HAL
open science

Study on fish-friendly inclined and angled trashracks

Sylvain Raynal, Ludovic Chatellier, Dominique Courret, Michel Larinier, Laurent David

To cite this version:

Sylvain Raynal, Ludovic Chatellier, Dominique Courret, Michel Larinier, Laurent David. Study on fish-friendly inclined and angled trashracks. La Houille Blanche - Revue internationale de l'eau, 2015, 3, pp.31-36. 10.1051/lhb/20150030 . hal-01619347

HAL Id: hal-01619347

https://hal.science/hal-01619347v1

Submitted on 19 Oct 2017

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Open Archive TOULOUSE Archive Ouverte (OATAO)
OATAO is an open access repository that collects the work of Toulouse researchers and makes it freely available over the web where possible.

This is an author-deposited version published in : http://oatao.univ-toulouse.fr/
Eprints ID : 18380

To link to this article : DOI:10.1051/lhb/20150030
URL : http://dx.doi.org/10.1051/lhb/20150030

To cite this version : Raynal, Sylvain and Chatellier, Ludovic and Courret, Dominique and Larinier, Michel and David, Laurent *Study on fish-friendly inclined and angled trashracks.* (2015) La Houille Blanche (3). pp. 31-36. ISSN 0018-6368

Any correspondence concerning this service should be sent to the repository administrator: staff-oatao@listes-diff.inp-toulouse.fr

Study on fish-friendly inclined and angled trashracks[1]

Sylvain RAYNAL[1], Ludovic CHATELLIER[1], Dominique COURRET[2], Michel LARINIER[2], Laurent DAVID[1]

[1.] *Institut Pprime, UPR3346, CNRS, Université de Poitiers, ENSMA, Bd Marie et Pierre Curie, Téléport 2, BP 30179, 86962 Futuroscope, France Laurent.David@univ-poitiers.fr*

[2.] *ONEMA, Pôle Ecohydraulique, Institut de Mécanique des Fluides de Toulouse, Allée du Professeur Camille Soula, 31400 Toulouse, France Dominique.Courret@onema.fr*

ABSTRACT. – This paper presents the results on trashrack head losses obtained by Raynal *et al.* [2013 a,b], [2014] for several configurations. More especially, it compares the head loss formulae proposed in these studies with various equations from the literature to improve energy losses prediction in fish-friendly configurations. These new predictive laws of head losses are applied to the renovation of a hydropower plant and show that inclined trashracks or angled trashracks with streamwise bars are reliable solutions when the bar spacing is reduced.

Key-words: fish-friendly trashracks, water framework directive, head-losses, inclined and angled trashracks

Etude de grilles ichtyocompatibles inclinées et orientées

RÉSUMÉ. – Ce papier présente les résultats des pertes de charge sur des plans de grille obtenus par Raynal *et al.* [2013 a,b], [2014] pour de nombreuses configurations. Il s'inscrit dans le cadre d'une étude expérimentale et numérique plus générale, menée dans le but de caractériser les différents aspects des grilles ichtyocompatibles. Ainsi, les autres résultats obtenus, associés notamment aux répartitions de vitesses à l'amont et à l'aval des différentes grilles ainsi qu'aux conditions d'écoulement à l'entrée de l'exutoire, ont été restranscrits dans la thèse de Raynal [2013] et ne sont pas traités ici. Ce papier se concentre donc sur la comparaison des formules de pertes de charges, construites à partir de résultats expérimentaux sur différents types de grille, avec d'autres equations issues de la littérature afin d'améliorer la prédiction de ces pertes pour des configurations de prises d'eau ichtyocompatibles. Les avantages et les limites de ces nouvelles lois de pertes de charge sont décrits et ces dernières sont ensuite utilisées sur un cas de prise d'eau de centrale en rénovation. Cette application sur un cas réel montre que les grilles inclinées ou orientées avec des barreaux dans le sens de l'écoulement sont des solutions viables et que, dans ces configurations, l'effet de la réduction de l'écart entre les barreaux sur l'énergie disponible pour la turbine demeure assez faible.

Mots-clés : prise d'eau ichtyocompatible, directive cadre européenne, pertes de charges, plans de grille incliné et orienté

I. INTRODUCTION

Since 2000, several European and national Directives have raised the global concern about fish mortality during migrations, especially for diadromous species such as European eels, sea trout or salmon smolts. During downstream migration, fish may face hydropower plants and may have to cross turbines. Several studies have shown that fish may be lethally injured during their passage through turbines.

In order to address this issue, several solutions have been developed to prevent fish from being injured, such as fish-friendly turbines, but most of them have a restricted operating range. Alternatively fish-friendly trashracks may be adapted to a broader range of conditions. Their role is to prevent fish from entering into turbines and to guide them toward bypasses.

In 2008, Courret and Larinier defined the conception and dimension bases of such fish-friendly trashracks. They appear as an adaptation from conventional trashracks (used to stop large debris) with a narrower bar spacing and an angle to the flow. Trashracks may therefore be either inclined from the floor or angled from the bank. Leaning on literature and in-situ observations, they determined some fish-friendly criteria that need to be met for these fish-friendly trashracks.

According to the size of migrating fish species, a bar spacing around 20 mm is desirable. They also recommend to pay attention to the ratio of tangential to normal velocity components at the trashrack. For angled racks, this V_t/V_n ratio must be higher than 1 along the rack. For inclined ones, in which fish must move vertically, this ratio must be higher than 2. This criterion is coupled with a maximum value for the normal component of the velocity, related to fish swimming capacity, with $V_n \leq 0.5$ m/s. These criteria related to the trashrack are also completed by other criteria related to bypass entrances at the end of the rack (dimension, discharge, etc…).

These values recommended by the French National Agency for Water and Aquatic Environments (ONEMA) are similar to recommendations given by other national agencies [OTA, 1995; NMFS, 2011; Environmental Agency, 2012], even though, some variations in the maximum allowed bar spacing remain due to the age and the size of local species (for example, a bar spacing of 2 mm is recommended for salmonid fry in the Pacific coast of the USA).

1. Sylvain Raynal a obtenu le prix de la SHF Jean Valembois 2015 pour sa thèse.

Through theoretical analysis, Courret and Larinier [2008] determined two angles that should meet these fish-friendly criteria. Thus, a maximum angulation of $\alpha = 45°$ and a maximum inclination of $\beta = 26°$ should apply for angled and inclined trashracks, respectively. Raynal *et al.* [2013 a,b] have carried out an experimental study on model trashracks. Using different measurement devices, they measured velocities upstream and downstream of the rack for various trashrack parameters (angle, bar spacing, bar shape, …). Their results confirmed the angles determined by Courret and Larinier [2008]. However, their results also revealed some issues at the downstream end of angled trashracks, where normal velocities were rather high and may increase fish impingement risks. Therefore, for these angled racks, trashracks may be more angled and the acceptable approach velocity range may be more restricted.

In addition with these modifications on velocity distributions, these trashracks also interfere with energy production. Since bar spacing is lower and bars are no longer vertical and aligned with the flow, trashrack head losses may be quite different from those generated by conventional racks used to stop large debris (with a large bar spacing, rectangular shaped bars and vertical rack).

This paper summarizes the results on trashrack head losses obtained by Raynal *et al.* [2013 a,b], [2014], and more especially, compares the head loss formulae proposed in these studies to improve energy losses prediction in fish-friendly configurations. Section 2 gathers some results from literature on head losses and details the parameter range tested. Section 3 describes the experimental set-up used during these experiments on model trashracks to measure head losses. Section 4 presents new head loss equations constructed from measurements and compares their prediction with those obtained from by various equations from literature in fish-friendly configurations. Then, results are applied to the case of the hydropower plant of Saverdun, on the Ariège river, and lead to some conclusions.

II. PREVIOUS MEASUREMENTS OF HEAD LOSSES

Trashrack head losses have been studied for several decades and many researchers have obtained experimental results in this field. However, studies in literature generally focus on specific configurations and may not be appropriate for fish-friendly trashracks.

Kirschmer [1926] was one of the first authors to study trashrack head losses and to propose an empirical equation. He studied vertical racks with a dozen of bar shapes for various bar thickness b on bar spacing e ratios. He also studied inclined trashracks, with rectangular bars for one single bar spacing, covering angles from $\beta = 90°$ (vertical) to $\beta = 60°$ (Eq. 1). His equation took into account the b/e ratio, the bar shape using the coefficient K_F and the trashrack inclination with $\sin(\beta)$. In 1966, Mosonyi completed Kirschmer's formula and added a tabulated coefficient that takes into account angled trashracks for various angles and b/e ratios (for example, at $b/e = 0.5$ and $\alpha = 45°$, $K_{K.-M.}$ is approximately 2.25).

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

After Kirschmer, few authors investigated inclined trashracks and many studies lean on Kirschmer equations [Berezinski, 1958; Meusburger, 2002]. Some rare studies tried to propose new head loss formulae for inclined trashracks like Breinig *et al.* [2003] who investigated Johnson® trashracks, which are inclined trashracks composed by horizontal bars with a triangular cross-section. They used an head loss equation similar to Kirschmer's one where the head loss coefficient ξ may be calculated as $K_{90}*\sin(\beta)$, where K_{90} was the coefficient for a similar but vertical rack. Results show that predicted coefficients were not in agreement with measurements and they eventually produced head loss abacus. This proves that the effect of the inclination may not be always modelled by a sinus function.

Angled trashracks have been much more investigated. Some researchers, like Mosonyi [1966] or Idel'cik [1979], gave tabulated coefficients or abacus to calculate head loss coefficients for angled trashracks but more recent studies generally provide empirical head loss equations.

Clark *et al.* [2010] determined that the trashrack head-loss coefficient may be calculated as a function of O_g^2. This equation was obtained with blockage ratio O_g values between 37% and 8%, i.e. e/b ratio between 1.75 and 12, but for rectangular bars only. Other bar shapes have been investigated for $e/b = 2.26$ and the influence of bar section was modelled by the coefficient η.

$$\xi_{Clark} = 7.43\eta * O_g^2 * \left(1 + 2.44 \tan(90 - \alpha)\right), \qquad (2)$$

Meusburger [2002] proposed another equation developed through experiments with angled trashracks (α between 90 and 60°) with rectangular bars and blockage ratio O_g values between 55% and 19% (e/b ratio between 1 and 9 respectively). He especially investigated numerous clogging configuration on vertical trashrack (with one single O_g ratio) and modelled the effect with a function of the clogging ratio (not shown here). Moreover, Meusburger extended his formula by using Kirschmer's terms (K_F and $\sin(\beta)$) to model bar shape and inclination effects.

$$\xi_{Meusburger} = K_F * \left(\frac{O_g}{1 - O_g}\right)^{1.5} * \frac{\alpha}{90} * O_g^{-1.4*\tan(90-\alpha)} * \sin(\beta), \qquad (3)$$

In summary, many studies on trashrack head losses proposed empirical head loss equations. Some salient parameters tend to be used in all existing equation, such as angles and bar spacing or blockage ratio, but these parameter may also be involved in other terms of the equations. This is particularly true for the effect of the trashrack angulation but also for the effect of the trashrack blockage ratio.

However, these studies investigated trashrack configurations that do not necessarily correspond to fish-friendly ones ($\alpha \leq 45°$ or $\beta \leq 26°$ and $e \leq 20$ mm). Generally, researches in literature used rather narrow bar spacings: e/b ratios were often close to one, which is sufficient for fish-friendly purposes (for example, in a real case, a 10 mm thick bar and a 20 mm bar spacing would result in $e/b = 2$). Angled trashracks were investigated by some studies, but the most recent ones, which are the only ones that proposed mathematical expressions, did not test angles lower than $\alpha = 60°$. Concerning inclined trashracks, Kirschmer's results (obtained with β between 90° and 30°) are the main ones and have been mainly used to extend head loss formulae,

even if other studies showed that the term for inclination can not be efficient for all trashrack configurations.

Therefore, only few studies dealt with fish-friendly trashrack configurations. Some rare studies tested fish-friendly angles but only one bar shape and bar spacing were generally experimented. A better description of inclined and angled trashracks for various parameter ranges (different bar spacing, bar shape, clogging ratios) was therefore needed to best characterize the effect of these eco-friendly devices on energy losses.

III. EXPERIMENTAL SET-UP

Head losses have been studied in a 10-metre long open channel. The channel was 0.9 m deep and 0.6 m wide and the water level was adjusted by a weir at the outlet of the channel. According to trashrack configurations and measurement capacities, the upstream water depth H_1 was generally set between 0.3 and 0.35 m.

Three different kinds of rack have been studied. Racks inclined from the floor by an angle β set between 90° (i.e. vertical rack) and 15° have been investigated. Racks angled from the channel wall by an angle α have also been studied with two different bar directions. Bars may be either perpendicular to the rack (conventional trashrack design) or aligned with the channel axis. For both orientation, α angles between 90° and 30° have been investigated.

In all case, head losses were obtained by measuring upstream and downstream water depths with two acoustic sensors (Microsonic™ Mic+25/IU/TC). These instruments were located at x = - 1 m and x = 2.6 m (x = 0 m was the location at the upstream end of the rack) and timely integrated measurements (40 second period, generally) have been recorded. The uncertainties of these water depths ranged between 0.5 and 1 mm, depending on the surface waves, which led to a maximum overall uncertainty of 3 mm [Raynal *et al.*, 2013a].

Bars were 5 mm thick (b) and the bar spacing e was between 5 and 15 mm, leading to e/b ratios between 1 and 3. These values may be compared to real installation where bar spacing should be around 20 mm (to stop migrating fish) and bar thickness was generally around 8 or 10 mm according to conception choices. The experimental e/b values between 1 and 3 therefore included the real e/b ratios that are around 2 or 2.5.

Two different bar shapes have been studied: rectangular bars (*PR*) and hydrodynamic bars (*PH*) that had a rounded leading edge and a thinner trailing edge. The bar depth (measured perpendicularly to the bar length, i.e., for vertical bars, measured along the x-axis) was always 40 mm for *PH*-bars. For *PR*-bars, 25mm, 60 mm and 80 mm deep bars have been investigated for some vertical and angled trashrack configurations.

In summary, head losses have been measured in 150 configurations (around 60 inclined and 90 angled racks), approximately. Moreover, perforated plates, with a circle or square hole pattern, were also added upon trashracks to model clogging in some fish-friendly configurations.

IV. HEAD LOSSES IN FISH-FRIENDLY CONFIGURATIONS

IV.1. Measurements and new empirical equations

All head loss measurements allowed to determine the effect of various rack parameters on energy losses. More specifically, they allowed to get data from vertical racks to fish-friendly configurations. We tried to fit these measurements with head loss coefficients calculated with various equations from literature presented in the section 2. For both inclined and angled racks, these comparisons showed that existing equations are not adapted to fish-friendly configurations. One of the main reason is the fact that existing equations, that have not necessarily been obtained with such low angles, result from measurements were interdependences have not been taken into account. For example, Kirschmer [1926] investigated a large range of bar shapes for vertical racks but only considered rectangular bars for inclined ones. His head loss equation therefore supposed that the effect of the inclination is the same for all bar shapes. In the same way, Meusburger [2002] supposed that the effect of the angulation is the same for all bar shape and that the clogging effect does not depend on the rack design.

Figure 1: *Different trashrack configurations tested. From left to right: inclined rack (observed from upstream), angled rack with perpendicular bars (observed from downstream) and angled rack with streamwise bars (observed from upstream).*

Three equations were eventually proposed [Raynal *et al.*, 2013a, 2013b, 2014] for fish-friendly trashracks. For inclined racks, measurements showed that the effect of bars ($K_{b,PR}$ = 3.85, $K_{b,PH}$ = 2.1) had to be separated from the effect of spacers (K_{sp} = 1.79). As a consequence, two different partial blockage ratio were used (O_b for bars and $O_{sp,H}$ for spacers).

$$\xi = K_{b,i}\left(\frac{O_b}{1-O_b}\right)^{1.65}\sin^2(\beta) + K_{sp}\left(\frac{O_{sp,H}}{1-O_{sp,H}}\right)^{0.77} \quad (4)$$

For angled racks, one single equation may be used for both bar orientations. The K_i coefficient value depends on the bar shape (K_{PR} = 2.89 and K_{PH} = 1.7) and the effect of the angle α is modeled by the term K_α which varies according to the bar orientation.

$$\xi = K_i\left(\frac{O_g}{1-O_g}\right)^{1.6} K_\alpha \quad (5)$$

where $K_\alpha = 1 + k_i\left(\frac{90-\alpha}{90}\right)^{2.35}\left(\frac{1-O_g}{O_g}\right)^3$ for perpendicular bars and $K_\alpha = 1$ for streamwise bars.

These equations have been determined for clean trashracks. Measurements with clogging showed that, while clogging always increase the head losses, a same clogging ratio can lead to different head loss increases for different trashrack parameters. For example, profiled bars are generally more affected by clogging than rectangular bars. As a consequence, a head loss formula covering all possible trashrack parameters can hardly be constructed, but values corresponding to some specific fish-friendly configurations have been determined.

IV.2. Comparison in fish-friendly configurations

The aim of this section is to compare various head loss coefficients. Those measured in our study in fish-friendly configurations is compared with empirical coefficients obtained using equations (4) and (5). Some other coefficients calculated with existing equations [Kirschmer, 1926; completed by Mosonyi, 1966; Meusburger, 2002; Clark, *et al.*, 2010] are also written for comparison.

Table 1 compares these head loss coefficients for six fish-friendly configurations: *PR* and *PH* bars for inclined racks (β = 25°) and for the two types of angled racks (α = 45°). For angled racks with streamwise bars, velocity measurements [Raynal, *et al.*, 2014] showed that the exact fish-friendly angle should be lower than 45° (around 41°). However, since the nearest tested angle in head loss measurements is 45°, this angle is kept in Table 1.

For all the selected configurations, the head loss equations determined in our previous papers lead to better estimations than existing formulae, even if, in some *PR* configurations, Meusburger's equation [2002] also produces good estimations.

This table also allows to compare head losses for clean fish-friendly trashracks. Inclined racks are less penalizing than the other configurations, even though, with *PH* bars, head losses generated by angled racks with streamwise bars are also rather low. On the opposite, angled racks with perpendicular bars approximately generate four times as many energy losses than inclined racks.

V. APPLICATION TO AN EXISTING HYDROPOWERPLANT

Several fish-friendly trashrack configurations may be implemented upstream of hydro power plant to make it compatible with fish downstream migration. Among them, three have been selected for this study, even if other configurations, such as angled racks with horizontal bars, could also be a worthwhile solution.

The goal of this section is to apply results obtained in Raynal *et al.* [2013, a, b] and [2014] on the case of the Saverdun hydropower plant, located on the Ariège river, and to compare possible trashrack implementation in terms of several economical factors.

V.1. Hydropower plant characteristics

The hydropower plant is located on the right bank of the river. The channel upstream of the plant is B = 7.8 m wide, and is H_1 = 3.7 m deep in normal conditions. The water discharge dedicated to this hydropower plant is Q = 20.7 m^{3}s^{-1}, with 0.7 m^{3}s^{-1} reserved for the bypass alimentation. This leads to approach velocities around V_1 = 0.72 ms^{-1}.

V.2. Trashrack characteristics

For the three trashrack configurations selected, some parameters, respecting fish-friendly criteria, need to be set:

— Bars are 8 mm thick and spaced by 20 mm

Table 1: Comparison of measured head loss coefficients ξ with calculated ones for various fish-friendly configurations.
[1]: These value are calculated for bars with rounded edges instead of a PH shape.
[2]: Since this kind of trashrack has not been studied before, the values for Kirschmer-Mosonyi [1966], Meusburger [2002] and Clark et al. *[2010] are those calculated for vertical racks.*

Trashrack configuration	Bar shape	Measured coefficient	Raynal *et al.* [2013, 2014]	Kirschmer-Mosonyi [1966]	Meusburger [2002]	Clark *et al.* [2010]
Inclined rack (β = 25°)	*PR*	0.78	0.67	0.41	0.62	-
	PH	0.55	0.54	0.18	0.38	-
Angled rack with perpendicular bars (α = 45°)	*PR*	3.29	3.33	2.16	2.70	5.06
	PH	2.39	2.46	0.92	1.15	3.39 [1]
Angled rack with streamwise bars (α = 45°)[2]	*PR*	1.29	1.39	0.96	1.59	1.79
	PH	0.60	0.82	0.41	0.67	1.20 [1]

— Bars may be either *PR*- or *PH*-shaped
— Bars spacers are circular, their diameter is 20 mm and they are separated by one meter.
— Longitudinal supporting bars are placed along the trashrack to rigidify it. They are 50 mm wide and are separated by one meter.

For inclined trashrack, impingement risks are rather low and an approach velocity of V_1 = 0.72 m/s does not require a specific trashrack angle. Therefore, the inclination angle is the maximum one, i.e. β = 26°. On the contrary, for both bar orientation in angled configurations, the maximum angle of α = 45° may only be used with low approach velocities (lower than 0.6 m/s). Therefore, some adjustements need to be made. For angled trashracks with perpendicular bars, measurements at α = 30° showed that the maximum normal velocities were approximately 0.75 V_1, which corresponds here to maximum V_n around 0.54 m/s. This value is rather close to the fish-friendly criterion defined to avoid fish impingement. As a consequence, this angle of α = 30° is selected for this comparison. For angled trashracks with streamwise bars, velocity measurements showed that the maximum normal velocities can be related to the trashrack angle using equation (6).

$$V_{n,max} > \frac{sin(\alpha)}{0.8} V_1 \qquad (6)$$

This results in α = 33.8°, which is a lower limit in a case where no bypass is used. Since bypasses are used in real conditions and tend to improve velocity conditions, a slightly higher angle of 35° is selected.

V.3. Comparison of trashrack solutions

The determination of trashrack angles allowed to determine both the trashrack width B_g and length L_g for all configurations. Since bar width and spacing have been already defined, one may also determine the number of bars N_b in each configuration.

Table 2 compares four cases for the three configurations selected: *PR* or *PH* bars in clean racks or clogged racks with a clogging ratio of 25%. For each case, two economical factors are detailed: the total bar length and the head loss. This means that other possible criteria for comparison, such as velocity distribution downstream of the rack or minimum bypass discharge required, are not taken into account in this paper.

For clean racks, head losses are calculated using (4) and (5). For clogged racks, a multiplicative factor K_C is added to those equations, whose value has been experimentally measured (except for angled trashrack with streamwise bars for which K_C values are those corresponding to vertical trashracks, i.e. α = 90° and β = 90°).

Head losses are very different from one configuration to another. In clean configurations, angled trashracks with streamwise bars and inclined ones generate approximately five times less energy losses than angled trashracks with perpendicular bars. Clogging may level these differences but there is still a factor around three between these configurations. Concerning the bar length, for these specific channel width and depth values, the angled trashrack with streamwise bars require half the amount of bar length required in the other configurations. This means that for this hydropower plant, angled trashrack with streamwise bars account for the most interesting configurations. However, only two economical criteria have been taken into account during this comparison, and other ones, such as downstream velocity distribution or bypass design, may modify these conclusions.

VI. CONCLUSIONS

The effects of the bar spacing, the bar shape and the rack angle on head-losses have been investigated for different inclined and angled racks in an open channel flow. Different equations of the head losses have been proposed for both cases and have been compared with various equations from the literature. These new head loss equations, which take into account numerous parameters, showed better

Table 2: Comparison of three possible fish-friendly trashrack implementations at the Saverdun hydropower plant. Four scenarios, including two bar shapes and two clogging ratios, are detailed and resulting predicted head losses and total bar lengths are described.

	α (°)	β (°)	B_g (m)	L_g (m)	N_b	*PR/PH*	*C* (%)	K_C	ξ	ΔH (mm)	$\Delta H/H_1$ (%)	Total bar length (m)
Inclined trashrack	90	26	7,8	8,4	260	*PR*	0	1	0,87	23	0,5%	2194
						PH	0	1	0,66	17	0,3%	
						PR	25	3,3	2,86	75	1,5%	
						PH	25	3,3	2,17	57	1,1%	
Angled trashrack with perpendicular bars	30	90	15,6	3,7	519	*PR*	0	1	4,79	126	2,5%	1920
						PH	0	1	3,10	81	1,6%	
						PR	25	2	9,57	251	5,0%	
						PH	25	2	6,19	162	3,2%	
Angled trashrack with streamwise bars	35	90	13,6	3,7	260	*PR*	0	1	0,56	15	0,3%	962
						PH	0	1	0,33	9	0,2%	
						PR	25	4	2,24	59	1,2%	
						PH	25	5	1,64	43	0,9%	

approximation in fish-friendly configurations. The application of these equations to a real case of the hydropower plant revealed the differences in terms of head loss and bar number for three possible trashrack configurations. This especially showed the reliability of angled trashracks with streamwise bars for fish-friendly intakes that generate much lower head losses than those with perpendicular bars. These new kind of laws and of results could be useful for the validation of 3D simulations of the flow close to the trash rack and could help the engineer for the design of the entrance of the hydropower station.

VII. NOMENCLATURE

b	=	Bar thickness (m)
B	=	Channel width (m)
B_g	=	Trashrack width (m)
e	=	Clear space between two bars (m)
H_1, H_2	=	Upstream and downstream water depths (m)
k_i, K_i	=	Coefficient in (4) and (5) whose value depends on the bar shape (-)
K_a	=	Angular effect on the head-loss coefficient in (5) (-)
K_C	=	Increase of head-loss due to clogging (-)
L_g	=	Trashrack length (m)
N_b	=	Number of bars (-)
O_b	=	Blockage ratio due to bars and lateral supports (-)
O_g	=	Trashrack blockage ratio (-)
O_{sp}	=	Blockage ratio of the transversal elements to the upstream water depth (-)
p	=	Bar depth (m)
PR, PH	=	Bar shape (rectangular and hydrodynamic) (-)
Q	=	Flow rate (m^3s^{-1})
V_1	=	Upstream mean velocity (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)
a	=	Trashrack angle from wall (°)
b	=	Trashrack angle from bottom (°)
DH	=	Head loss due to the channel and head loss due to the rack (m)
x	=	Trashrack head-loss coefficient (-)

VIII. ACKNOWLEDGEMENTS

This work was funded by the European Regional Development Fund (ERDF), the Région Poitou-Charentes, ONEMA, ADEME, EDF, CNR and SHEM. Their support is greatly appreciated.

IX. REFERENCES

BEREZINSKI I. (1958) — *Hydraulisches Handbuch. Hrsg. Mostkov, M.A., Moscou.*

BREINIG T., CHORDA J., LARINIER M. (2003) — Etude hydraulique de grilles Johnson de faible porosité – Application à la dévalaison des larves de bichiques. *Rapport GHAAPPE RA03.02.*

CLARK S.P., TSIKATA J.M, HARESIGN M. (2010) — Experimental study of energy loss through submerged trashracks. *J.Hydraulic Res. P.* **48(1)** : 113-118

COURRET D., LARINIER M. (2008) — Guide pour la conception de prises d'eau «ichtyocompatibles» pour les petites centrales hydroélectriques. *Agence De l'Environnement et de la Maîtrise de l'Energie (ADEME). (www.onema.fr/IMG/pdf/2008_027.pdf)*

ENVIRONMENT AGENCY (2012) — *Hydropower Good Practice Guidelines. Screening requirements. (http://www.environment-agency.gov.uk/business/topics/water/126575.aspx)* 16 p

IDEL'CIK I.E. (1979) — Mémento des pertes de charge - Coefficients de pertes de charge singulières et pertes de charge par frottement. *Collection de la direction des études et recherches d'Electricité de France, Paris.*

KIRSCHMER O. (1926) — Untersuchungen über den Gefällverlust an Rechen. *Mitt. Hydr. Inst., Munich.*

MEUSBURGER H. (2002) — Energieverluste an Einlaufrechen von Flusskraftwerken. *PhD thesis, Bau-Ing., ETH-Zürich. (http://e-collection.library.ethz.ch/view/eth:26261)*

NMFS (NATIONAL MARINE FISHERIES SERVICE) (2011) — *Anadromous salmonid passage facility design. NMFS, Northwest Region, Portland.*

MOSONYI E. (1966) — Wasserkraftwerke, Band I, Niederdruckanlagen'. *VDI Verlag, Düsseldorf.*

OTA, (OFFICE OF TECHNOLOGY ASSESSMENT) (1995) — Fish passage technologies: protection at hydroelectric facilities. *OTA-ENV-641, Washington, DC. U.S. Government Printing Office.* 167 p

RAYNAL S. (2013) — Etude expérimentale et numérique des grilles ichtyocompatibles. *Thèse de Doctorat l'Université de Poitiers, 3 décembre 2013.*

RAYNAL S., COURRET D., CHATELLIER L., LARINIER M., DAVID L. (2013) — An experimental study on fish-friendly trashracks-Part 1: Inclined trashracks. *Journal of Hydraulic Research.* **51(1)** : 56-66

RAYNAL S., CHATELLIER L., COURRET D., LARINIER M., DAVID L. (2013) — An experimental study on fish-friendly trashracks - Part 2: Angled trashracks. *Journal of Hydraulic Research.* **51(1)** : 67-75

RAYNAL S., CHATELLIER L., COURRET D., LARINIER M., DAVID L. (2014) — Streamwise bars in fish-friendly angled trashracks. *Journal of Hydraulic Research.* **52 (3)** : 426-431