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# Experimental characterization of the flow across fish-friendly angled trashrack models

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**Abstract:** *An experimental study of open channels flows across conventional and fish-friendly trashrack models in a towing tank is reported. Experiments are conducted for two kinds of trashracks, respectively comprised of fixed-width rectangular and profiled bars. Various trashrack orientation angles, bar-to-bar spacings and incoming flow velocities are investigated, while detailed Particle Image Velocimetry measurements are carried-out upstream and downstream of the trashracks in the streamwise-spanwise plane, along with pressure recordings. A stitching technique applied to the quasi time-resolved PIV snapshots allows a precise reconstruction of the flows, leading to the investigation of extended datasets. The flow analysis reveals significant effects of the various trashrack configurations on the topology of the flow, with a strong influence on the mixing layer and on the extent of the downstream recirculation region.*

**Keywords:** *Trashrack, Fish-friendly, Intake, Pressure loss, Towing tank, Particle Image Velocimetry*

## 1. INTRODUCTION

European directives RES (Renewable Energy Sources) and WFD (Water Framework Directive), French Ecologic continuity frameworks (Trame bleue, Plan de gestion de l'anguille) state the need for avoiding, or limiting, the mortality of fishes descending through hydropower plants, with a focus on Atlantic salmon and sea trout smolts and silver eels. One solution is to design fish-friendly water intake. Fish-friendliness consists in three aspects: ability to (1) stop and divert fishes from water turbines, (2) guide fishes towards secondary exit flows (by-pass) and (3) transfer fishes downstream the hydropower plant (Larinier and Travade 2002). Such a device can be designed using modified conventional intake trashracks, with respect to a range of biologic criterions.

Clear bar spacing ( $e$ ) must be reduced to 2.5 cm or less to induce an efficient behavioural repellent effect on smolts and to 1.5-2.0 cm to create a physical barrier for silver eels. The normal velocity through the rack ( $V_N$ ) should also not exceed 0.5 m/s to prevent premature passage of fish through (behavioural barrier) and fishes from being pressed against (physical barrier). To guide and transfer fishes, it is recommended to incline or angle the rack in order to create a significant tangential velocity along ( $V_T$ ), and to place fish by-passes at the downstream end of the rack (Courret and Larinier 2008).

A number of studies have focused on the adequation of such screens for fish diversion, with emphasis on the associated headlosses (Meusburger et al. 1999, 2001, Reuter et al. 2001). Some recent studies on the topology of the flows approaching angled trashracks have led to the establishment of prediction methods applied to the flow diverted through bypasses (Katopodis et al. 2005, Rajaratnam et al. 2006) or to the description of the flow characteristics across angled trashrack bars (Tsitaka et al. 2009).

But there still lacks information and methods to characterize topologies of flows approaching angled trashrack composed of conventional vertical bars, which would allow appreciating their fish-friendliness. The present study focuses on this trashrack configuration with an investigation of the influence of kinematic and geometric parameters on the flow topology. A particular attention is put on

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the balance between the normal and tangential flow approaching the trashracks.

As it has been shown that head-losses strongly depend on the geometry and spatial distribution of trashrack bars (Meusburger 1999, 2001), the significant orientation angles and small bar clear spacings required for fish-friendliness inevitably lead to higher head loss coefficients, potentially reducing the net drop exploited by hydro-power plants. Considering this aspect, it is expected that trashracks using simple, machinable, profiled bars may sensibly this effect to acceptable values.

## 2. EXPERIMENTAL PARAMETERS

The present study concerns angled trashracks, as sketched in Figure 1. The characteristic dimensions of the prototype and of the 1/2-scale experimental trashrack model are listed in Table 1.

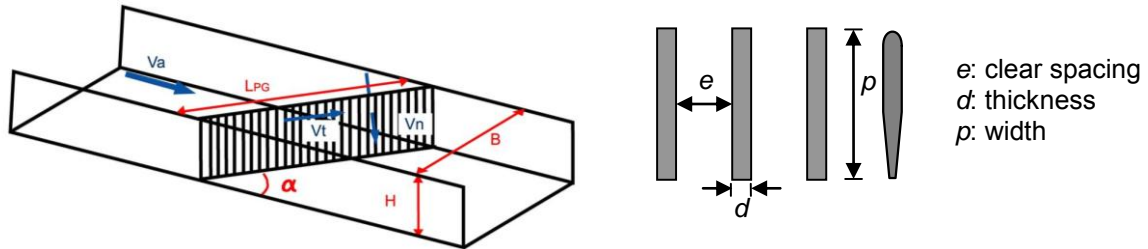


Figure 1: Oriented trashrack, with definition of normal and tangential approach velocities (left); studied rectangular and “hydrodynamic” bar profiles (right)

Table 1: Experimental parameters - Prototype and 1/2-scale model

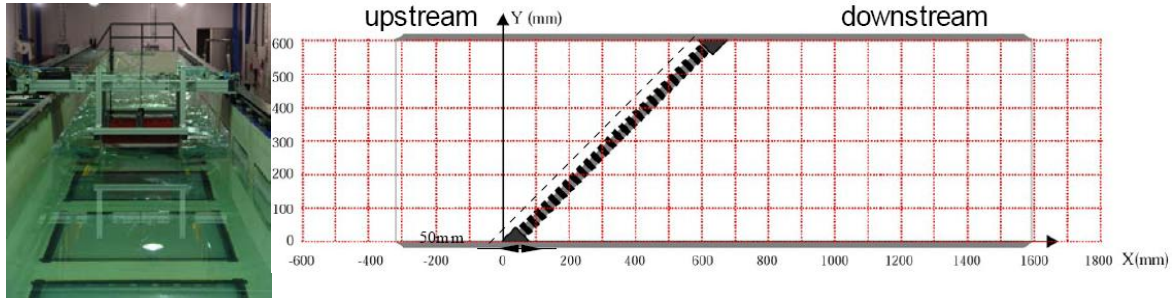
		Prototype (1:1)	Model ( 1:2)
<b>No Reynolds</b>		$5000 < Re_d < 11000$	$1750 < Re_d < 4000$
<b>No Froude</b>		$0.05 < Fr < 0.2$	$0.15 < Fr < 0.5$
<b>Approach velocity</b>		$0.5 \text{ m/s} < V_a < 1.1 \text{ m/s}$	$0.35 \text{ m/s} < V_a < 0.8 \text{ m/s}$
<b>Depth</b>		$3 \text{ m} < H < 10 \text{ m}$	$0,25 \text{ m} < H < 0.55 \text{ m}$
<b>Width</b>		variable	$B = 600 \text{ mm}$
<b>Bar</b>	<b>Width</b>	$p = 40 \text{ mm}$	$p = 20 \text{ mm}$
	<b>Thickness</b>	$d = 10 \text{ mm}$	$d = 5 \text{ mm}$
	<b>Spacing</b>	$10 \text{ mm} < e < 30 \text{ mm}$	$e = \{10 \text{ mm}, 15 \text{ mm}, 20 \text{ mm}, 30 \text{ mm}\}$
	<b>Blockage ratio</b>	$25\% < d/(e+d) < 50\%$	$14\% < d/(e+d) < 33\%$
<b>Angled trashrack</b>			
<b>Approach angle</b>		$\alpha = \{30^\circ, 60^\circ, 45^\circ\}$	
<b>Bar Profile</b>		Standard ; Hydrodynamic	

Due to load limitations on the carriage, the Froude similarity could not be fully achieved while ensuring Reynolds numbers leading to significantly turbulent flows. The model Froude number is then exceeding the prototype values by a factor 2.5 to 3, with a maximum value of 0.5.

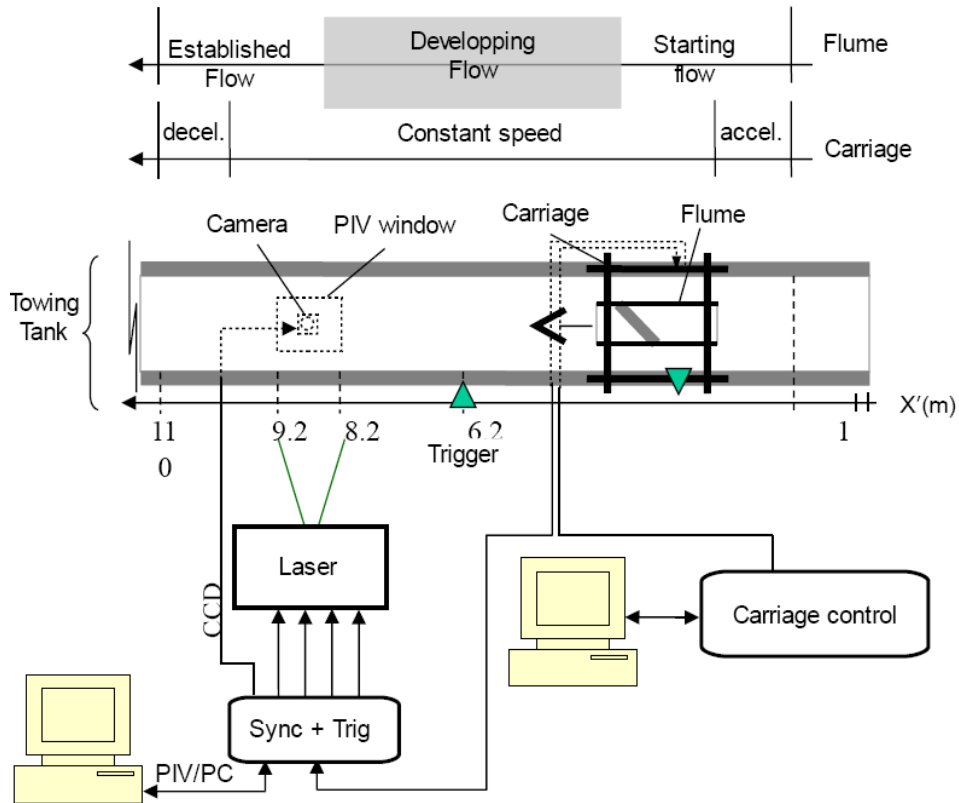
The geometric parameters of the study are the orientation angle  $\alpha$  and the bar spacing  $e$ . Two bar profiles are tested, the standard rectangular section profile and an “hydrodynamic” profile characterized by a circular leading edge and truncated trailing edge. These parameters relate to the work of Meusburger (2002) and span an extended range of fish-friendliness conditions.

### 3. EXPERIMENTAL SETUP

The experimental setup is comprised of 1.9m long, 0.6m wide and 0.5m high flume carried in 20m long a towing tank (Figure 1). Water level is set to  $h=0.3\text{m}$ , and the carriage velocities are set to 0.5m/s, 0.7m/s and 1.4m/s.



**Figure 2: Overview and dimensions of the experimental flume, with coordinate system and approach velocities measurement line.**



**Figure 3: PIV apparatus synchronized with carriage control system**

The flume is made of transparent material (PMMA) in order to allow Particle Image Velocimetry (PIV) Measurements. Static and Total pressure measurements are also carried out at different positions upstream and downstream of the trashrack.

The PIV apparatus is synchronized with the carriage control system, as sketched in Figure 2. The carriage control system allows acceleration and deceleration ramps, set to  $\pm 0.5\text{m/s}^2$  here, and constant velocity stages. External optical measurements have shown that the constant velocities are respected within a 0.01m/s range.

Pressure measurements have revealed the zones of starting, developing and established flow along the carriage displacement, allowing PIV measurements to be carried out within the established flow region. As shown in Table 2, the PIV interrogation window covers the entire width of the flume, so that a reconstruction of the velocity field upstream and downstream of the trashrack can be performed from

a single acquisition series. The reproductibility of these PIV measurements has been assessed, and shows that the accuracy of the synchronization between the carriage control and the imaging apparatus is less than  $3\mu\text{s}$ . It is also verified that the upstream flow is perfectly stationnary, whereas the downstream flow is logically turbulent, but exhibits an identical topology in all the experiments.

**Table2: PIV parameters**

<b>Laser</b>	Big Sky Laser, Quantel USA Nd-Yag double-cavity, 120 mJ
<b>Camera</b>	PULNIX Dual Tap AccuPiXEL 12bit, 2048*2048 px
<b>Lens</b>	Nikon 28mm
<b>Measurement plane</b>	$z=h/2=150\text{mm}$ ; $L_x*L_y=688\text{mm} * 688\text{mm}$
<b>Seeding</b>	RILSAN E5 Blanc 160 $\mu\text{m}$
<b>Synchronization / Acquisition</b>	RD Vision EG v.3.42 / Hiris v.4.1 5*2 images/s ( $V_c=0.5;0.7$ m/s) 6*2 images/s ( $V_c=1.4$ m/s)
<b>PIV Software</b>	LaVision Davis 7.2 Multi-passe: 64x64@75% ; 32x32@50%
<b>PIV Algorithm</b>	Normalized FFT Cross-Correlation Multi-pass with window shifting and iterative deformation - Pass 1-2 : 64x64 pixels - 75% overlapping - Pass 3-5 : 32x32 pixels – 50% overlapping Subpixel interpolation on last pass

The use of a towing tank for this kind of experiments significantly extend the range of available approach velocities but doesn't allow a precise control of the entry flow, which is sensibly influenced by the headlosses generated by the trashrack. Thus, approach velocities of 0.3m/s, 0.4m/s and 0.75m/s, chosen within the range defined in Table 1, are obtained for 0.5, 0.7 and 1.4m/s carriage velocities, respectively, and cannot be strictly identical for each trashrack configuration. The intake water level is fixed at  $h=0.35\text{m}$  and is unchanged during the carriage run, leading to approach Froude numbers of 0.16, 0.27 and 0.38.

Depending on the carriage velocity and the corresponding imaging frequency, reconstructed upstream velocity fields are obtained using 3 ( $V_c=1.4\text{m/s}$ ), 5 ( $V_c=0.7\text{m/s}$ ) or 7 ( $V_c=0.5\text{m/s}$ ) consecutive velocity fields. The downstream flow can also be reconstructed using 3 ( $V_c=1.4\text{m/s}$ ), 11 ( $V_c=0.7\text{m/s}$ ) or 14 ( $V_c=0.5\text{m/s}$ ) velocity fields, but the strongly aerated downstream flow for  $V_c=1.4\text{m/s}$  cannot be optically investigated for locations exceeding  $X=1100\text{mm}$ . Finally, the flows approaching and issuing from the trashrack can be analysed up to a minimal distance of 50mm from the bars leading and trailing edge.

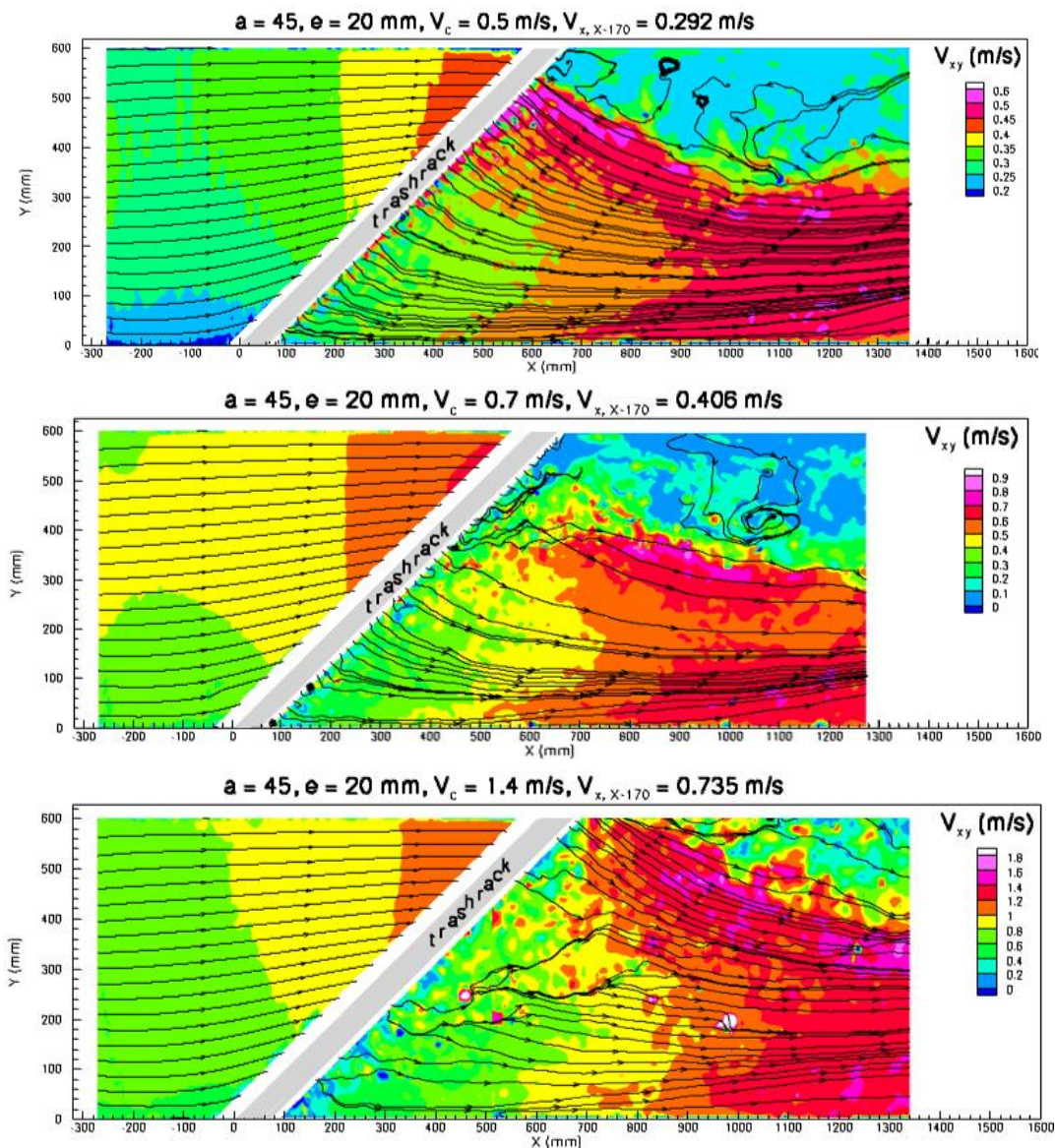
## 4. RESULTS

Qualitatively, an angled trashrack generates a strongly confined flow in the downstream part of the grid ( $Y>B/2$ ). A tangential flow is then created, which competes with the lateral boundary and the normal flow induced by the orientation of the bars (Figures 4 and 5). In the reference configuration ( $\alpha=45^\circ$ ,  $e=20\text{mm}$ ), the incoming flow is clearly deflected tangentially to the trashrack, and then normally along its bars, as it can be easily observed for both the hydrodynamic and standard profiles in Figures 4 and 5. Depending on the local ratio between these normal and tangential flows, the flow may be deflected of  $30^\circ$  to  $60^\circ$  in the 50mm zone preceding the grid, before issuing normally in the downstream region. Downstream jets created in the clear spacings of the trashrack are also clearly observable, and result in an exclusively normal flow associated to a large recirculation region which covers half the width of the flume. Longitudinally, this region covers approximately two flume widths. The blockage effect induced by this topology generates an accelerated confined flow which holds the totality of the exit flow. Again, the normal downstream flow competes with the opposite lateral boundary, and is deflected to a longitudinal flow, which tends to limit the extent of the recirculation region. To some extent, these observations can be compared to the results obtained by Tsitaka et.al.

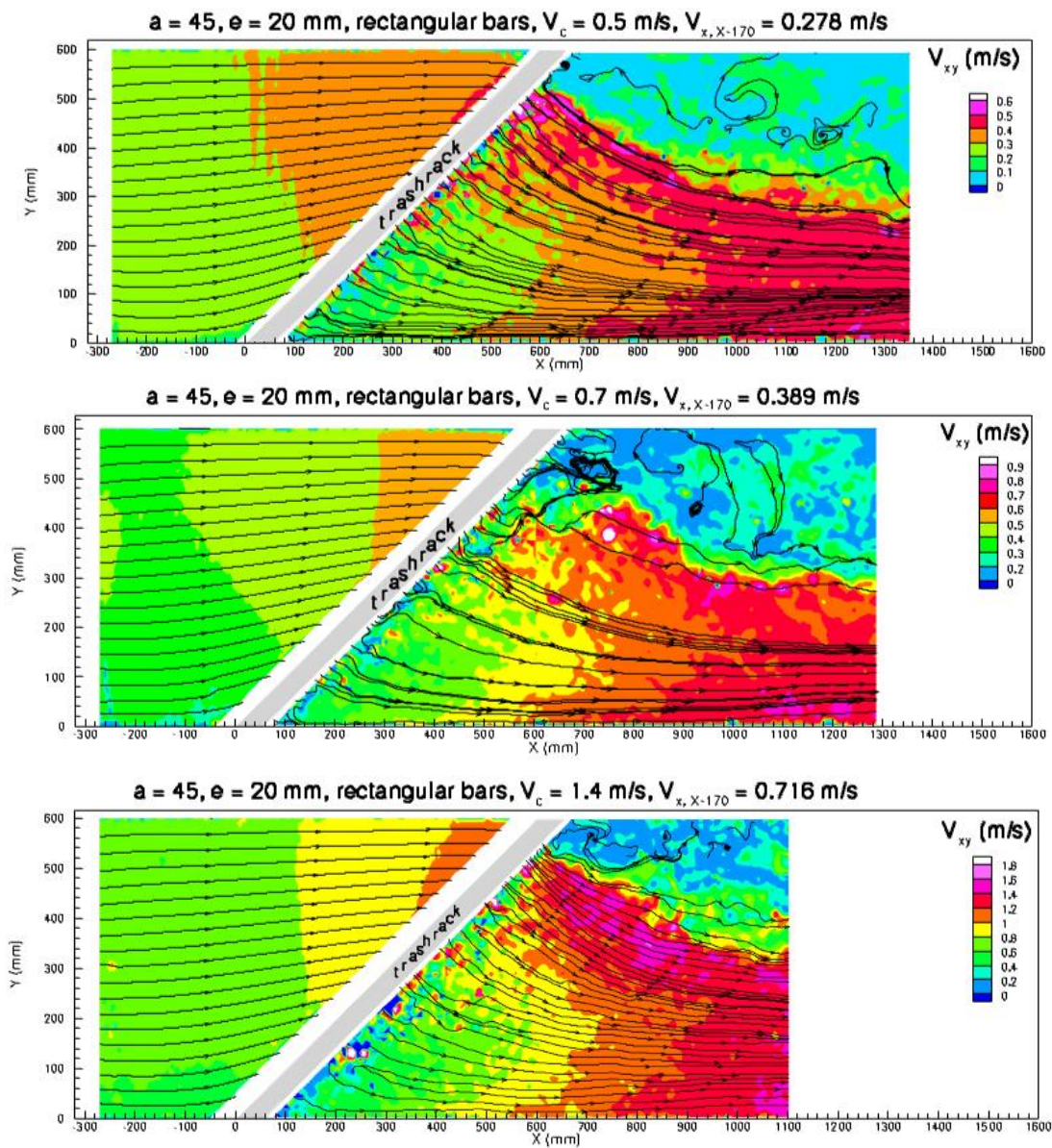
(2009), for which the initial deflexion is created by the oriented bars only.

Despite the significant confinement of the upstream flow, continuity - computed from the 2-component PIV results - is preserved in this region, showing that the flow can be considered quasi two-dimensional up until the leading edge of the trashrack. Comparatively, the downstream flow is clearly turbulent and three-dimensional, with instantaneous streamlines revealing attractive or repulsive foci, and 2D-continuity not being preserved.

Flow observations also reveal a strongly inhomogenous water level immediately behind the trashrack, corresponding to the discharge of the flow confined along the trashrack. Pitot tubes measurements carried out in the up- and downstream regions support these observations, though they cannot provide reliable quantitative data in the downstream non stationary flow.



**Figure 4: Reconstructed instantaneous upstream and downstream velocity fields for an angled trashrack with hydrodynamic bars and clear spacing  $e=20\text{mm}$  (reference case)  $V_c=0.5;0.7;1.4\text{m/s}, H=0,35\text{m}$ .**

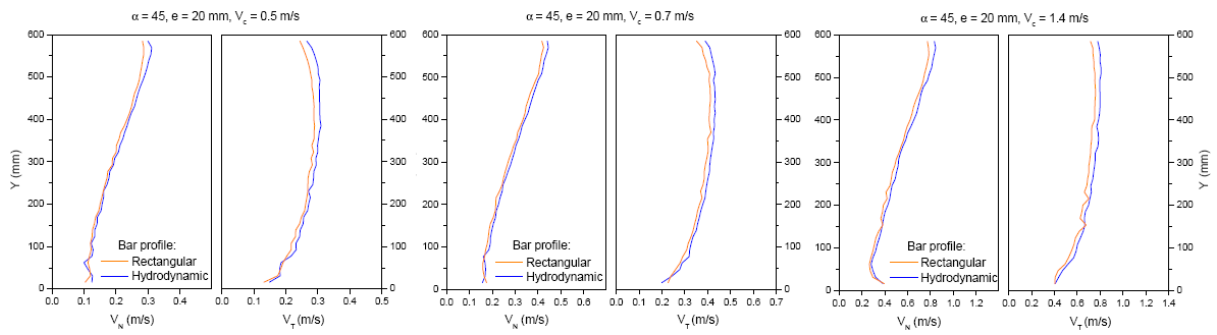


**Figure 5: Reconstructed instantaneous upstream and downstream velocity fields for an angled trashrack with rectangular bars and clear spacing  $e=20$ mm.  $V_c=0.5;0.7;1.4$ m/s,  $H=0,35$ m .**

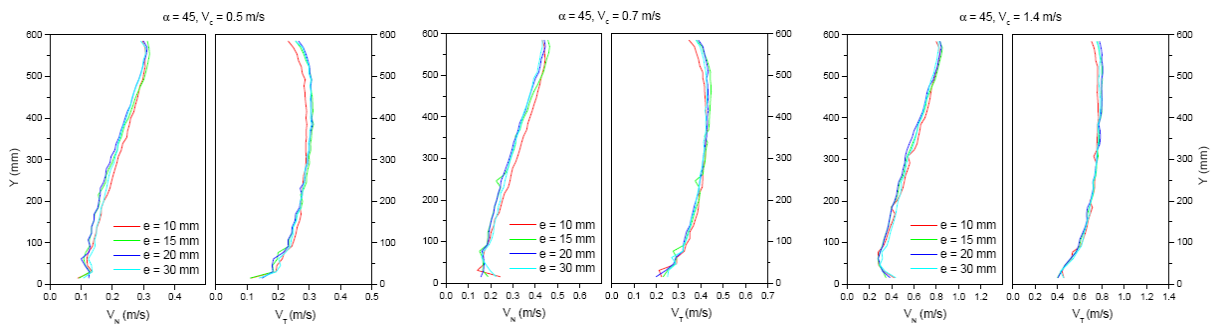
Fish-friendliness of the trashracks must be assessed with reference to the distribution of normal and tangential approach velocities, and compared with the biological criteria retained in Courret and Larinier (2008). These approaching velocity profiles have been measured along a line parallel to the trashrack plane and situated 50mm upstream of the grid (Figure 1). Here, attention is put on the value of these velocity components and on their ratio in order to reveal zones where bypasses may be successfully installed.

First, Figures 6 to 8 indicate that the normal and tangential velocities typically illustrate the confined flow, with a mostly tangential direction in the upstream part of the grid, and a normal flow gradually, mostly linearly, increasing towards the upstream confinement zone ( $Y>B/2$ ). Both the maximum tangential and normal approach velocities are of the same order of the entry velocity, which results in the biological limit being locally exceeded for  $V_c=1.4$ m/s. It can also be observed on Figure 9 that the ratio  $V_T/V_N$  changes significantly along the grid line, exhibiting a maximum value of 2 for the reference case and decreasing to approximately 1 near the boundary, this unit ratio being preserved across the boundary layer.

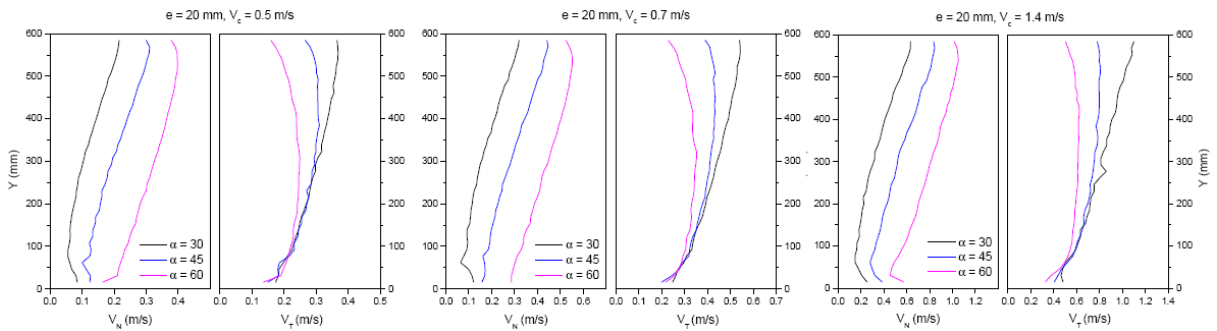




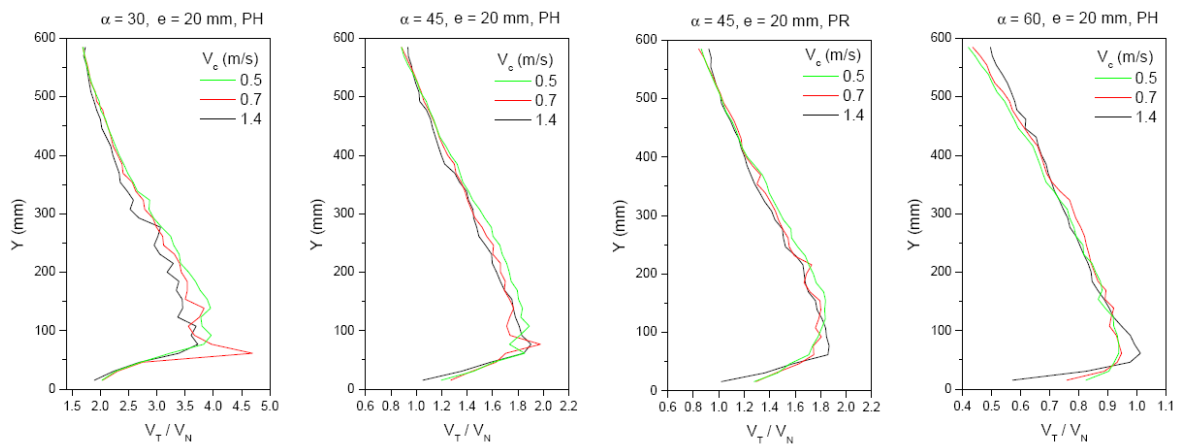
**Figure 6: Normal and tangential approach velocities : influence of bar profile**



**Figure 7: Normal and tangential approach velocities : influence of clear spacing**



**Figure 8: Normal and tangential approach velocities : influence of orientation angle**



**Figure 9: Ratio of normal to tangential approach velocities : influence of profile and orientation**

For all cases, increasing the Reynolds number sensibly favors the tangential flow in the boundary layer near  $Y=B$ , which results in a slightly increased  $V_T/V_N$  ratio in this zone.

Figures 4 and 5 indicate that rectangular or “hydrodynamic” bar profiles lead to identical upstream and downstream flow topologies, and similar approach velocities (Figure 6). However, the hydrodynamic profile slightly favors both the tangential and normal flows, with up to 8% increase near the  $Y=B$  boundary.

The clear spacing parameter doesn't influence the flow topology nor the distribution of approach velocities (Figure 7), which indicates that this within this range of blockage ratios, this fish-friendliness criterion may not be a significant limiting factor in terms of hydraulic efficiency.

Logically, the orientation parameter is the most influencing factor in terms of topology and distribution of approach velocities. Compared to the reference case, a  $30^\circ$  orientation angle leads to a 7% decrease of the entry velocity, whereas a  $60^\circ$  angle leads to a 18% increase. In these experimental conditions, such variations illustrate the head-losses to be expected.

## 5. CONCLUSION

The flow across oriented trashracks has been investigated over a set of geometric configurations relating to commonly identified fish-friendliness criteria. Pressure and PIV measurement carried out in a trashrack model installed in a towing tank have revealed topological aspects of the flow upstream and downstream of the grid plane.

These results will allow to establish parametric formulations characterizing the topologies of flows approaching angled trashrack, of the type :  $V_{N,y} = f ( y/B ; \alpha ; V_A , e , \dots )$ . The aim is to be able to examine the compliance with the criteria of fish-friendliness on normal and tangential velocities, whatever configuration of angled trashrack.

The use of “hydrodynamic” profiles results in velocity distributions which may favorize bypass flows while regularizing the flow approaching and leaving the trashrack. The trashrack rigs are currently undergoing an additional experimental campaign in order to confront these observations with head-loss and time-resolved localized velocity measurements.

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