Hydraulics and Guidance Efficiency of Fish Guidance Structures

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Zusammenfassung

Die Hydraulik und Fischleiteffizienz von modifizierten *bar racks*, einem vielversprechenden vertikalen Fischleitrechentyp, wurden für verschiedene Konfigurationen und Fischspezies in einem 1:1 Froude-Modell in ethohydraulischen Laborversuchen systematisch untersucht. Dabei fanden u.a. Konfigurationen mit zwei Rechenwinkeln, α = 15° und 30°, und mit Sohlleitwand Anwendung, an denen fünf Fischarten getestet wurden. Der Rechenwinkel hatte einen signifikanten Einfluss auf das Strömungsbild. Die Fliessgeschwindigkeit in Längsrichtung war vor dem Bypasseinlauf sowohl mit als auch ohne Sohlleitwand deutlich grösser beim Leitrechen mit α = 15° als für α = 30°. Bei ersterer Konfiguration wurde zudem am Bypasseinlauf eine starke Querströmung in Richtung Rechen festgestellt, welche bei letzterer nur wenig ausgeprägt war. Die Installation einer Sohlleitwand verbesserte die Strömungsbedingungen nahe des Bypasseinlaufs, indem sohlnah keine Strömungsablenkung in Richtung Leitrechen mehr stattfand. Die Ergebnisse zeigen unter Beachtung der methodischen Besonderheiten der Studie keine wesentlichen Unterschiede zwischen den untersuchten Konfigurationen hinsichtlich der über alle verwendeten Fischarten gemittelten Fischleiteffizienz, jedoch kann eine Sohlleitwand die Effizienz deutlich erhöhen. Die Resultate der vorliegenden Studie stellen eine wichtige Grundlage zur Weiterentwicklung von Fischleitrechen dar, mit denen zukünftig abwandernde Fische an mitteleuropäischen Wasserkraftwerken erfolgreich zu Bypässen geleitet werden sollen.

Abstract

The hydraulics and guidance efficiency of modified angled bar racks (MBR)as a promising vertical type of fish guidance structures (FGS) were systematically experimentally investigated for a range of rack configurations and fish species at 1:1 Froude scaled models in an ethohydraulic laboratory channel. The study involved configurations with two main rack angles α = 15° and 30°and a bottom overlay (BO) at which five fish species were tested. The effect of rack angle on the flow field was significant. The streamwise flow velocity in front of the bypass was much higher for the rack with α = 15° than for the rack with α = 30°, both with and without a BO. Moreover, the former created a strong flow diversion towards the rack in front of the bypass while it was mild for the latter. Implementation of a BO improved the flow conditions near the bypass by causing no flow diversion near the flume bottom. The results of the live fish experiments demonstrated that the fish guidance efficiency (FGE) was similar, with differences mainly being fish species dependent. The use of the BO improved the flow field near the bypass and hence produced higher FGE for both rack configurations up to at least 90%. The findings of the present study provide an important foundation to continue the development of FGS designed to guide Central European fish species to a downstream bypass.

1 Introduction

Re-establishing river continuity is of key importance for the fish fauna. Therefore, the Association of Aare-Rhine Power Plants (Verband Aare-Rheinwerke, VAR) commissioned the Laboratory of Hydraulics, Hydrology and Glaciology (VAW) at ETH Zurich in collaboration with the Swiss Federal Institute of Aquatic Science and Technology (Eawag) with an inter-disciplinary research project. The project involved the evaluation and development of fish-protection systems for use at larger pre-Alpine rivers in Central Europe (Boes *et al.* 2015). The goal of the project was to improve the sustainable and efficient usage of hydropower plants (HPP) by providing safe downstream fish guidance past the hydropower intake and guidance toward a fish-bypass system while minimizing negative economic impacts. Analysis of the state-of-the-art systems revealed that FGS such as louvers and angled bar racks (Fig. 1) are promising measures to protect the fish fauna at large HPP with design discharges $Q_d > 80$ m^3/s (Boes *et al.* 2015).

Louvers and angled bar racks are used to guide anadromous fishes to a bypass at several HPP in the Northeast U.S. (EPRI 1999, Amaral *et al.* 2003). Both FGS create high turbulent flow zones, flow separations around the bars, changes in flow velocities as well as direction so that approaching fish can sense them and show behavioral avoidance reactions (Amaral 2003). Louvers consist of vertical bars placed at an angle of $\beta = 90°$ to the flow mounted in a rack. The rack is placed across an intake canal or forebay at an angle to the flow direction of typically $\alpha = 15°$ (Fig. 1). Angled bar racks are similar to louvers but their bars are placed at 90° to the rack axis so that β varies with the main angle α, i.e. $\beta = 90° - \alpha$. Important hydraulic parameters include approach and bypass velocities. For a better louver and angled bar rack design biological parameters, e.g. behavioral patterns and swimming capabilities of target species and their size classes must also be considered (Amaral *et al.* 2003, OTA 1995).

The Alden Research Laboratory (EPRI and Dominion Millstone Laboratories 2001) investigated the FGE of louvers and angled bar racks with $\alpha = 15°$ and 45° for eight fish species. They concluded that (i) 45° angled bar racks and louvers are not appropriate for diverting riverine fish species away from water intakes and (ii) structures with $\alpha = 15°$ have a considerable potential for guiding fish to a bypass.

Raynal *et al.* (2013) re-visited the topic of angled bar racks. They tested various bar shapes and spacings for $\alpha = 30°$, 45°, 60° and 90° and proposed a new head-loss equation accounting for the effect of the tested parameters. In addition, they provided new results and answers concerning downstream-migration aspects such as admissible approach velocities and guidance efficiency as a function of the trash rack angle. However, their findings have to be confirmed with live-fish experiments in relation to FGE of different FGS.

Available literature data show a lack of knowledge on flow fields around louver and bar racks and their FGE for Central European target fish species. Furthermore, the relation between β and α is not addressed. Therefore, a systematic investigation on the rack configurations where β varies independently from α, hereafter called ‘modified angled bar rack’ (MBR, Fig. 1) was conducted in a 1:1 Froude scaled laboratory channel. The focus points included: (i) the flow pattern around the MBRs and in the bypass and (ii) a brief discussion of the FGE of the tested MBR for five fish species, namely barbel, spirlin, grayling, eel and brown trout.

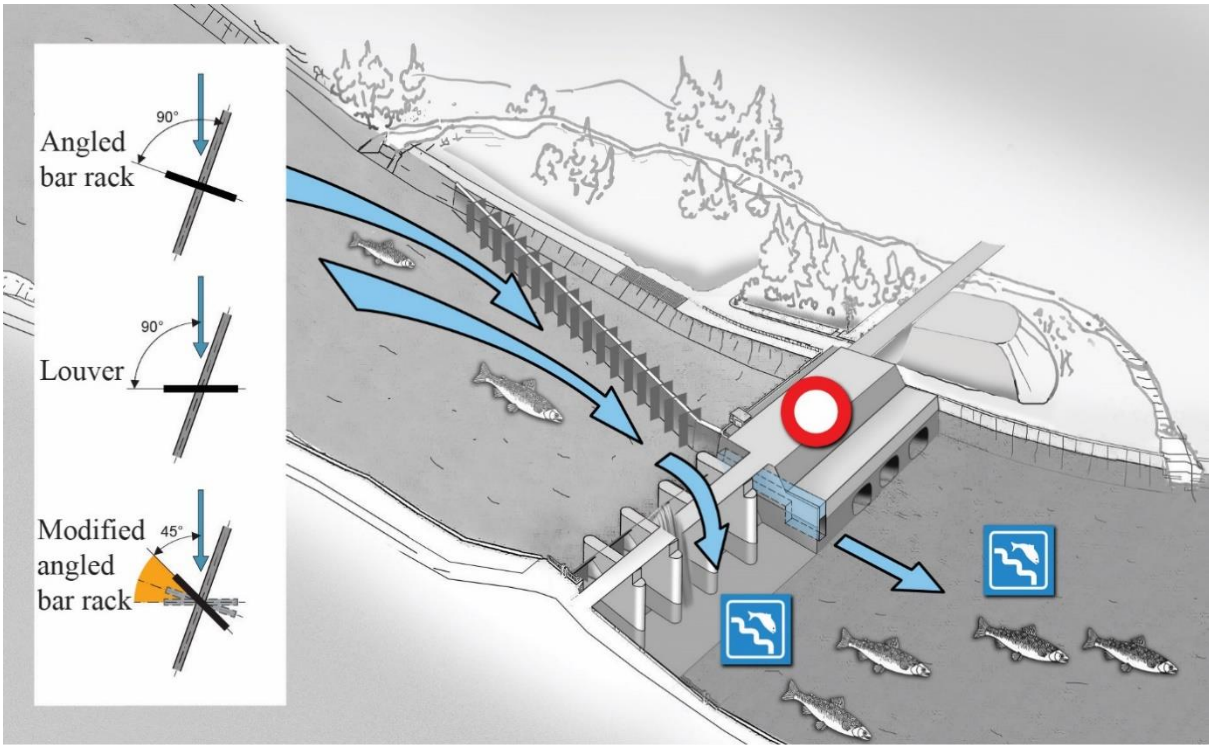

Fig. 1 Fish protection and guidance system with vertical bars and detailed view of louver, angled bar rack and modified angled bar rack (Kriewitz *et al.* 2015)

2 Experimental Set-Up and Procedure

Experiments were conducted in a 1.5 m wide, 1.2 m deep and 30 m long open channel with a maximum discharge of Q = 1200 l/s (Fig. 2a). The channel bed was concrete-lined. The coordinates in the streamwise, spanwise and vertical directions are x, y and z (Fig. 1a). The time average flow velocities in the x, y and z- directions are U, V and W, respectively. The cross-sectional average velocity is $U_o = Q/(h_oB)$. The approach flow depth was h_0 = 0.90 m and the channel width B, was 1.5 m. For each run the water surface was mapped using ultrasonic sensors (Fig. 2a). Four experiments were conducted at U_o = 0.60 m/s. In Table 1 the Reynolds number R and Froude number F are based on U_o and the hydraulic radius R_h and h_0, respectively (Table 1).

$$\mathsf{R} = 4U_oR_h/\nu \quad [1]$$

$$\mathsf{F} = U_o/\sqrt{gh_o} \quad [2]$$

where ν is the kinematic viscosity of water.

Velocity measurements were carried out using two Acoustic Doppler Velocimetry devices (ADV) at a sampling frequency of 25 Hz for 2 minutes on a horizontal grid with a transverse spacing of 0.25 m and a longitudinal spacing of 0.75 – 1.5 m. At each grid position three measurements in the vertical direction were taken, i.e. z/h_0 = 0.055, 0.125 and 0.5. The bypass width was 0.20 m resulting in the bypass discharge Q_B varying between 15% and 17% of the total discharge depending on the FGS configuration.

The experimental matrix included four FGS configurations. The bar angle to the flow direction was β = 45° for all configurations. The FGS was oriented at α = 15° to the flow direction for S1 and S2 while it was at α = 30° was for S3 and S4 (Fig. 2b). The difference between S1 and S2, and S3 and S4 was the inclusion of a BO with a height of $0.11h_0$. The bar spacing *b,* thickness *s* and length *l*, were 0.05 m, 0.01 m and 0.10 m, respectively (Fig. 2b).

Table 1 Hydraulic parameters and FGS configurations of the experiments

Exp.	FGS angle α [°]	Bar angle β [°]	Bar spacing *b* [cm]	Mean flow velocity U_0 [m/s]	Discharge Q_o [m³/s]	Bottom overlay BO	Reynolds number R (10^5)	Froude number F
S1	15	45	5	0.60	0.80		9.81	0.20
S2	15	45	5	0.60	0.80	x	9.81	0.20
S3	30	45	5	0.60	0.80		9.81	0.20
S4	30	45	5	0.60	0.80	x	9.81	0.20

In addition to the hydraulic experiments, live-fish experiments were carried out in the same channel and hydraulic conditions in collaboration with Eawag. Five fish species typically found in Swiss plateau rivers and listed as either vulnerable, or near threatened were tested. These are barbel, spirlin, grayling, eel and brown trout. For a detailed description of the test configurations and fish species, see Flügel *et al.* (2015). The foci of the present study, in contrast, are the quantitative and descriptive presentation of the hydraulics of the FGS, their FGE and the brief discussion of their effects on the fish behavior.

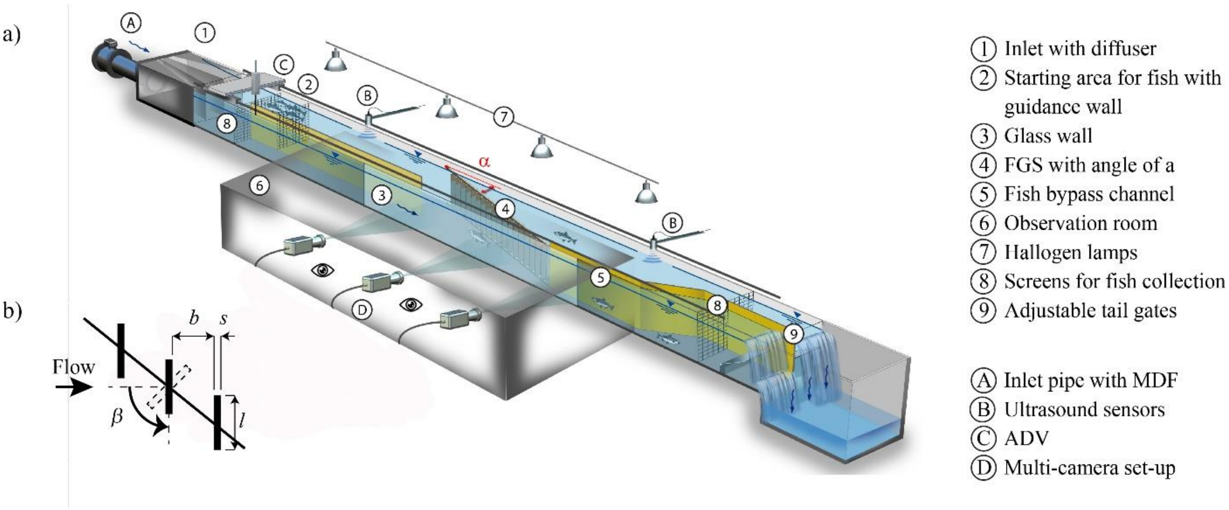

Fig. 2 (a) Sketch of ethohydraulic test rig with the model components and measurement techniques, (b) detail of louver and modified angled bar rack geometries

3 Results and Discussions

3.1 Modified Angled Bar Rack with α = 15°

Figure 3 shows 2D vector maps with the time averaged longitudinal velocities, *U* (*x*, *y*) and transverse velocities, *V* (*x*, *y*) normalized by U_0 for S1 (a, b) and S2 (c, d) at z/h_0 = 0.055 i.e. close to the channel bed. The lateral distribution of streamwise velocity *U* upstream of the rack shows a slight asymmetry being faster close to the left side wall at y/h_0 = 1.5. *U* starts gradually increasing from the upstream end of the structure and reaches maximum value of U_{max} = 1.6U_0 at x/h_0 = +5.0. At the foot of the rack, i.e. at the bypass entrance, U sharply decreases from 1.6U_0 to approx. 1U_0. Regarding the transverse velocity, the flow is strongly diverted to the left side of the channel from the upstream end of the rack. The maximum transverse velocity occurs at x/h_0= 0 with V_{max} = 0.2U_0. Along the rack V loses its strength until reaching the bypass, being negative at the foot of the structure (Fig. 3b). In this critical area the value of V becomes -0.1 U_0 indicating a risk of fish entrainment or impingement. With installation of a BO (S2, Fig. 3c, d), the situation is considerably improved and the flow acceleration is smaller with U_{max} = 1.4U_0 at x/h_0 = +5.0 (Fig. 3c). Furthermore, the flow is quasi-uniformly diverted to the left side of the channel along the rack with no flow diversion towards the rack near the bypass. As a result, low risk of fish entrainment and high fish guidance efficiency are expected.

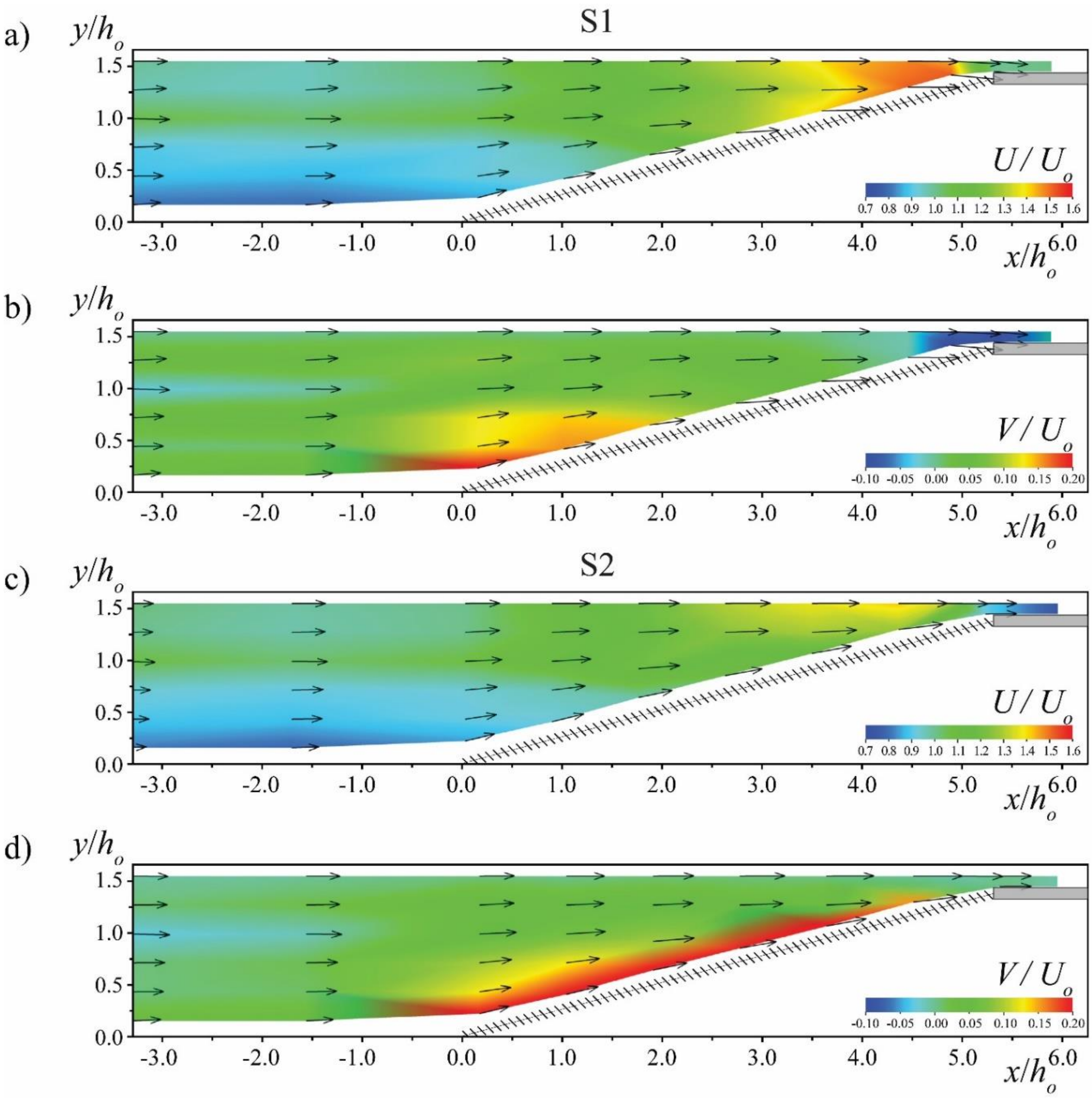

Fig. 3 MBR with α = 15°: 2D velocity vector map with the normalized time averaged longitudinal velocities, U (x, y) and transverse velocities, V (x, y) in the background for S1 (a, b) and S2 (c and d) (adapted from Albayrak *et al.* 2015)

3.2 Modified Angled Bar Rack with α = 30°

Figure 3 shows 2D vector maps with the time averaged longitudinal velocities *U* (*x*, y) and transverse velocities *V* (*x*, *y*) normalized by U_0 for S3 (a, b) and S4 (c ,d) at $z/\ h_0$ = 0.055. Figure 4a shows similar flow properties as detected with S1 and S2. The streamwise flow is asymmetrically distributed in the lateral direction. The velocities are higher at the left side of the channel. The flow becomes quasi-uniform around x/h_o = 1.0 with U = 1.1U_0. From this point downstream, the flow velocities continue increasing and reaches its maximum of 1.4U_0 around x/h_o = 2.0, which is smaller than for S1. Once again, similar to S1, the flow velocity decreases through the bypass. Regarding to transverse velocities, a strong flow diversion to the left side of the channel occurs upstream of the rack for S3 (Fig. 4b). Its strength decreases along the rack and the transverse flow velocity becomes zero and even slightly negative in front of the bypass. In contrast, for the rack configuration S4, the BO diverts the flow to the left side of the channel along the rack up to the bypass (Fig. 4d) while it slows down the streamwise velocity compared to S3. Consequently, no flow diversion towards the rack occurs near the channel bed near the bypass similar to S2.

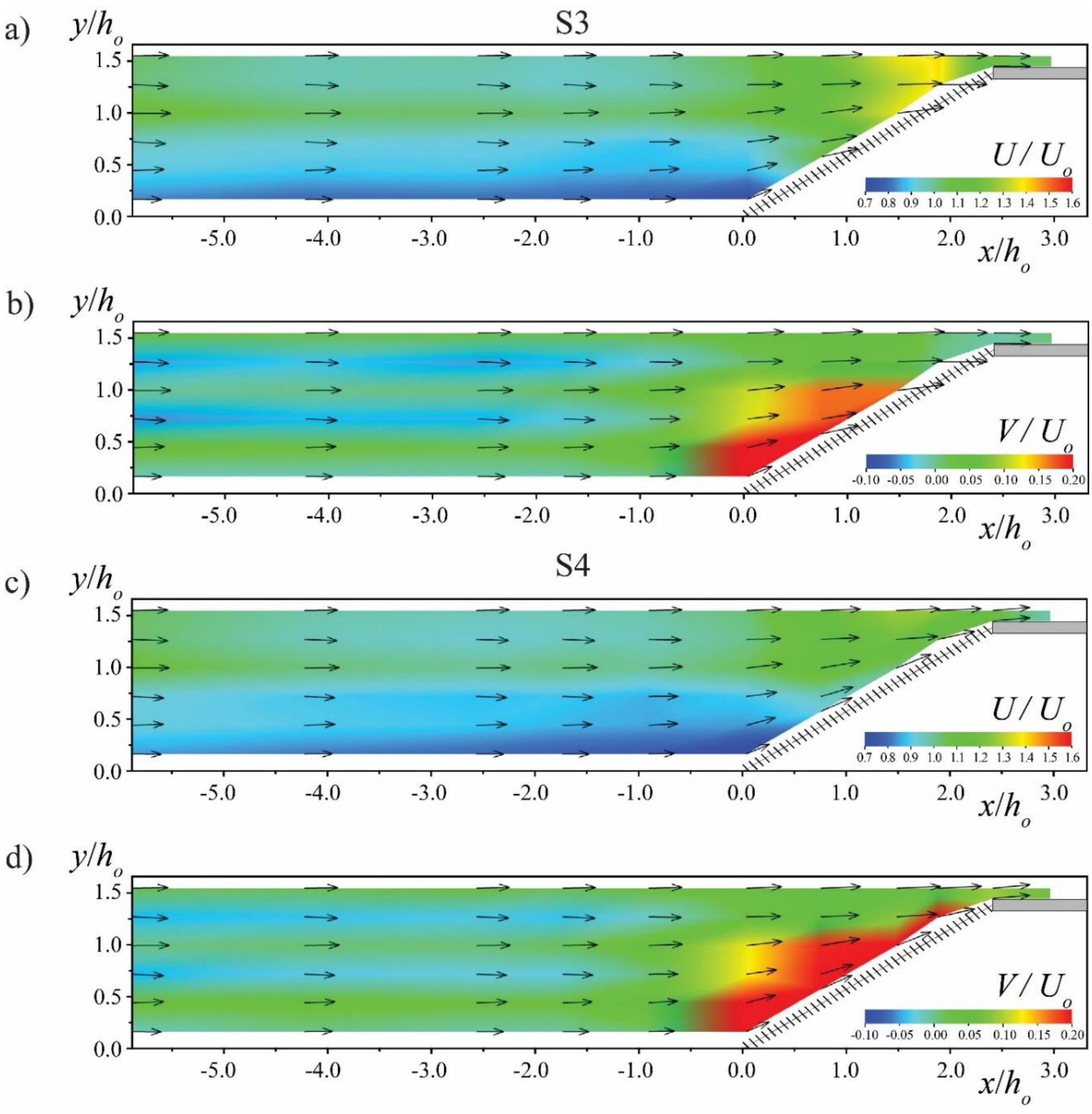

Fig. 4 MBR with α = 30°: 2D velocity vector map with the normalized time averaged longitudinal velocities, *U* (*x*, *y*) and transverse velocities, *V* (*x*, *y*) in the background for S3 (a, b) and S4 (c and d) (adapted from Albayrak *et al.* 2015)

3.3 Fish Guidance Efficiency of Modified Angled Bar Racks

The FGE of the studied MBR was determined with live-fish experiments in the ethohydraulic channel (Fig. 2a). Ethohydraulics describes the study of interactions between aquatic fauna and hydraulic structures under laboratory conditions (Adam and Lehmann 2011). The FGE is defined as the percentage of fish successfully bypassed (Flügel *et al.* 2015, Kriewitz 2015). The MBR were tested with different fish species such as barbel, spirlin, grayling, eel and brown trout. Table 2 lists the fish species for each MBR.

It is evident that the implementation of a BO significantly increases the cross-species FGE (S2 and S4, Fig. 5). FGE of both S2 and S4 was at least 90% and the difference between them is negligible, while the minimum FGE were 75% and 80%, respectively (Fig. 5). The comparison of the mean FGE for all tested species between S1 and S3 suggests that S1 has a distinct advantage with a smaller rack angle α = 15° over S3 with α = 30°, which is in agreement with EPRI and Dominion Millstone Laboratories (2001). However, the reason for this result lies in the highly differentiated behavior of Grayling, which were tested only for the MBR with α = 30°. For S3 without a BO, 65% of individuals refused to enter the bypass. Unlike the small-sized fish spirlin, this behavior i.e. avoidance is not because of graylings' exceeding sprint speed but rather sudden flow velocity decrease at the bypass. This condition was improved with the BO (Fig. 4d) resulting in a greatly increased FGE i.e. 96% for grayling. Moreover, it is assumed that the FGE of S1 would similarly be affected if it was tested with graylings. Therefore, one can hypothesize that the optimization of the bypass flow condition, which did not vary for any of the configurations, the acceptance of graylings to enter the bypass can be increased even without the use of a BO (Kriewitz 2015).

In summary, MBR with either 15° or 30° rack angle showed similarly promising results with high FGE for most tested species (Kriewitz *et al.* 2015). From an economic perspective 15° angled MBR offers lower hydraulic losses, while 30° angled MBR provides a good alternative considering lower initial construction costs due to their shorter length.

Table 2 Fish species tested for different MBR configurations in the ethohydraulic experiments

Exp.	Barbel	Spirlin	Grayling	Eel	Brown trout
S1	X	X		X	X
S2	X			X	X
S3	X	X	X		
S4	X	X	X	X	X

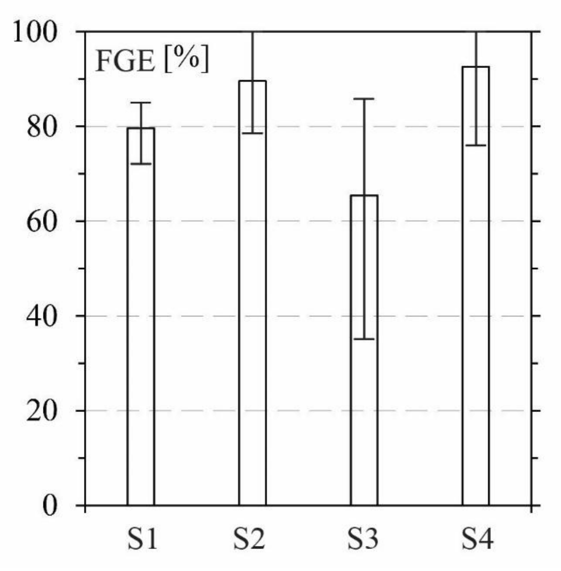

Fig. 5 Mean, minimum and maximum cross-species averaged FGE for the rack configurations, S1 to S4 (Kriewitz 2015)

4 Conclusions

Modified angled bar racks (MBR) were studied in an ethohydraulic laboratory channel at moderate Reynolds numbers. Profiles of longitudinal and transversal flow velocity components were measured near the FGS and in the bypass. Four main rack configurations with a bar angle of β = 45° to the flow direction were tested: MBR with α = 15° with/without a bottom overlay (BO, S1, S2) and MBR with α = 30° with/without a BO (S3, S4), respectively.

Rack angle noticeably affected the flow field. The average flow velocities near the bypass were higher for the MBR with α = 15° than for the MBR with α = 30°, both with and without a BO. Moreover, the former created a strong flow diversion towards the rack in front of the bypass while it was mild for the latter. Implementation of a BO improved the flow conditions at the bypass by causing no-flow diversion.

Primary results of the live fish experiments without BO suggest that the fish guidance efficiency was higher for the MBR with α = 15° than for the MBR with α = 30° and the differences between them was significantly depending on the fish species tested here. If the result of Grayling tests were excluded, the FGE of both MBR were similar. The use of a BO produced higher FGE for all tested species. However, there is still more research required especially on the bypass geometry and resulting flow conditions for further increase of the FGE.

The present research study provides an important step towards the understanding of (I) flow structures created by FGS, e.g. MBRs, (II) behavior of fish species in the Central European rivers and (III) fish interactions with FGS.

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References

Adam, B., Lehmann, B. (2011). Ethohydraulik - Grundlagen, Methoden und Erkenntnisse. Springer-Verlag, Berlin, Heidelberg, Deutschland.

Albayrak, I.; Kriewitz, C.R.; Beck, C.; Boes, R.M. (2015). Flow fields around fish guidance structures. Proc. IAHR Congress *2015*, The Hague, the Netherlands (online published).

Amaral, S. V. (2003). The use of angled bar racks and louvers for guiding fish at FERC-licensed projects*. FERC Fish Passage Workshop*, Holden, USA.

Amaral, S. V.; Winchell, F. C.; McMahon, B. J.; Dixon, D. (2003). Evaluation of angled bar racks and louvers for guiding silver phase American eels. American Fisheries Society, Symposium 33: 367-376.

Boes, R.M., Albayrak, I., Kriewitz, C.R., Peter, A. (2015). Fischabstieg mittels Leitrechen - aktueller Forschungsstand*.* Aqua viva 57(4): 16-19, http://www.aquaviva.ch/wissen/zeit-schrift.

EPRI (Electric Power Research Institute) (1999). Review of Downstream fish passage and protection technology evaluations and effectiveness. Alden Research Laboratory, Inc., EPRI Report No. TR-111517.

EPRI; Dominion Millstone Laboratories (2001). Evaluation of angled bar racks and louvers for guiding fish at water intakes. Palo Alto, CA and Waterford, CT, USA. Report 1005193: 106 S.

Flügel, D.; Bös, T.; Peter, A. (2015). Untersuchungen zum Fischabstieg entlang eines vertikalen, schräg ausgerichteten Fischleitrechens an grösseren mitteleuropäischen Flusskraftwerken - Ethohydraulische Untersuchungen in einem Versuchsgerinne, Eawag, Kastanienbaum, Schweiz, www.swv.ch/Portrait/Verbandsgruppen/Aare-Rheinwerke/Projekt-Fischabstieg.

Kriewitz, C. R. (2015). Leitrechen an Fischabstiegsanlagen - Hydraulik und fischbiologische Effizienz, VAW-Mitteilung 230 (R. Boes, ed.), Versuchsanstalt für Wasserbau, Hydrologie und Glaziologie, ETH Zürich, www.swv.ch/Portrait/Verbandsgruppen/Aare-Rheinwerke/Projekt-Fischabstieg.

Kriewitz, C. R.; Albayrak, I.; Boes, R. M. (2015). Forschungsprojekt „Massnahmen zur Gewährleistung eines schonenden Fischabstiegs an grösseren mitteleuropäischen Flusskraftwerken“, Wasser, Energie, Luft, 107(1): 17-28, www.swv.ch/Portrait/Verbandsgruppen/Aare-Rheinwerke/ Projekt-Fischabstieg.

Kriewitz, C. R.; Albayrak, I.; Boes, R. M. (2013). Massnahmen zur Gewährleistung eines schonenden Fischabstiegs, Aqua Viva, 55(5): 17-21.

Raynal, S.; Chatellier, L.; Courret, D.; Larinier, M.; Laurent, D. (2013). An experimental study on fish-friendly trashracks - Part 2. Angled trashracks. Journal of Hydraulic Research, 51(1), 67-75.

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