Alternative blade materials for technical and ecological optimization of a hydraulic pressure machine

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Abstract. The Hydraulic Pressure Machine (HPM) is an energy converter to exploit head differences between 0.5 and 2.5 m in small streams and irrigation canals. Previous investigations show that efficiencies above 60 % are possible. Several case studies indicate good continuity for aquatic life (e.g. fish) and bed load for the technology. The technology is described as an economically and ecologically viable option for small scale hydropower generation. Primary goal of this research is to improve the HPM blade design regarding its continuity properties by maintaining good efficiency rates. This is done by modifying the blade tip and testing within a large physical model under laboratory condition. Blade tips from steel (conventional – reference case) and a combination of EPDM rubber and steel as sandwich construction (rubber, steel, rubber – adhesive layered) are tested and compared. Both materials reach similar values for hydraulic efficiency (approx. 58 %) and mechanical power output (approx. 220 W). The variation of different gap sizes pointed out the importance of small clearance gaps to reach high efficiencies. For assessing the two blade tip materials regarding continuity for aquatic life, fish dummies were led through the wheel. Analysis of slow motion video of dummies hit by the blade show significant advantages for the EPDM blade tip. The EPDM rubber allows to bend and thus reduces the shock and the probability for cuts on the fish dummy. It was shown that blade tips from EPDM have certain advantages regarding continuity compared to standard blade tips from steel. No compromise regarding energy production had to be made. These results from the HPM can be transferred to breast shot water wheel and may be applied for new and retrofitting projects.

1. Introduction

The Swiss engineer Walter Zuppinger developed two types of water wheels. The well known *Zuppinger wheel* which is a classic breast shot water wheel and a similar wheel with a closed hub [1]. To the author's knowledge, figure 1 from the 1860ies is the first illustration showing a water wheel with a closed hub. In the following text, these kind of wheels are called Hydraulic Pressure Machines (HPM).

The HPM looks similar to a typical breast shot water wheel but has some significant differences. Special features of the technology are the fewer number of blades (around 12 to 24 - unlike traditional water wheels with around 36 to 48 blades) and a relatively large central and closed hub (measuring 1/3 of the outer diameter) to dam up the upstream water level (see figure 1 and 2). For optimal power extraction the upstream water level is kept at the top of the


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hub. Therefore the wheel runs at variable speeds, as it has to cope with the naturally changing flow.

The technology developed by Zuppinger was ignored completely during industrialization and was never applied for a real installation. But the technology was rediscovered in the beginning of the 21st century and investigated in detail by the University of Southampton (UK), the Darmstadt University of Technology (DE) and the University of Architecture, Civil Engineering and Geodesy in Sofia (BG) [2–5].

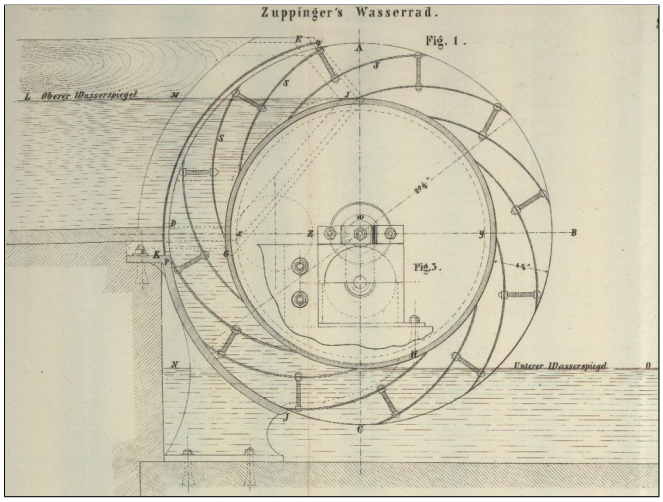

Figure 1: Hydraulic Pressure Machine (HPM) [1]

The HPM is run by the hydraulic pressure difference between up- and downstream water levels [3]. Experimental results indicate that the technology is suitable for power extraction in sites with small head differences (0.5 to 2.5 m) [6]. Furthermore, it was found that one of the main benefits of the HPM compared to other hydraulic machines like traditional water wheels and turbines is, that the wheel allows a good continuity for aquatic life (e.g. fish) and bed load [3]. This advantage is due to the slow rotational speed (2 to 12 min^{-1}) and the small number of blades, which creates a relatively large space between two blades. Efficiency rates from 60 up to 80 % were achieved [1, 3, 4, 7].

To further improve the continuity for fish at HPMs, alternative blades or rather blade tip materials and different bottom clearance gap sizes are investigated in this study. The main goal is to find a blade tip material, with which the level of injury for fish hit by the blade can be reduced. The alternative blade tip design however should not result in significant power losses.

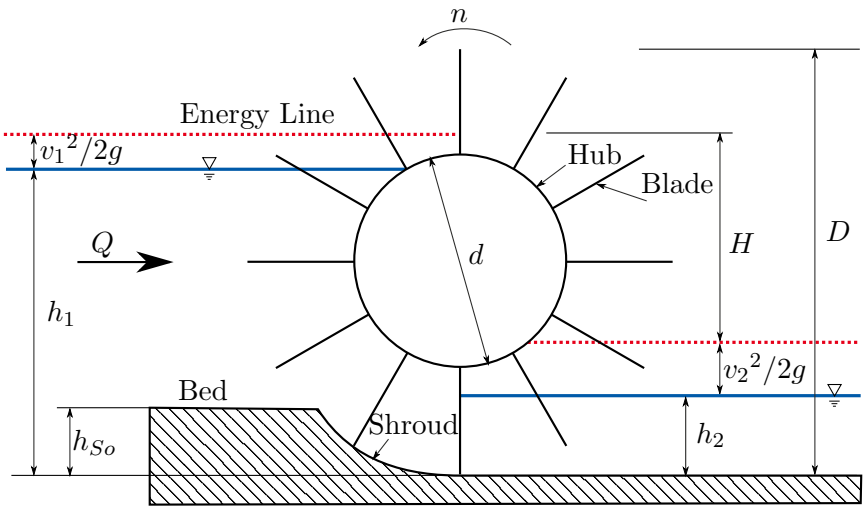

Figure 2: Functional principle of a Hydraulic Pressure Machine (HPM)

2. Experimental program

The objective of the experimental program is to evaluate (1) the efficiency and power output of the wheel, (2) the level of injury of fish dummies due to blade-strike and (3) the influence of three different clearance gap sizes. A physical model of a HPM was built and tested under laboratory condition to investigate these three main questions. To minimize scale effects, achieve high precision results and keep the option for prospective experiments with live fish, a large scale physical model was chosen. The model scale corresponds roughly 1 : 2.5 to a real installation in Bulgaria [5].

2.1. Test rig

The model of the HPM wheel was installed in a 20 m long and 3 m wide concrete flume in the hydraulic laboratory of the University of Applied Sciences Darmstadt (D). Figure 3 left shows the flume with the tested HPM on the right and parts of a slot fish pass on the left.

The wheel itself has an outer diameter (D) of 1.1 m, a hub diameter (d) of 0.4 m and a width (W) of 0.8 m. 12 flat, 2 mm thick blades from stainless steel are diagonally mounted at the circumference of the hub. The blades are set at an angel of 15° to the shaft of the wheel. The hub is machined from polyethylene. The shaft and load bearing disks (mounted on the shaft) are made of stainless steel. The blades are bolted to the three load bearing disks at the sides and middle of the hub. The wheel is placed over a concrete curved shroud following the outer diameter of the wheel. The inlet and outlet channels are 1.2 m wide (W_1, W_2). Figure 3 (right) shows the wheel in detail. Table 1 summarizes the main geometrical details of the tested wheel. The model itself is designed for maximum flexibility, in order to allow further modification of blade geometry, blade number etc. The blade border at the tip and the sides of the blade are exchangeable. This enables tests of different blade tip versions and the variation of the clearance gap (up to 20 mm).

Table 1: Model parameter summary

Parameter		Dimension
Outer Diameter	D	1.1 m
Hub Diameter	d	0.4 m
Machine Width	W	0.8 m
Width In- and Outlet	W_1, W_2	1.2 m
Number of blades		12
Blade angle (to shaft)		15°

2.2. Measurement technique

To determine the power output and efficiency of the converter we measured values for water levels up- and downstream (h_1, h_2), flow rate (Q), torque (M) and speed of the wheel (n). It is important for the operational characteristics of a HPM to keep the upstream water level constant. Thus, a control system is mandatory.

The HPM test setup is electronically braked by a coupled magnetic powder brake FRAT 2002 from Mobac Gmbh. The torque (M) is logged by torquemeter TRS 200 by Liedtke, the revolution (n) by shaft encoder ITD 01 A 4 1024 H NX KR1 S6 by Thalheim and the water levels up and downstream of the wheel (h_1, h_2) by ultrasonic sensor BUS R06K1-XA-12/070-S75G by Balluff. The water levels are measured from above to the water surface. A V notch weir is used for flow rate (Q) measurement (see figure 3 left, background). The head over the

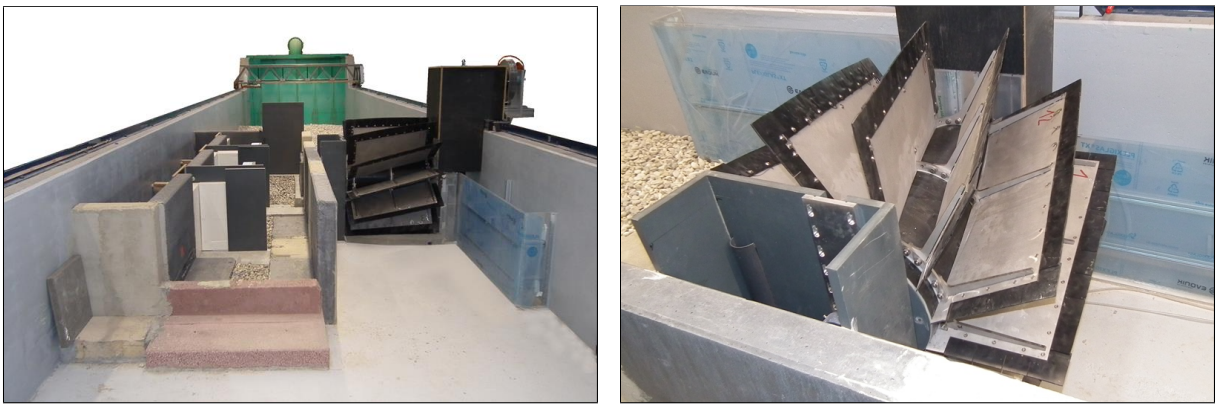

Figure 3: Photo of the test rig from down- to upstream (left) and the wheel in detail with EPDM blade tips mounted (right)

weir is measured via ultrasonic sensor (same make as for the water levels). As a control system for the brake and for data acquisition purpose a LabVIEW based software in combination with a CompactRIO-9074 from National Instruments is used. A measurement period of 30 s and sampling rate of 50 Hz applies for all collected data. Table 2 summarizes the measuring devices and their accuracy used for data acquisition.

Table 2: Data acquisition system

Parameter		Make	Model	Accuracy
Water level	h_1, h_2	Balluff	BUS R06K1-XA-12/070-S75G	±0.15 %
Flow rate	Q	Unknown	V notch weir	±1.25 %
Speed	n	Thalheim	ITD 01 A 4 1024 H NX KR1 S6	±0.23 %*
Torque	M	Liedtke	TRS 200	±0.60 %
* speed dependant (exaple for 8 min^{-1})				

2.3. Analysis

Data analysis is done in accordance with IEC 60193 *Hydraulic turbines, storage pumps and pump-turbines – Model acceptance tests*. The most important parameter for comparison with other converters is the hydraulic efficiency (η_{Hy}). It is the quotient of the measured mechanical power (P_{Me}) at the output shaft of the wheel and the energy in the flowing water called hydraulic power (P_{Hy}).

The energy in the flowing water can be described by the product of the total energy head (H) in m, the flow rate (Q) in $\mathrm{m^3\,s^{-1}}$, the density of the water ($\varrho = 1000\,\mathrm{kg\,m^{-3}}$) and the acceleration of gravity ($g = 9.81\,\mathrm{m\,s^{-2}}$).

$$P_{Hy} = H\ Q\ \varrho\ g \tag{1}$$

with

$$H = h_1 + \frac{{v_1}^2}{2\,g} - \left(h_2 + \frac{{v_2}^2}{2\,g}\right) = \frac{{v_1}^2 - {v_2}^2}{2\,g} + h_1 - h_2 \tag{2}$$

The flow velocity up- and downstream of the wheel (v_1, v_2) in $\mathrm{m\,s^{-1}}$ is calculated according to the law of continuity and not measured. The values therefore represent the mean velocity, with bed elevation upstream (h_{So}) and channel width (W_1, W_2) upstream and downstream of the wheel (see figure 2).

$$v_1 = \frac{Q}{W_1\ (h_1 - h_{So})} \qquad v_2 = \frac{Q}{W_2\ h_2} \tag{3}$$

The mechanical power measured at the shaft of the wheel is described as the product of torque (M) in N m and the speed of the wheel (n) in $\mathrm{s^{-1}}$.

$$P_{Me} = 2\ \pi\ M\ n \tag{4}$$

The hydraulic efficiency is the quotient of mechanical power and hydraulic power.

$$\eta_{Hy} = \frac{P_{Me}}{P_{Hy}} = \frac{2\ \pi\ M\ n}{H\ Q\ \varrho\ g} \tag{5}$$

The uncertainty involved in the measured data is calculated according to the constant odd combination method [8]. Experimental data contains random (statistical) and bias (systematic or fixed) error. Random error is calculated based on standard deviation of multiple measurements taken at the same condition. Fixed error is calculated based on the specification of the used measurement equipment. Table 2 summarizes the average accuracy of all measurement equipment used. The overall uncertainty for each measured value is calculated as the root sum square of the fixed error and random error. To calculate the uncertainty of computed values, namely mechanical power output (P_{Me}) and hydraulic efficiency (η_{Hy}), the method of uncertainty propagation is used [8]. The overall uncertainty for power output is summarized in Eq. (6) and for the hydraulic efficiency in Eq. (7).

$$\frac{\delta P_{Me}}{P_{Me}} = \pm\sqrt{\left(\frac{\delta M}{M}\right)^2 + \left(\frac{\delta n}{n}\right)^2} \tag{6}$$

$$\frac{\delta \eta_{Hy}}{\eta_{Hy}} = \pm\sqrt{\left(\frac{\sqrt{\delta h_1^2 + \delta h_2^2}}{h_1 - h_2}\right)^2 + \left(\frac{\delta Q}{Q}\right)^2 + \left(\frac{\delta M}{M}\right)^2 + \left(\frac{\delta n}{n}\right)^2} \tag{7}$$

2.4. Test procedure

Two different blade tip materials were chosen for comparison. The interchangeable blade tip spans the entire width of the blade and is approx. 60 mm long. First, a steel blade tip (2 mm thick), representing a conventional blade design as a reference case, is analyzed (see figure 4 left). Secondly, a combination of EPDM rubber (EPDM/SBR Shore hardness of 80° ±5°, 2 mm thick) and steel (stainless steel, 0.8 mm thick) is tested (see figure 4 right). The two materials are combined as a sandwich construction (rubber, steel, rubber adhesive layered). The blade tip itself is divided into 10 cm wide sections which are partly flexible. Each individual section is reinforced by a middle steel sheet and therefore is stiff enough to resist the usual hydraulic forces that arise during regular operation. Three sides of each section are flexible enough to allow the blade to bend against an object (e.g. fish). Main goal of this alternative blade design is to reduce the impact and thus the level of injury if a fish gets hit by the blade while passing the wheel.

To assess the influence of the size of the bottom clearance gap (between blade and shroud) on the efficiency and mechanical power output, three different sizes (1, 5 and 10 mm) are



Figure 4: Metal (left) and EPDM (right) blade tip

investigated. We analyzed the gap sizes for the two different blade tips, in order to register possible interdependency between blade material and gap size.

For all tests the water level upstream is kept at the top of the hub ($h_1 = 750\,\mathrm{mm}$) and the downstream water level is at the bottom of the hub ($h_2 = 350\,\mathrm{mm}$). Earlier research showed that this water level combination results in optimal energy extraction of these machines [9]. All experiments are conducted with flow rates between 30 and $180\,\mathrm{L\,s^{-1}}$ in steps of 5 and $10\,\mathrm{L\,s^{-1}}$. The variation of flow is done to evaluate whether the properties especially of the EPDM blade tip remain constant over the whole band of operation.

For the resulting optimal operation point (see section 3.1) a set of self-made fish dummies is guided through the wheel. The dummies consist of a paraffin wax core and a 3 mm thick malleable outer layer from Plastic-Fermit, a permanently plastic, kneadable sealant compound based on plastic. Two dummy sizes were produced and tested: 12 and 20 cm long representing real fish of the size 30 and 50 cm (according to the scale of the model of 1 : 2.5). Slow motion videos of their passage through the wheel are analyzed to assess the impact of the blade on the dummy. Due to the malleable surface of the dummy, the degree of damage/injury can be seen and evaluated after the passage. The fish dummies passage through the wheel is analyzed qualitatively based on underwater video capture.

3. Results

3.1. Results on power output and efficiency

Figure 5 shows the efficiency and mechanical power output of two different blade tips. The curves indicate that there is no significant difference in mechanical power output or efficiency between the two blade tip versions. The diagrams demonstrate that the metal blade tip has slightly higher efficiency and the EPDM blade a slightly higher mechanical power output. These differences lie within the uncertainty range of the measured data and can therefore be described as insubstantial.

The maximum efficiency reached by metal blade tips (reference case; 1 mm gap) is $57.8 \pm 1.7\,\%$ at $60.2\,\mathrm{L\,s^{-1}}$ and the maximum mechanical power is $217 \pm 2\,\mathrm{W}$ at $130.7\,\mathrm{L\,s^{-1}}$. For the the EPDM blade tips a maximum efficiency of $57.2 \pm 1.6\,\%$ at $66.0\,\mathrm{L\,s^{-1}}$ and a maximum mechanical power of $222 \pm 2\,\mathrm{W}$ at $128.6\,\mathrm{L\,s^{-1}}$ is reached.

We conclude that no disadvantages regarding power extraction can be noticed by using alternative EPDM blade tips.

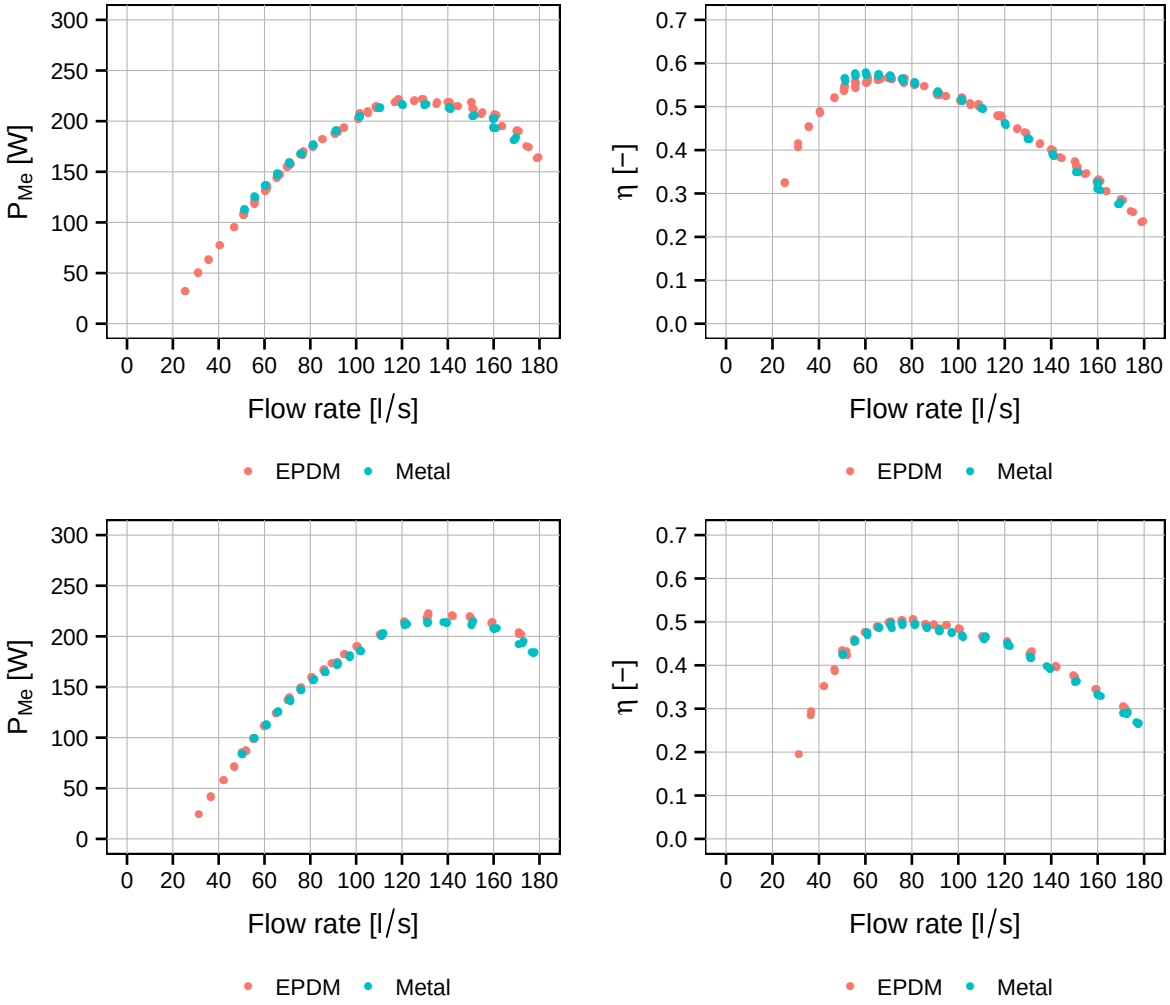

Figure 5: Comparison of different blade tip materials: mechanical power (left), efficiency (right), 1 mm clearance gap (top) and 10 mm clearance gap (bottom) | For better clarity error bars are suppressed

3.2. Results on clearance gap

Three clearance gap sizes (1, 5 and 10 mm) are tested. For a compact representation of the results only 1 and 10 mm are discussed here. With a 10 mm clearance gap, the metal blade tips reach $49.7 \pm 1.4\,\%$ efficiency at $76\,\mathrm{L\,s^{-1}}$ and a mechanical power of $214 \pm 2\,\mathrm{W}$ at $151.1\,\mathrm{L\,s^{-1}}$. For EPDM blade tips at 10 mm clearance, $50.6 \pm 1.4\,\%$ efficiency at $80.6\,\mathrm{L\,s^{-1}}$ and $223 \pm 2\,\mathrm{W}$ mechanical power at $131.6\,\mathrm{L\,s^{-1}}$ are reached.

The difference between 1 and 10 mm clearance gap for metal blade tips is an efficiency of $8.1 \pm 3.1\,\%$ and for EPDM blade tips it is $6.6 \pm 3.0\,\%$. Regarding power output the difference between the two gap sizes is $3 \pm 4\,\mathrm{W}$ for metal and $1 \pm 4\,\mathrm{W}$ for EPDM blade tips. These results show the importance of small clearance gaps to reach high efficiency rates. It is therefore of special importance to keep the clearance gap to a minimum. The differences between metal and EPDM lie within the uncertainty range of the measured data. This supports the above made conclusion that there is no disadvantages for EPDM in comparison to metal blade tips regarding power extraction. The maximum measured mechanical power is identical for different gap sizes and the two different materials.

3.3. Experimental results on dummies
The analysis of slow motion video shows clear advantages for EPDM blade tips. If the fish dummy gets hit by the blade it can be clearly seen that the EPDM rubber bends against the object and displaces. Based on this observation we assume that the shock on the fish is significantly reduced compared to an unyielding material like steel. It is further assumed that the likelihood of cuts is reduced due to the lack of sharp edges with EPDM blade tips. Visual evaluation of the plastic deformation on the dummies surface supports these assumptions.

4. Conclusion
To improve fish protection of the HPM, an alternative blade tip material has been investigated in this study. A blade tip combining stainless steel and EPDM rubber as a sandwich construction was found to be worth considering for further research. A conventional blade design (steel edge) was investigated as a reference case. For analysis and comparison, a large scale physical model was built. Both materials reached approx. 58 % hydraulic efficiency and a maximum mechanical power of approx. 220 W. Regarding power extraction and machine behaviour in general, no differences between the two analyzed blade tip materials were found. Results regarding the variation of the clearance gap size underlines the importance of minimal gap sizes for high efficiency rates and optimal power extraction. The analysis of slow motion videos of fish dummies led through the wheel show clear advantages for the EPDM blade tip. Observations show that the blade can evade the fish to a certain extent. This led to the assumption that the probability for cuts and serious injuries is reduced with EPDM blade tips. Thus, it can be concluded that EPDM blades had a considerable advantage when looking at fish protection, compared to usual sharp edged steel blades. The results found here for a HPM can easily be transferred to the technology of breast shot water wheels: The outermost lath (usualy larch wood) of the blade can easily be replaced by EPDM in existing conventional water wheels.

Nomenclature

d	Hub diameter	[m]	n	Rotational speed	$[s^{-1}]$
D	Outer diameter	[m]	P_{Hy}	Hydraulic power	[W]
g	Acceleration of gravity	$[m\,s^{-2}]$	P_{Me}	Mechanical power	[W]
h_1	Water level upstream	[m]	Q	Flow rate	$[m^3\,s^{-1}]$
h_2	Water level downstream	[m]	v_1, v_2	Flow velocity	$[m\,s^{-1}]$
h_{So}	Bed elevation	[m]	W	Width	[m]
H	Energy head	[m]	ϱ	Density	$[kg\,m^{-3}]$
M	Momentum	[N m]	η_{Hy}	Hydraulic efficiency	[−]

Acknowledgments
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