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An experimental study on fish-friendly trashracks – Part 2. Angled trashracks

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ABSTRACT

Experimental results for fish-friendly trashracks placed in an open water channel are presented. Model trashracks with different bar shapes, spacing and angles were tested. The numerous configurations provided results on head losses and on changes in velocity along the rack for a large range of situations, including fish-friendly trashracks. Previous head-loss equations found in the literature were applied to these configurations and were compared with measurements. A new head-loss equation is proposed that takes into account the effect of the different tested parameters. Velocity measurements provided new results and answers concerning downstream-migration aspects such as admissible approach velocities and guidance efficiency as a function of the trashrack angle.

Keywords: Angled trashrack; downstream migration; experimental hydraulics; head loss; velocity distribution

1 Introduction

Fish mortality caused by turbines at hydroelectric plants during the downstream migration of fish is increasingly taken into account in Europe and particularly in France (Travade and Larinier 2006, Travade *et al.* 2010), in the context of (1) restoration of amphibiotic species, such as salmon (*Salmo salar*) and sea trout (*Salmo trutta*), (2) the European Council regulation (no. 1100/2007) for the recovery of European eel stocks

(*Anguilla anguilla*) and (3) the restoration of the ecological continuity for the good ecological status of rivers aimed by the European Water framework directive (2000/60/EC).

To address the downstream-migration issue, the solution studied here is generically called “fish-friendly trashracks” and consists of an adaptation of conventional trashracks used at intakes to stop debris (Courret and Larinier 2008). Such trashracks must prevent fish from passing through and be implemented with bypasses in order to allow a safe downstream passage. More

details on the design criteria of fish-friendly intakes are provided in Part 1 (Raynal *et al.* 2012).

This second part, addressing angled trashracks, completes the first part on inclined trashracks (Raynal *et al.* 2012). It focuses on head losses, an important issue for hydroelectric operators, and on velocity distributions which influence the fish behaviour near the trashrack.

Several equations have been proposed to assess the head losses due to angled trashracks.

Mosonyi (1966) extended Kirschmer's (1926) equation, which was proposed for vertical or inclined trashracks, to include trashracks set at an angle α from 90° (trashrack perpendicular to the channel) to 30° . The Kirschmer–Mosonyi equation (Eq. 1) includes the bar-shape factor K_F used by Kirschmer (1926), the ratio between the bar spacing e and the bar thickness b , as well as a multiplicative term $K_{K.-M.}$, whose value depends on (e/b) and on the angle α of the approach flow. Mosonyi provided tabulated values of $K_{K.-M.}$ for a discrete number of cases

$$\xi_{Kirschmer-Mosonyi} = K_F \left(\frac{b}{e} \right)^{4/3} K_{K.-M.} \quad (1)$$

Idel'cik (1979) proposed a relationship in chart form where the head-loss coefficient is the product of two terms, one depending on the bar shape and the rack angle α , the other depending on the ratio (b/e) and on α . According to this formulation, the effect of the bar shape should vary with the angle of the rack.

Meusburger (2002) proposed an equation with a broader field of application (Eq. 2), where the blockage ratio O_g and the rack angle are coupled. However, his equation used the K_F bar shape coefficient from Kirschmer (1926), without considering a possible coupling between the rack angle and the bar-shape

$$\xi_{Meusburger} = K_F \left(\frac{O_g}{1 - O_g} \right)^{1.5} \left(\frac{\alpha}{90^\circ} \right) O_g^{-1.4 \tan(90^\circ - \alpha)} \quad (2)$$

Clark *et al.* (2010) also proposed a similar, but simpler equation that was obtained from experiments with angled trashracks with α between 90 and 60° and for a single e/b ratio of 4.41

$$\xi_{clark} = 7.43 \eta [1 + 2.44 \tan^2(90^\circ - \alpha)] O_g^2 \quad (3)$$

Except for Mosonyi (1966), all the above equations were obtained from experiments carried out in specific flume configurations which all involved oblique approach flows. Because these configurations were designed to align the downstream flow with the trashrack bars, they are not representative of hydroelectric plants where angled racks are inserted inside a straight forebay channel.

Zimmermann (1969) investigated different types of angled trashrack. The entire channel was straight and the trashrack was perpendicular to the channel, with bars that could be rotated with α from 90 to 45° . The resulting equation (Eq. 4) takes into

account the coupling between the ratio (b/e) and α and also adds the ratio of the bar thickness b to the bar depth p , highlighting the effect of the bar depth on head losses.

$$\xi_{Zimmermann} = 3.87 \tan^{7/4}(90^\circ - \alpha) + K_F \left(\frac{b}{p} \right)^{4/3} + \frac{K_F}{\sin^3(\alpha)} \left[\left(\frac{b}{e} \right)^{4/3} - \left(\frac{b}{p} \right)^{4/3} \right] \quad (4)$$

Meusburger *et al.* (2001) also included this effect in the calculation of trashrack head losses, but only one bar depth was tested.

The applicability of the equations quoted above has not been systematically assessed for racks with small bar spacings or set to low angles. This paper reports on experimental investigations carried out in a straight flume in which a different type of angled trashrack was inserted (Fig. 1), to check these equations and to extend them to trashracks with low inclination angles and narrow bar spacing. The interdependence of the different parameters was analysed over a wide range of configurations.

A characterization of flow velocities along the rack was also conducted to estimate the magnitude of currents likely to guide fish. Other studies focusing on velocities also exist. Tsikata *et al.* (2009) measured velocities around vertical racks comprising a small number of bars using particle image velocimetry (PIV). However, they focused on the flow between and around bars, whereas the present study was more interested in the velocity distribution along and downstream of the entire rack. Katopodis *et al.* (2005) measured velocities along angled wedge-wire screens, with $\alpha = 10.4, 17.5$ and 26.8° . Some of their configurations were similar to ours and the velocity values were compared to those measured in the present study.

Section 2 describes the experimental set-up and presents the main characteristics of the hydraulic installation, the model trashrack and the different measurement devices. Section 3 focuses on head losses and provides a comparison with the existing equations and proposes a new equation for fish-friendly trashracks. Section 4 analyses the velocity profiles. These results are then discussed and recommendations are made for the design of fish-friendly water intakes with angled trashracks.

2 Experimental set-up

The experiments were carried out with the equipment described in Part 1 (Raynal *et al.* 2012). The model trashrack, composed of elements scaled to half size, was placed in a 10-m long open channel that was 0.9 m deep and 0.6 m wide (B). Bars were 5 mm thick (b), 40 mm deep (p), 0.52 m long (L_g) and had either a rectangular (PR) or a more hydrodynamic (PH) shape (Fig. 1).

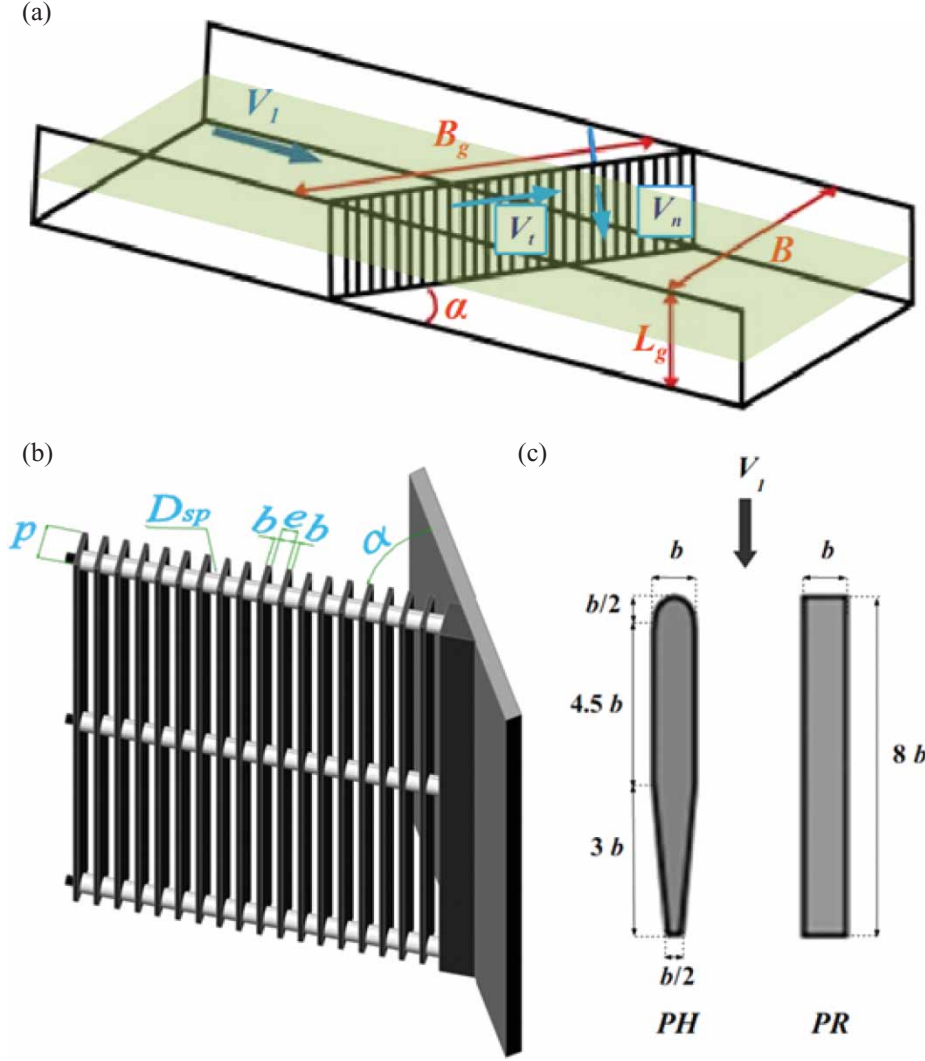


Figure 1 Representation of the angled trashrack in the channel (a) and details on the initial segment of the trashrack (b) with the two bar shapes tested (c). The green plane on the overall view represents the position of the laser sheet in PIV measurements

For a given trashrack angle α , the number of bars was determined as a function of b and e . Different spacers were inserted around rods. Their diameter (D_{sp}) was always 20 mm. The minimum space between bars e was 5 mm, i.e. equal to the bar thickness. Other values for e were 7.5, 10 and 15 mm. These values reproduced real bar spacings between 10 and 30 mm and e/b ratios between 1 and 3.

For each configuration, the sides of the trashrack were attached to the flume using specific triangular support (Fig. 1). Four trashrack angles were tested, covering most configurations in real hydraulic plants. The smallest angle was $\alpha = 30^\circ$ and the other angles were $\alpha = 45, 60$ and 90° (trashrack perpendicular to the channel). The rack was vertical ($\beta = 90^\circ$).

A comparison of the extreme values for the trashrack angle and the bar-spacing in our experiment and in other studies is shown in Table 1. All the possible combinations between α and e/b have not necessarily been investigated.

All the elements described above determine the trashrack blockage ratio O_g , which appears in some head-loss equations.

Table 1 Comparison of minimum and maximum α and e/b values in different studies

	α ($^\circ$)		e/b	
	Min	Max	Min	Max
Kirschmer–Mosonyi (1966)	30	90	1	5
Zimmermann (1969)	45	90	2.3	14.3
Meusburger (2002)	60	90	1	9
Clark <i>et al.</i> (2010)	60	90	1.75	11.6
This study	30	90	1	3

O_g may be broken down into two variables (Eq. 5), one representing the lateral blockage ratio O_b due to the bars and the other the blockage ratio O_{sp} due to rows of spacers

$$O_g = O_b + O_{sp} \quad \text{with} \quad O_b = \frac{N_b b + 2b_{ext}}{B_g};$$

$$O_{sp} = (1 - O_b) \frac{N_{sp,im} D_{sp}}{L_{g,im}} \quad (5)$$

where N_b , b , b_{ext} , B_g , $N_{sp,im}$, D_{sp} and $L_{g,im}$ are, respectively, the number of bars, the bar thickness, the thickness of the specific triangular support, the trashrack width, the number of immersed spacer rows, the spacer diameter and the immersed bar length. For a vertical angled rack, $L_{g,im} = H_1 \approx 350$ mm.

The flow rate Q (about 130 l/s), measured by an electromagnetic flowmeter, and upstream and downstream water depths (respectively H_1 and H_2), measured with thin plates that were set flush with the free surface at $x = 1$ m and $x = 2.6$ m, respectively ($x = 0$ m at the upstream end of the rack), were sufficient to calculate mean velocities (V_1 and V_2) and head losses. Because head losses are higher for angled trashracks than for inclined ones, the velocities downstream of the trashrack are quite important. Given the diversion of the flow due to the trashrack, the free surface was highly disturbed and water-depth measurements were subject to larger errors. However, in most cases, this accounted for only 5% of the head loss. Upstream and downstream water depths and mean velocities provided the overall head loss from which the part due to the channel ΔH_0 was subtracted. The result was the head loss due to the rack ΔH , thus making it possible to determine ξ (Eq. 6)

$$H_1 + \frac{V_1^2}{2g} = H_2 + \frac{V_2^2}{2g} + \Delta H + \Delta H_0; \Delta H = \xi \frac{V_1^2}{2g} \quad (6)$$

The PIV measurements previously carried out in a towing tank by Chatellier *et al.* (2011) were completed with 3D-acoustic Doppler velocimetry (ADV) measurements. A Sontek/YSI 16-MHz MicroADV coupled with a 2D-traverse system acquired velocity profiles at a 50 Hz sampling rate for all the trashrack configurations.

Head-loss and ADV measurements were carried out for 32 different combinations of 2 bar shapes, 4 bar spacings and 4 rack angles.

3 Trashrack head-loss coefficient

The invariance of the head-loss coefficient with the Froude and the Reynolds numbers was discussed in Part 1 (Raynal *et al.* 2012), in which the applicability of the experimental results to actual installations was proved for rectangular bars. For profiled bars, the behaviour of ξ for full-scale R_b values had to be assumed on the basis of the behaviour of $\xi(R_b)$ for rectangular bars.

Figure 2 shows, for each bar shape, the changes in measured head-loss coefficients ξ as a function of the bar spacing and the rack angle. For a perpendicular rack ($\alpha = 90^\circ$), the rack was identical to that with $\beta = 90^\circ$ in Part 1. Therefore, the head-loss coefficient for vertical racks perpendicular to the flow still depends on the bar shape and on the blockage ratio O_g , i.e. on the bar spacing e , the bar width b and the spacer diameter D_{sp} . For angled trashracks ($\alpha < 90^\circ$), the two diagrams illustrate that ξ increases with the decreasing rack angle α . It also appears that the rack angle has less influence for high blockage ratios than for low blockage ratios and for *PR* bars than for *PH* bars.

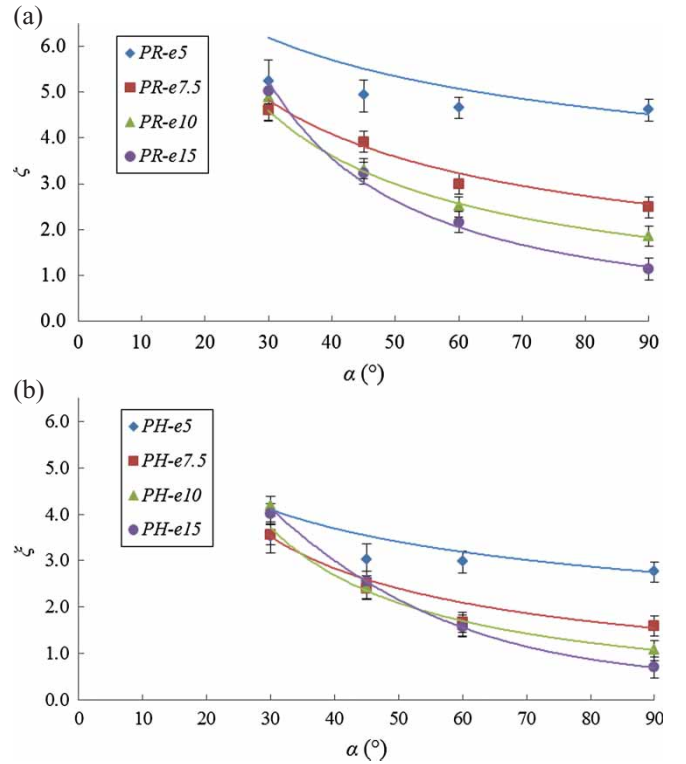


Figure 2 Variation of measured (marks) and predicted (lines) ξ for two bar shapes (rectangular shape *PR* and hydrodynamic shape *PH*) and different bar spacings, as a function of α

The equations found in the literature suggest that the effect of the rack angle may depend on three parameters: the blockage ratio O_g (or at least the ratio b/e), the bar shape and the ratio b/p . This means that the part of ξ dealing with the angle of the rack should include all three parameters. However, during this study, bar depth and thickness were fixed, with $p = 40$ mm, $b = 5$ mm and $b/p = 0.125$. Therefore, the study focused only on the two first parameters.

Figure 3 compares, for *PR* bars and two different bar spacings, the head-loss coefficients measured in the present study and those predicted by Mosonyi (1966), Zimmermann (1969), Meusburger (2002) and Clark *et al.* (2010). For both bar spacings, few equations produce results consistent with the measured coefficients:

- Head-loss coefficients given by the Kirschmer–Mosonyi equation are far too low.
- Head-loss coefficients given by the Zimmermann's (1969) equation are too low at $\alpha = 90^\circ$, which may be due to the fact that Zimmermann did not take into account the horizontal elements. Then, for lower α values, the coefficients quickly rise above the measured ones. This means that this equation, which is adapted to configurations with rotating bars in a rack perpendicular to the channel, cannot be applied to configurations in which the entire trashrack is angled.
- Head-loss coefficients given by the Clark *et al.* (2010) equation differ widely from the measured ones for $e = 7.5$ mm (or

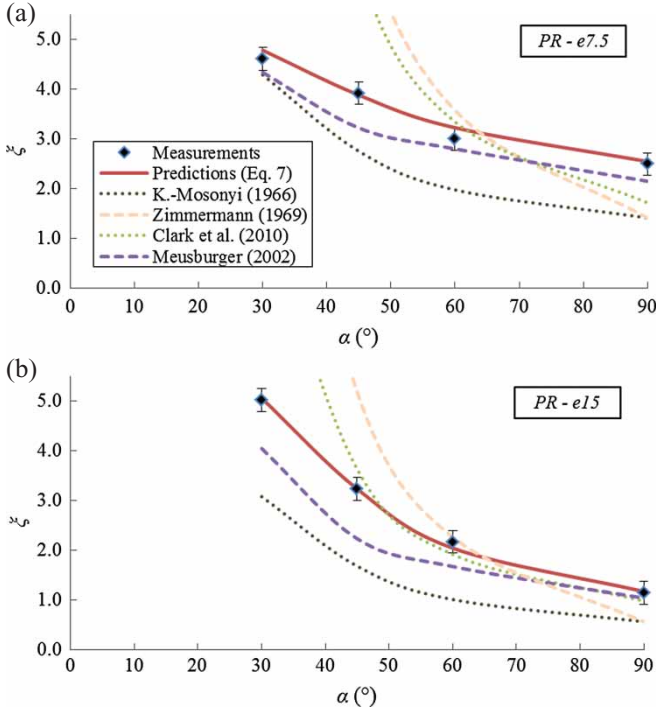


Figure 3 Comparison of measured head-loss coefficients and coefficients predicted by the quoted equations. Bars are rectangular and $e = 7.5$ mm, i.e. $e/b = 1.5$ (a) and $e = 15$ mm, i.e. $e/b = 3$ (b)

$e/b = 1.5$). For $e = 15$ mm (or $e/b = 3$), their coefficients are rather close, but diverge at lower angles ($\alpha < 45^\circ$).

- Meusburger's (2002) equation is the only one that shows good accuracy with our experimental data, though they slightly underestimate head-loss values in configurations with low rack angles, for which the channel alignment may have greater influence. This equation differs from the others in that it includes the blockage ratio in the part dealing with the angle of the rack.

For PH bars, even Meusburger's (2002) equation produces head-loss coefficients 30–60% lower than the measured values.

The difference between our configuration (angled racks inserted inside a straight channel) and the configuration of other authors may partly explain some of the discrepancies. However, the prediction accuracy also depends on the variables considered in each equation. The comparison of these five equations and our measurements highlighted the necessity of taking the link between the bar shape, the blockage ratio O_g and the rack angle α into account.

Thus, we have provided a new equation (Eq. 7, Figs. 2 and 3),

$$\begin{aligned} \xi &= K_i \left(\frac{O_g}{1 - O_g} \right)^M K_\alpha \text{ with } K_\alpha(K_F, O_g, \alpha) \\ &= 1 + k_i \left(\frac{90^\circ - \alpha}{90^\circ} \right)^{2.35} \left(\frac{1 - O_g}{O_g} \right)^3 \end{aligned} \quad (7)$$

in which K_i is either K_{PR} or K_{PH} depending on the bar shape.

To fit the measured head-loss coefficient for perpendicular trashracks, we determined bar shape coefficients $K_{PR} = 2.89$ and $K_{PH} = 1.70$ for rectangular and hydrodynamic bars, respectively, and $M = 1.6$. The expression of K_α meets the following boundary condition: $K_\alpha \rightarrow 1$ when $O_g \rightarrow 1$ and $K_\alpha = 1$ when $\alpha = 90^\circ$. The dependence of K_α on the bar shape is taken into account through the coefficient k_i , whose values are $k_{PR} = 1.69$ and $k_{PH} = 2.78$. The correlation coefficient, calculated for all the measured head-loss coefficients and those predicted by Eq. (7), was approximately 96.8%. The influence of the bar depth has not yet been included in this equation and further experiments with different b/p ratios must be carried out to further validate or enhance it. The proposed equation is applicable to trashracks inserted in a straight channel, with blockage ratio O_g between 36 and 60%, angle from wall α between 90° (perpendicular to flow) and 30° , and for rectangular or profiled bars with horizontal spacers and b/p ratio close to 0.125. This includes the configurations of angled fish-friendly trashracks with narrow spaces between bars.

4 Velocity distribution along an angled rack

ADV measurements were carried out on the trashrack in a large range of configurations in order to complete the PIV measurements provided by Chatellier *et al.* (2011). In Part 1, the comparison of ADV and PIV techniques showed that the two systems produced complementary results.

The streamlines superimposed on colour maps in Fig. 4 show the overall results for angled racks. Two specific results should be mentioned.

- The flow accelerated towards the end of the trashrack partly due to containment by the wall. The maximum U value for $\alpha = 60^\circ$ was almost $1.4V_1$, whereas U increased up to $2V_1$ for $\alpha = 30^\circ$.
- Upstream of the rack, streamlines were mainly streamwise. This observation did not take into account what occurred in the zone nearest the rack (within about 20 mm).

Figure 5 shows the flow pattern downstream of an angled trashrack. Streamlines were modified by the angle of the bars. At the downstream end of the trashrack, this diversion created a fairly large recirculation zone, which led to a contracted and accelerated flow on the opposite side. The flow downstream of the trashrack was asymmetric and disturbed, which could impact turbine performance. This contrasted with inclined trashracks for which downstream disturbances were limited (Raynal *et al.* 2012).

All these general observations obtained via the PIV measurements were completed with ADV profiles, providing a more detailed view of the velocity distribution along the rack in a larger range of configurations. The normal and tangential velocity components were measured along a profile located

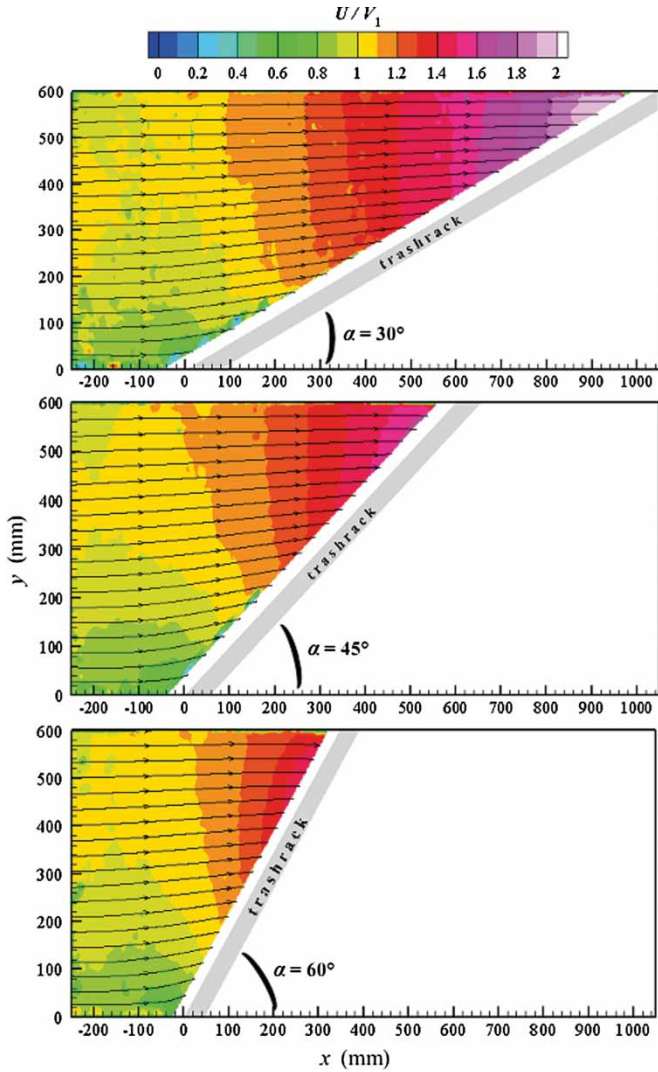


Figure 4 Velocity maps (normalised streamwise U/V_1) upstream of an angled trashrack with $\alpha = 30, 45$ and 60° (from Chatellier *et al.* 2011)

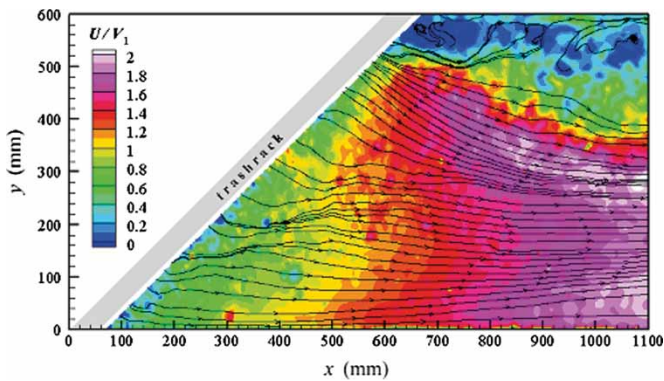


Figure 5 Streamlines superimposed on a velocity map (normalised streamwise velocity U/V_1) downstream of a trashrack angled at $\alpha = 45^\circ$ (from Chatellier *et al.* 2011)

50 mm upstream of the rack (distance calculated perpendicularly to the rack). The size of the ADV probe prevented velocity measurements near the channel walls. To validate the data, an additional ADV profile was obtained for a larger trashrack

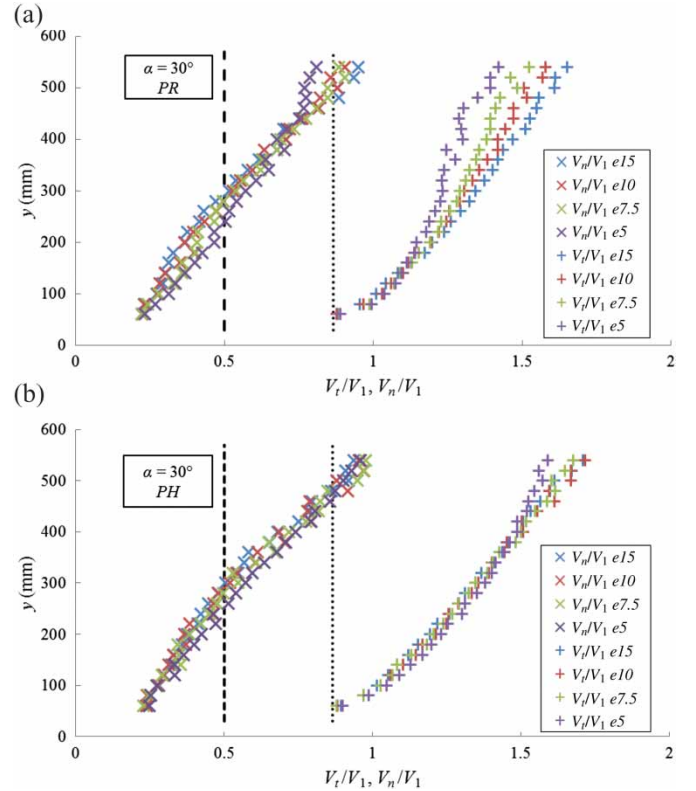


Figure 6 Comparison of V_t/V_1 and V_n/V_1 profiles along the angled rack ($\alpha = 30^\circ$) for different bar spacings e and bar shapes. The dashed and dotted vertical lines show the theoretical values for V_n/V_1 and V_t/V_1 respectively, calculated by geometrical projection

($B = 840$ mm). The results were found to be consistent with the present measurement series.

Figure 6 compares the transversal profile of V_t/V_1 and V_n/V_1 along the rack ($\alpha = 30^\circ$) for different bar shapes and bar spacings. This rack angle was the one for which the largest differences between *PR* and *PH* occurred. *PH* values were up to 20% higher than *PR* values, but these differences were located mainly at the downstream end of the trashrack and were significant only for very close bars. Bars separated by 5 mm led to velocity profiles which slightly differed from those separated by 15 mm. For close bars, the normal component was slightly higher in the upstream two-thirds of the rack and lower in its last third, whereas the tangential component dropped along the entire rack. These variations reached 20% for *PR* racks, but did not exceed 10% for *PH* racks. In conclusion, bar shapes and spacings had fairly little influence on the velocity distribution along the rack.

Figure 7 compares velocity profiles for a *PR* rack set to three angles ($30, 45$ and 60°). In order to observe the slight velocity variability, configurations representing the two extreme bar spacings were plotted ($e = 5$ and 15 mm). Generally, V_n increased along the rack. For $\alpha = 60^\circ$, the normal component in the first part of the rack equalled $0.7\text{--}0.8V_1$ and increased up to $1.1V_1$ towards the end of the rack. For $\alpha = 30^\circ$, V_n started at $0.2V_1$ and reached $0.8\text{--}1.0V_1$ in the end of the rack. Similarly, the behaviour of V_t along the rack was not the same for all angles. At $\alpha = 60^\circ$,

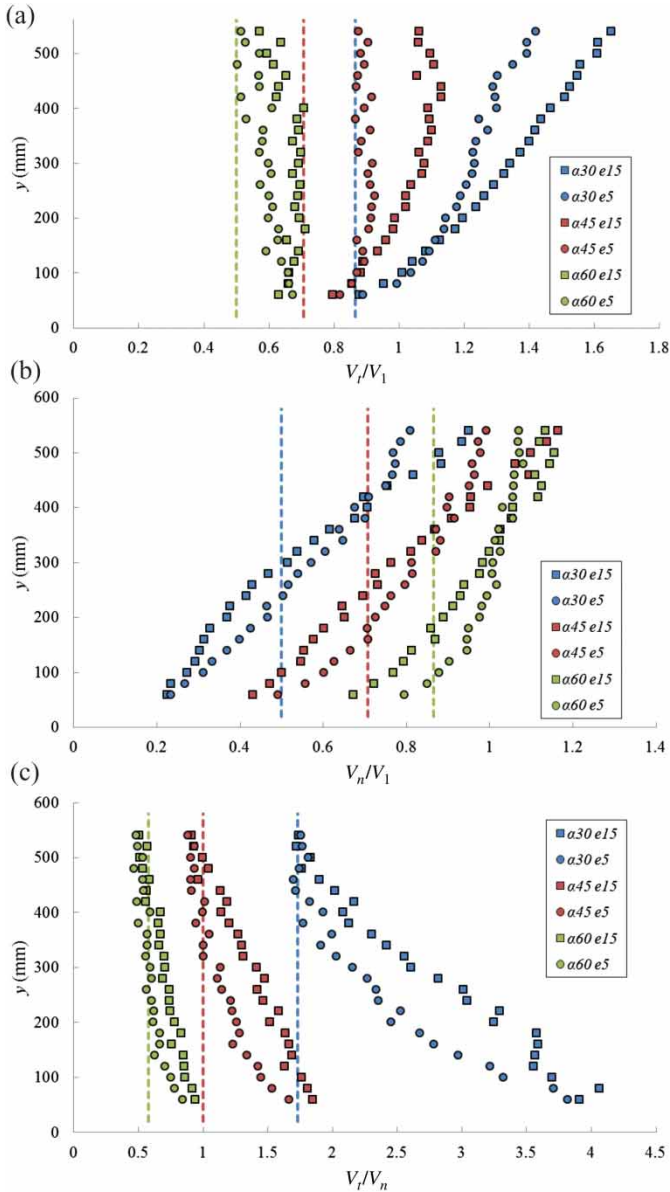


Figure 7 Comparison of V_t/V_1 (a), V_n/V_1 (b) and V_t/V_n (c) profiles for three PR trashrack angles (30, 45 and 60°, respectively the blue, red and green marks) and two bar spacings (5 and 15 mm, respectively, the round and square marks). Dashed lines represent theoretical values obtained by geometrical projection

V_t tended to decrease slightly from $0.65V_1$ to $0.55V_1$, whereas at $\alpha = 30^\circ$, V_t increased from $0.9V_1$ to 1.4 – $1.6V_1$. The trashrack angle was therefore the most significant parameter influencing velocities along the rack.

Katopodis *et al.* (2005) carried out similar measurements along wedge-wire screens angled at 10.4, 17.5 and 26.8° with a blockage ratio of 32%. Their rack had many more horizontal elements and about 30% of the incoming flow went into a bypass located at the downstream end of the rack. One of their experiments consisted of measuring V_n and V_t along a rack with $\alpha = 26.8^\circ$ and $O_g = 32\%$. They found $V_t = 0.8V_1$ and $V_n = 0.2V_1$ at the beginning of the trashrack and $V_t = 1.6V_1$ and $V_n = 0.7V_1$ at the end. We tested a rather similar configuration with $\alpha = 30^\circ$ and $e = 15$ mm (i.e. $O_g = 38\%$, see the blue

marks in Fig. 7), which produced comparable velocity values ($V_t = 0.88V_1$ and $V_n = 0.22V_1$ at the beginning and $V_t = 1.65V_1$ and $V_n = 0.95V_1$ at the end). Except for the higher normal velocity at the downstream end of our trashrack, which may be explained by increased flow containment due to the absence of a bypass, our results are consistent with the ones of Katopodis *et al.* (2005).

Moreover, Figs. 6 and 7 enable comparison of measured velocities with those predicted by the theoretical projection of V_1 (dashed lines) in the normal and tangential directions. V_t was higher than the predicted velocities along the entire rack, whereas high values of V_n occurred only at the downstream end of the trashrack. V_t/V_n ratio decreased along the rack and reached their theoretical values at the end of the rack.

5 Conclusions

The effects of the trashrack bar spacing, shape and angle on head-losses and velocity profile upstream were studied in a large number of configurations.

A new head-loss equation was developed which closely fit our experimental measurements covering trashracks in positions ranging from perpendicular to the flow to low angles. The head-loss coefficient is a function of the blockage ratio, the bar shape and the rack angle. The effect of the angle is a function of the blockage ratio, the bar shape and possibly the bar depth. The new equation proposed here is consistent with previous equations found in the literature for vertical and perpendicular racks. It was designed to be adaptable to narrow spacing in angled racks. This new equation was also designed to complement other equations obtained in slightly different set-ups (Meusburger 2002).

The profiled bars improved the acceptability of fish-friendly trashracks by decreasing the head loss due to the bars by up to 40%. However, the overall effect of the bar shape decreases with the angle (lower α). For example, using hydrodynamic bars results in a 30% reduction in the head-loss coefficient for $\alpha = 45^\circ$, but only a 22% reduction for $\alpha = 30^\circ$.

Nevertheless, head-loss coefficients of angled trashracks are quite high, in particular compared with those of inclined racks (Raynal *et al.* 2012). This may limit their acceptability and it could be worthwhile to test angled trashracks whose bars are aligned with the direction of flow.

The most significant changes in the velocity distribution were induced by changes in the rack angle α . Bar spacing and bar shape produced less of an effect on velocities. To meet the guidance criterion $V_t/V_n > 1$ indicated by Courret and Larinier (2008), this study confirms that trashracks must be sharply angled to $\alpha \leq 45^\circ$. To avoid impingement of smolts and silver eels on the rack, it is also recommended that the normal velocity V_n does not exceed 0.5 ms^{-1} . For $\alpha \leq 45^\circ$, V_n reaches values between $0.8V_1$ and $1.2V_1$ in the downstream part of the rack. Consequently, the maximum values of V_1 are respectively 0.63 and 0.42 ms^{-1} . These values are particularly restrictive, as approach velocities in

most water intakes are between 0.6 and 0.9 ms⁻¹. These considerations may reduce the potential applications of angled racks. Nonetheless, the positioning of a bypass entrance at the end of the rack would probably reduce normal velocities and therefore would allow higher approach-velocity values.

This study estimated the reliability of fish-friendly intakes with an angled trashrack and produced practical recommendations concerning French criteria for silver eels, salmon and sea-trout smolts. Coupled with previous results on inclined trashracks (Raynal *et al.* 2012), these results should help designers to adapt inclined and angled trashrack solutions to the water-intake characteristics and biological constraints on each site. The use of trashracks with narrow bar spacing may however raise concerns about increased clogging effects and trashrake design.

Acknowledgements

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Notation

b, b_{ext}	= bar thickness and thickness of the lateral support (m)
B	= channel width (m)
B_g	= trashrack width (m)
D_{sp}	= spacer diameter (m)
e	= clear space between two bars (m)
g	= gravitational acceleration (ms ⁻²)
H_1, H_2	= upstream and downstream water depths (m)
k_{PR}, k_{PH}	= coefficient in the head-loss equation for angled racks (–)
K_F	= bar shape coefficient (–)
$K_{K,-M}$	= coefficient in the head-loss equation proposed by Mosonyi (1966) (–)
K_{PR}, K_{PH}	= bar shape coefficient in Eq. (6) (–)
K_α	= angular effect on the head-loss coefficient (–)
$L_g, L_{g,im}$	= total and immersed bar lengths (m)
M	= coefficient in the head-loss equation for vertical racks (–)
N_b	= number of bars (–)
$N_{sp,im}$	= number of immersed spacers rows (–)
O_b	= blockage ratio due to bars and lateral supports (–)
O_g	= trashrack blockage ratio (–)
$O_{sp}, O_{sp,H}$	= blockage ratio of the transversal elements to the trashrack surface or to the upstream water depth (–)
p	= bar depth (m)
PR, PH	= bar shape (rectangular and hydrodynamic) (–)
Q	= flow rate (ms ⁻³)

R_b	= bar Reynolds number (–)
U, V, W	= velocity components along x, y and z respectively (ms ⁻¹)
V_1, V_2	= upstream and downstream mean velocities (ms ⁻¹)
V_t, V_n	= components of the velocity tangential and normal to the rack face (ms ⁻¹)
x, y, z	= streamwise, transversal and vertical coordinates (m)
α	= trashrack angle from wall (°)
β	= trashrack inclination angle from floor (°)
$\Delta H_0, \Delta H$	= Head loss due to the channel and head loss due to the rack (m)
λ	= laser wavelength (m)
ξ	= trashrack head-loss coefficient (–)

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