratory. No-slip wall boundary conditions have been specified on all solid walls. The area of calculation has been enlarged above the fishway, thus enabling the boundary to be moved away from the area of the free surface of the flow. A symmetry condition has been imposed on the boundaries of this enlargement. Boundary conditions are recalled on Figure 2.

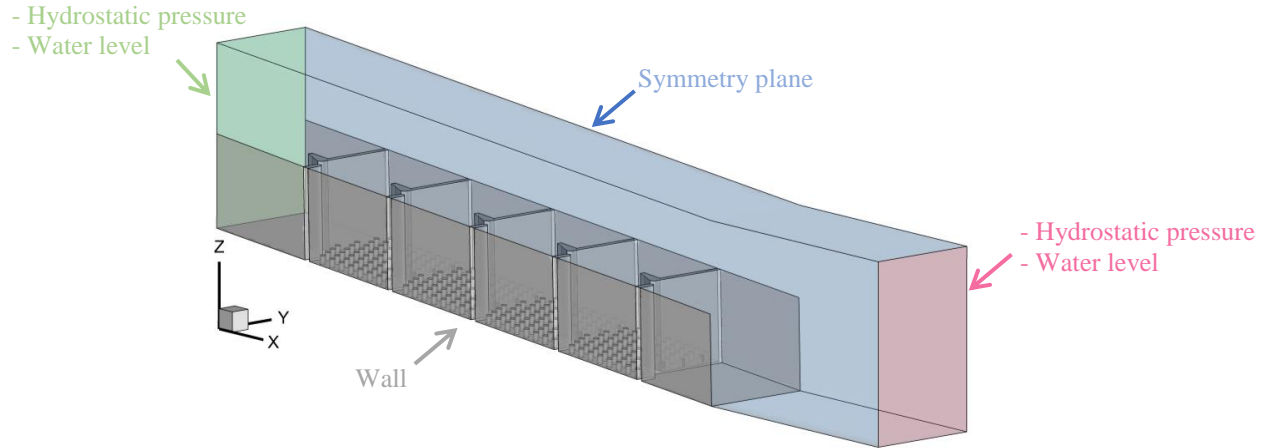


Figure 2. Boundary conditions used for LES simulations.

The size T^* of the cells of the different parts of the domain has been defined with respect to the width of the slot (T^*/b). This ratio has been set to 1/4 (Figure 3) in all the pools except in the third pool where it has been refined with a ratio of 1/8 to get a better description. This mesh allows on the one hand to obtain a good definition of the geometry but also to have reduced spatial discretization errors. Since the water level is determined experimentally, the mean position of the free surface in each pool can be estimated. The mesh has been refined to $T^*/b=1/8$ in an area around this position ($\pm 20\%$). The part of the domain which contains only air (above the free surface) has been meshed with a mesh size $T^*/b=1$. For the simulation of the flow in the VSF in the vicinity of macro roughnesses, a refinement ($T^*/b=1/8$) was carried out in an area delimited by the height of the cylinders. In LES, the anisotropy of the near-wall mesh must be very limited. To resolve inner-layer eddies, the streamwise and spanwise grid sizes in wall unit, respectively, $\Delta x^+ \cong 100$ and $\Delta z^+ \cong 20$ have been used.

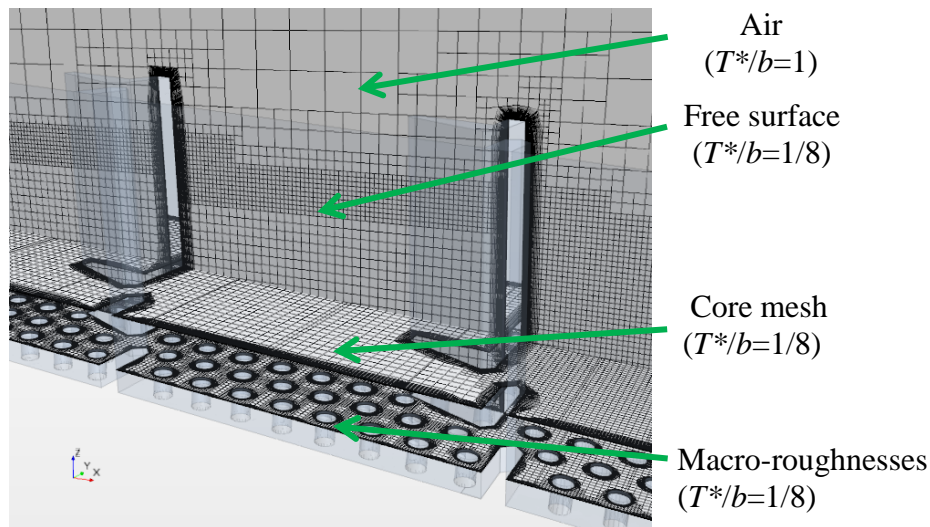


Figure 3. Mesh generated for simulation of the flow in a VSF with macro-roughnesses (Ballu 2017).

The initial conditions are derived from URANS calculations such as pressure, velocity, and volume fraction to start from an equilibrium of the water inside the fishway. Detailed information for the simulation is available in Ballu et al. (2017).

3. Influence of Macro-Roughnesses on the Mean Flow and the Flow Topology

The numerical simulations carried out in LES were used to analyze the flow generated both above and through macro-roughnesses. The flow description is done using essentially two normalized heights (Z/h_r) or (Z/b) with respect to the height of the roughness (h_r) and the width of the slot (b) in order to facilitate comparisons with the results from the literature. The following numerical study was carried out for a pool width $B/b=9$ and $d_r=15\%$, a slope $s=7.5\%$, and a discharge $Q=0.023 \text{ m}^3/\text{s}$. The analysis of the mean flow velocity fields, obtained in a smooth floor VSF configuration (Tarrade 2007, Ballu 2017), showed that the flow was essentially two-dimensional. The 3D effect of the water drop stays local in depth. To visualize the effect of macro-roughnesses on the flow, the mean velocity field is represented on different horizontal planes located at $Z/b=0.5, 2$ and 4 for the smooth floor configuration (Figure 4) and $Z/h_r=0.75, 1.2$ and 4.5 for macro-roughnesses configuration (Figure 5). The velocity magnitude $\|V\|_{3D}$ is divided by the maximum velocity in the pool V_d ($V_d=\sqrt{2 \cdot g \cdot \Delta h}$ with g the acceleration of the gravity (m/s^2) and Δh the head (m)) located in the slot.

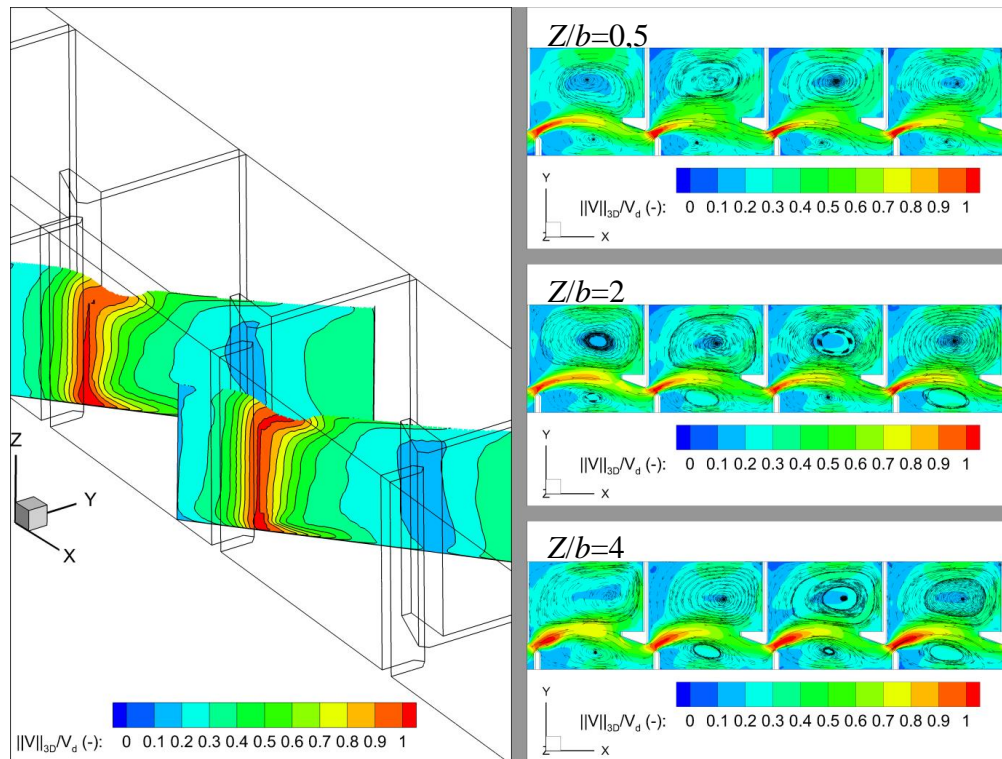


Figure 4. Mean velocity fields in a smooth floor configuration for $B/b=9$. Left: cutting planes in the middle of slots 2 and 3 (at 45°); right: horizontal planes at $Z/b=0.5, 2$ and 4 .

In the smooth floor configuration, the structure of the mean flow is similar in each pool (Figure 4). The jet exits the upstream slot and joins the downstream slot following a curved trajectory. It creates two counter-rotating recirculation areas whose shapes and positions don't vary significantly from one pool to another. The flow pattern observed on the different altitudinal planes confirms the essentially two-dimensional character of the flow (Wu et al. 1999, Puertas et al. 2004, Tarrade et al. 2011). Furthermore, the flow pattern is the same regardless of the pools of the VSF observed.

With regards to the macro-roughnesses configuration on the plane furthest from the floor ($Z/h_r=4.5$), the flow pattern has the same main shape from one pool to another. The jet has a curved trajectory, generating two counter-rotating recirculation areas on its left and on its right. The upper vortex is deformed with respect to the smooth floor configuration and its vortex center is offset downstream. At $Z/h_r=1.2$, the flow is globally identical in each pool. On the other hand, it appears more disturbed, especially for the upper vortex that has a less well defined shape. The mean flow patterns and the velocity field values obtained from these two water depths are similar to those measured by Bourtal (2012) using PIV measurements for a slope of 10% . The $Z/h_r=0.75$ plane makes it possible to visualize the average flow existing within the roughnesses in the canopy. The jet splits into two unsymmetrical parts when

meeting the first cylinder (macro-roughness). On the bottom of the different pools, the main part of the flow is directed to the right of the first cylinder directly to the second one located on the same line. It is then divided into two parts, which are rather symmetrical. It then continues to the downstream slot by following the paths formed by the alignment of the macro-roughnesses. The other part of the flow is directed to the left of the first cylinder towards the wall opposite the slot. It then encounters other macro-roughnesses aligned on a diagonal passing through the middle of the first cylinder and oriented at 60° with respect to the longitudinal axis. Thus, the jet is divided on a large part of the surface available in the canopy, generating numerous wakes area and facilitating the dissipation of the kinetic energy.

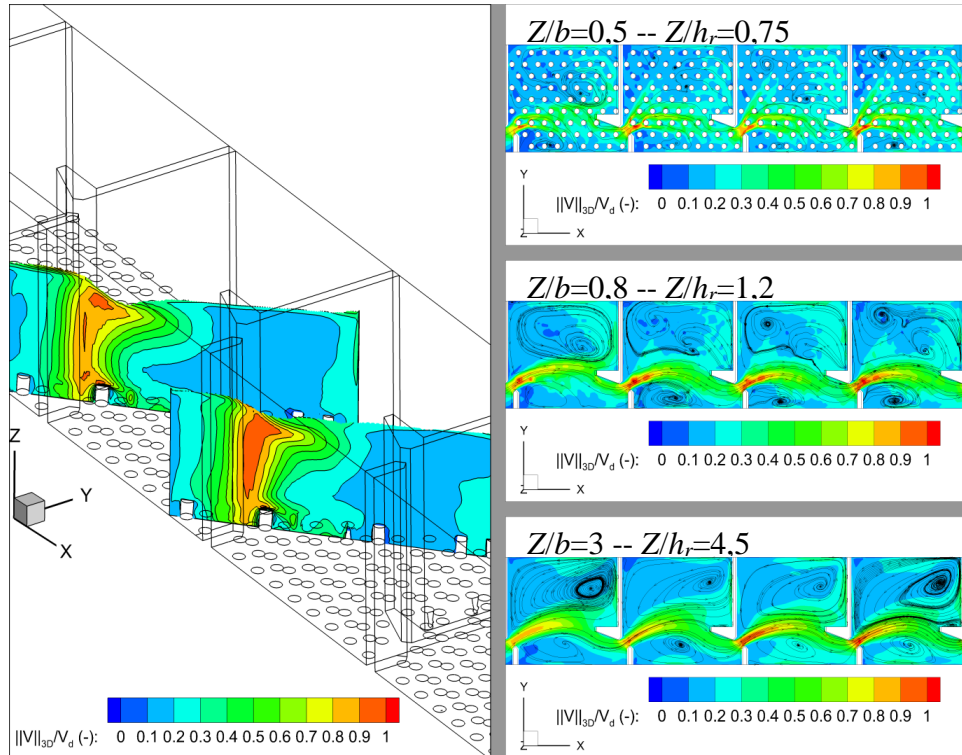


Figure 5. Mean velocity fields in configuration $d_r = 15\%$ for $B/b = 9$. Left: cutting vertical planes in the middle of slots 2 and 3 (at 45°); right: horizontal sectional planes at $Z/b = 0.5; 0.8$ and 3 , respectively, equivalent to $Z/h_r = 0.75; 1,2$ and $4,5$.

The iso-contours of the mean velocity field in the vertical planes passing through the middle of the slots (Figure 4) make it possible to demonstrate that the jet undergoes greater velocity variations on the water column in this configuration than in the case of a smooth floor configuration.

4. Influence of Macro-Roughnesses on the Unsteady Characteristics of the Flow

The flow inside a VSF is highly unsteady. Also, the analysis of only the mean characteristics of the flow may be insufficient to explain the behavior of the fish and the difficulties they may encounter. Tarrade et al. (2011) showed that the unsteady flow in the smooth floor configuration could be described by three successive main phases. Numerical simulation in LES allows to find those three unsteady phases in the smooth floor configuration (Figure 6). Bourtal (2012) found experimentally these three same phases in a configuration with macro-roughnesses whose density is identical to that studied here.

During phase (a), the jet has a curved trajectory oriented directly towards the downstream slot. It then tends to move towards the side wall and divides into two parts (phase (b)). The first part of the jet runs along the wall of the central deflector and the side wall, thus feeding the upper recirculation zone. The second part of the jet follows the inclined side of the central deflector and then out through the downstream slot. Finally, in phase (c), the jet adopts a more

pronounced curvature and feeds the lower recirculation zone (behind the upstream side deflector) whose shape evolves rapidly over time.

When the macro-roughnesses are present, the flow is three-dimensional and the unsteady phenomena, such as the fluctuations of the jet, are not necessarily of the same frequency and amplitude over the water column. To verify this, the instantaneous velocity fields of the three phases of the flow have been reported on Figure 7 on a plane $Z/h_r=3$ (parallel to the floor) and at the same times on a plane close to macro-roughnesses $Z/h_r=1.2$.

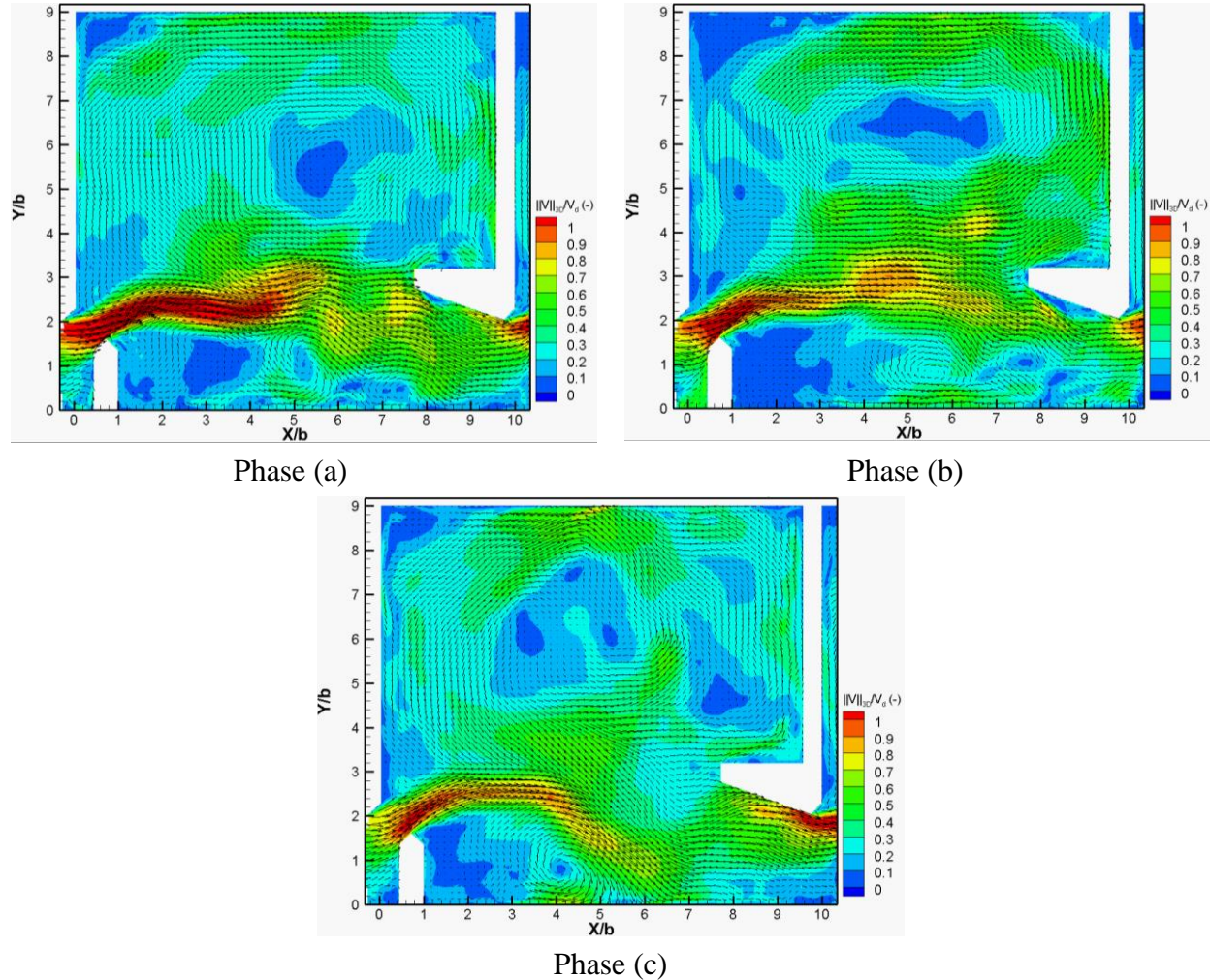


Figure 6. Instantaneous velocity fields resulting from the LES numerical simulation in the smooth floor configuration, characterizing the different phases of the flow (in the plane $Z/b=2$).

There are notable differences between the instantaneous velocity fields obtained above macro-roughnesses at $Z/h_r=3$ and those obtained in the smooth floor configuration. The flow is globally less intensive throughout the upper recirculation zone in the configuration $d_r=15\%$ in whatever phase is observed. This decrease of kinetic energy in the main flow is the consequence of the increase of the dissipation near the top of the macro-roughnesses in the rough sub-layer.

Between the two planes $Z/h_r=1.2$ and 3, the instantaneous structure of the flow at the different phases is not similar, in particular, during phase (b), where the velocity burst feeding the upper recirculation zone is not present. Furthermore, the velocity burst is not observed in the plane closest to the bottom ($Z/h_r=1.2$). This observation seems consistent with the analysis of the mean velocity field in which the upper vortex was strongly inclined, indicating that it was fed 'by the top' of the water column.

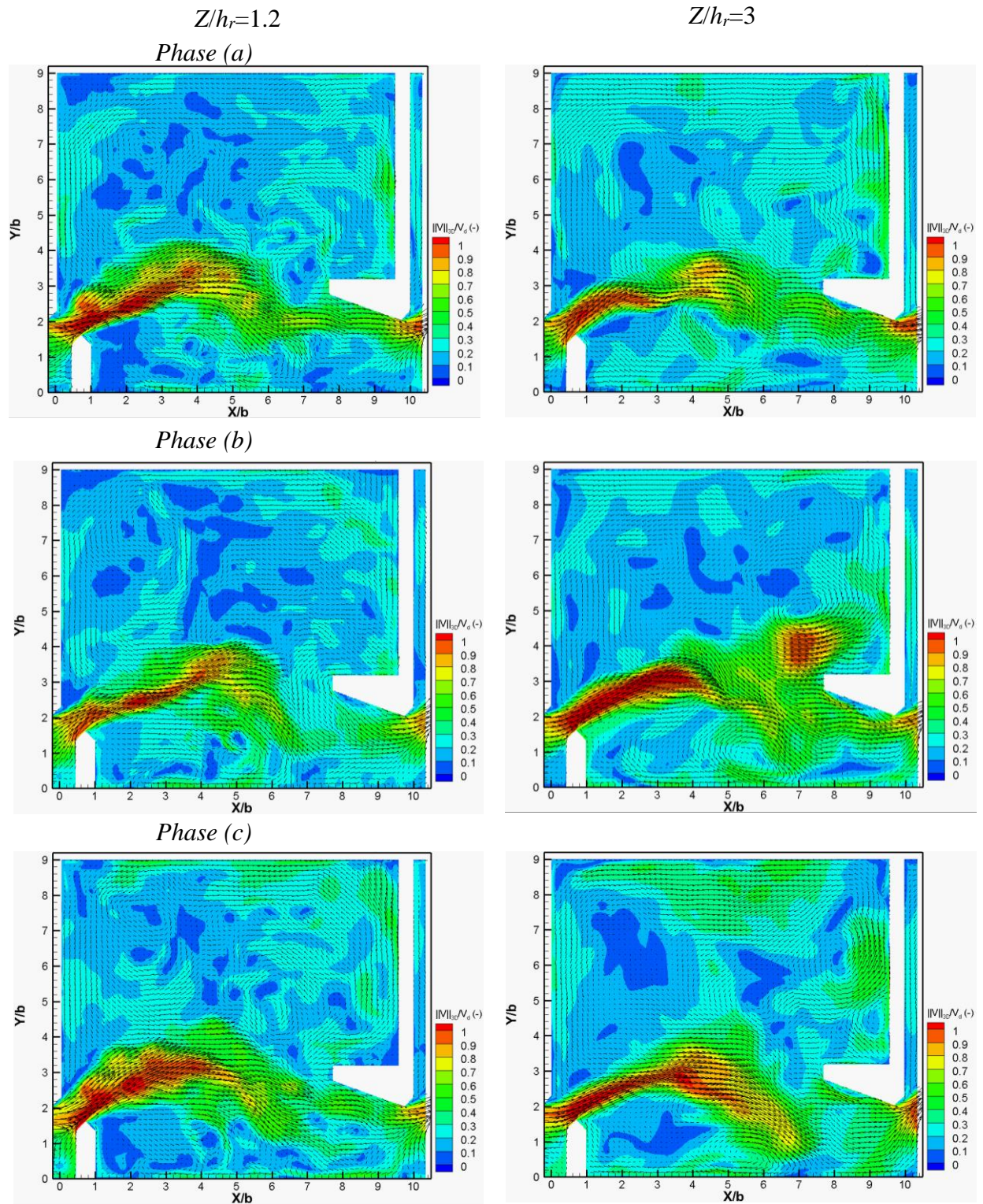


Figure 7. Instantaneous velocity fields resulting from the LES numerical simulation in the macro-roughness configuration, characterizing the different phases of the flow. Left: plane $Z/h_r=1.2$, Right: plane $Z/h_r=3$.

5. Conclusion

In this paper, the influence on the flow with the presence of macro-roughnesses fixed on the bed of a VSF was investigated using Large Eddy Simulation for one pool width, one slope of 7.5%, and a water discharge. The unsteady simulation allows the numerical modeling of the flow inside the pools and is in agreement with the flow observed in different experiments. With this powerful tool, two configurations with and without macro-roughnesses have been studied and compared. The presence of macro-roughnesses in the bottom of the pools doesn't modify the main flow topology compared to the flow with a smooth floor but increases the shear between the bottom to the free surface and also increases the three dimensionalities of the flow. The macro-roughnesses act directly to the flow by reducing the main velocity in a sub layer close to the bottom and accelerate the flow at the free surface.

Further works will characterize the effects of the macro-roughnesses with the pool width, the flow discharge and the density of macro-roughnesses.

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