THE ROTARY HYDRAULIC PRESSURE MACHINE FOR VERY LOW HEAD HYDROPOWER SITES

James SENIOR[1]
Patrick WIEMANN
Gerald MÜLLER
University of Southampton, U.K.

ABSTRACT

This short paper introduces a novel energy converter, the Rotary Hydraulic Pressure Machine (RHPM). This machine has been specifically developed to exploit very low head hydropower sites where the fall height is less than 5m. The RHPM is described and a theory behind its operation is outlined. This is followed by scale model testing, the results of which are used to estimate the full-scale performance. This found that hydraulic efficiencies up to 80% can be achieved, and estimated flow capacities for a 2m head installation of up to 3.6m^3*/s per m width of machine. A case study demonstrates that the increased flow capacity and lower construction costs, compared to a traditional Zuppinger waterwheel installation, result in specific costs as low as 3000 €/kW installed capacity. This represents a significant improvement in very low head hydropower technology, making the economics more attractive to investors.*

1. INTRODUCTION

In the western world much of the large scale, high output hydropower sites have now been exploited. Within Europe the focus has therefore shifted to Small Hydro-Power; installations with power outputs below 10MW. The target is to achieve an additional 2.4GW of power generation from Small Hydro-Power plants by 2010, relative to the 2005 generation levels (European Commission 2007). Within this bracket are sites with 'very low head' which refers to sites where the vertical distance through which flowing water falls over structures or terrain is less than 5m. At this point in time, no technology for this bracket satisfactorily meets the economic and ecological requirements required by investors and the authorities. As a result, the Seventh Framework Programme's 'Research Priorities for the Renewable Energy sector' set by the European Union includes the development of small turbines for very low heads under 5m as one of its long term targets (EURECA 2005).

2. THR ROTARY HYDRAULIC PRESSURE MACHINE

2.1 Description

The Rotary Hydraulic Pressure Machine (RHPM) is a novel energy converter developed at the University of Southampton in the UK for exploiting very low head hydropower sites, with fall heights under 5m. It is currently at the prototype stage, with a proposed theory and scale model results following in this paper.

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[1] Civil Engineering Department, University of Southampton, Highfield, Southampton, SO17 1BJ, U.K., phone: +44 238059 4658; e-mail: js1301@soton.ac.uk

Depicted in Figure 1, the RHPM has just one moving part; a wheel with a diameter between 1.5m and 7.5m which rotates about a horizontal axis. The wheel has two critical components:

- The central hub: This is a horizontal cylinder which spans the width of the machine, and has a diameter equal to the head of the site. The top of the hub is level with the upstream water surface and the bottom of the hub is level with the downstream water surface.
- Twelve blades: The blades are the surface on which the water's energy is extracted. In the given example, they have the same length as the diameter of the hub or head of the site. They extend radially from the hub, whilst twisting as they progress across the width of the wheel. Overall they can be thought of as 'diagonally mounted', such that the termination of each blade coincides with the start of the subsequent blade on the other side of the wheel. This design is critical, allowing the large blades to enter and exit with minimal losses, and ensuring continual blade tip entry and exit from the water resulting in smooth consistent rotation.

Also depicted in Figure 1 are the main components of the wheel support structure, including:

- The shroud: This curved section of river bed ensures that at least one entire blade is enclosed within a close fitting channel. This prevents any leakage flow of water between and along the diagonally mounted blades, entering from beneath the wheel.
- Side walls: These not only provide a mounting for the wheel's bearings, but prevent any leakage flow of water between the blades entering from the sides of the wheel. Importantly, the side walls do not extend up to the water surfaces or along the entire length of the wheel. Instead the sides of the wheel remain exposed to allow water to enter the compartments between the blades from the side of the wheel as well as the front. They also allow air to 'ventilate' the compartments from the side of the wheel. This process allows the water to drain from the compartments with ease once they have reached the downstream.

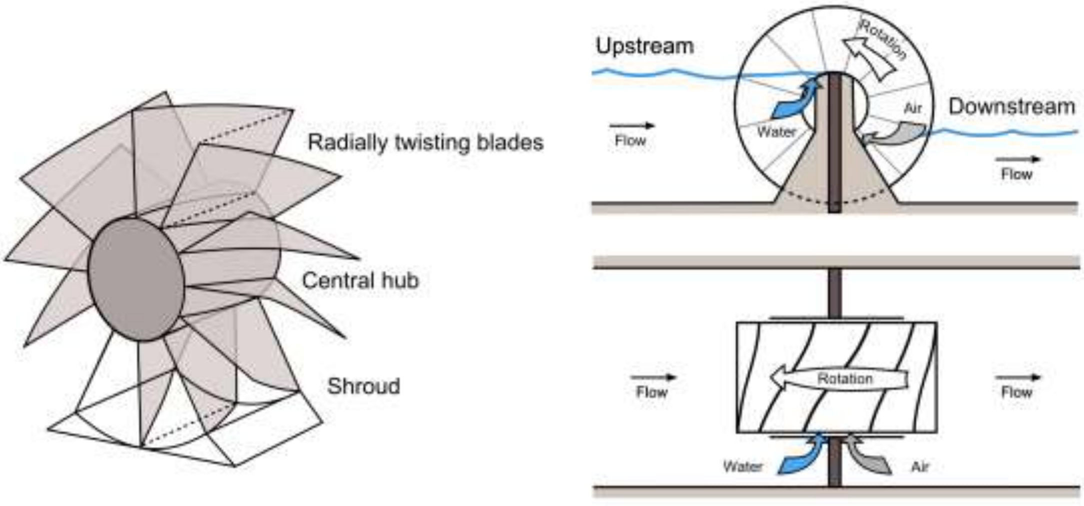


Figure 1: Depiction of the RHPM

The flow rate through the RHPM is proportional to the speed of rotation which is controlled by a 'load' such as a generator or mechanical power take-off.

It is envisaged that the RHPM could be employed in any conventional 'diversion' or 'run-of-river' installation, and would also be particularly suited for installation into bays of existing weir structures. Its complete symmetry would also allow it to operate with bi-directional flow, such as in tidal scenarios.

2.2 Theory

Starting from first principles, the Pressure, *P* at a depth of water, *h* with density, ρ of water, under the influence of gravity, *g* is:

$$P = h\,\rho\,g$$

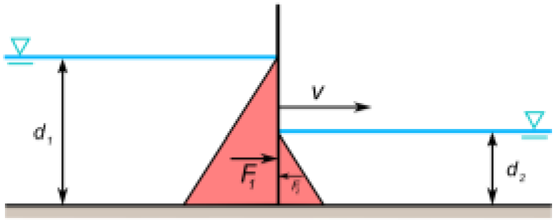


Figure 2: pressure acting on a simple vertical plate

Referring to Figure 2, consider a simple vertical plate which separates two dissimilar depths of water, d_1 and d_2. The triangles represent the hydrostatic pressure. The forces on either side of this plate of width, *W*, are F_1 and F_2:

$$F_1 = \rho\,g\frac{d_1^2}{2}W \qquad F_2 = \rho\,g\frac{d_2^2}{2}W$$

It can be seen that the force on the plate acting from the deeper water, F_1, is greater than that acting from the shallower water, F_2, and the total force acting on the plate, *F*, is:

$$F = \rho\,g\frac{(d_1^2 - d_2^2)}{2}W$$

If it is now imagined that the plate moves laterally with velocity, *v*, the power at the plate, *P*, is:

$$P = \left(\rho\,g\frac{(d_1^2 - d_2^2)}{2}W\right)v$$

The above example illustrates the most important principle behind the RHPM's operation: that two dissimilar depths of water acting across a vertical plate result in a force from which power can be extracted. In reality, it is not practical to have a vertical plate which moves laterally and indefinitely. Instead it is proposed that the plates, or *blades*, are mounted about an axle. This configuration adds additional complexity to the analysis as the water must flow from the deeper side of the RHPM to the shallower side.

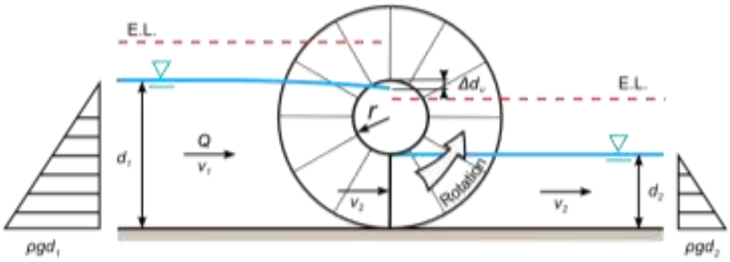


Figure 3: Operation of the RHPM

Referring to Figure 3 it can be seen in accordance with continuity that the velocity of the downstream water, v_2, is greater than that of the upstream water, v_1:

$$v_2 = \frac{d_1}{d_2} v_1$$

Therefore the water must undergo acceleration as it passes through the RHPM. Assuming for simplicity that the channel width is equal to that of the wheel, application of the energy equation gives the head drop associated with acceleration in the upstream, Δd_u as:

$$\Delta d_u = \frac{v_2^2 - v_1^2}{2\,g}$$

As all pressure forces acting directly on the central hub resolve towards the centre of the axel, only the pressure acting on the blade as it passes beneath the hub need to be considered. The force on the blade, F_p, is a function of the pressure difference across the blade and the area of the blade, A:

$$F_p = \rho\, g\; (d_1 - d_2 - \Delta d_u)\; A$$

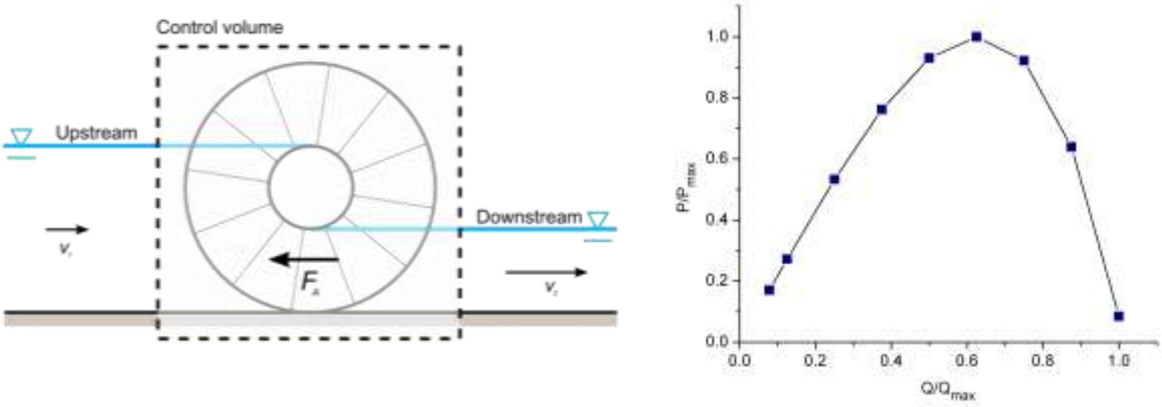


Figure 4: a) Reaction force on the RHPM, b) Theoretical power output of the RHPM

The force resulting from the pressure difference between the differing water depths, F_p, is not the only force that acts upon the RHPM. Figure 4a depicts a RHPM within a control volume, which can be thought of as a `black box' allowing the installation (wheel and all infrastructure) to be considered holistically. In passing through the control volume, a mass of water is accelerated from a lower speed, v_1, to a higher speed, v_2. In accordance with Newton's second and third laws, this acceleration must result in a force to which a counteracting force exists, provided by the installation itself. This counteracting force to the acceleration, F_A, is quantified by calculating the momentum change of the water, equal to the mass flow rate, Q, multiplied by the velocity change:

$$F_A = \rho\, Q\, (v_2 - v_1)$$

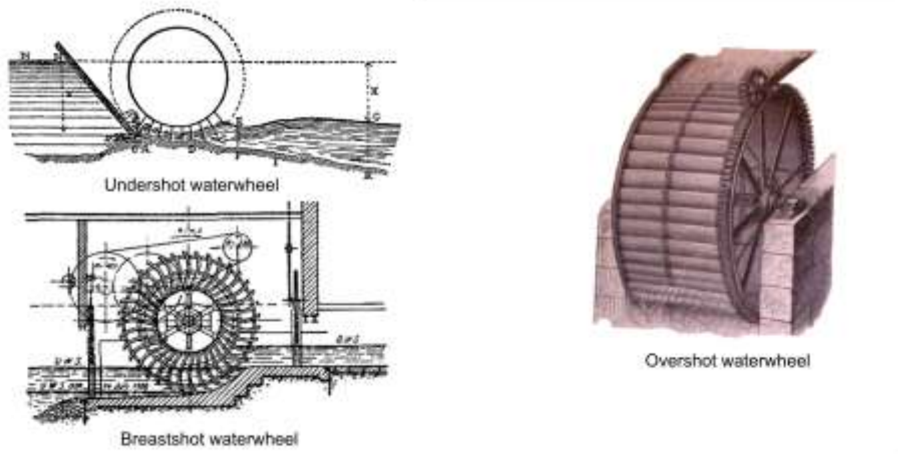
For simplicity it is assumed that all of the counteracting force to the acceleration of the water acts upon the blades. Also assuming no losses such as friction and turbulence, the theoretical power output, $P_{out\ ideal}$ is:

$$P_{out\ ideal} = (F_P - F_A)\; v_2$$

The theoretical output power for the RHPM is plotted in Figure 4b. The theoretical efficiency can also be plotted, however this requires analysis of the leakage flow through the gaps that exist between the wheel and the channel, and also all the sources of power loss including friction, turbulence etc. This part of the theory is design specific and is excluded from this short paper.

2.3 Differentiating properties

The RHPM can easily be confused with traditional waterwheels because of its large size and rotation about a horizontal axis. Such a comparison is misleading as the RHPM operates due to a different principle than traditional wheels.


Undershot waterwheel

Breastshot waterwheel

Overshot waterwheel

Figure 5: Common forms of traditional waterwheel

Figure 5 depicts the three regular forms of waterwheel. The *undershot* waterwheel was traditionally used for low heads and high flows; 0.5 – 2.5m head, 0.5 – 0.95m^3/s per m width (Müller and Kauppert 2004). The undershot waterwheel operated due to *impulse*, as a fast flowing stream of water impacted upon a blade moving at a slower velocity. Such waterwheels had maximum efficiencies in the range of 25% to 30% (Bresse 1876). The *overshot* waterwheel was used for relatively high heads and low flows; 2.5 - 10m head, 0.1 – 0.2m^3/s per m width (Muller and Kauppert 2004). The overshot waterwheel in comparison worked by *potential*, as it was the weight of the water within the buckets that drove the wheel. These had efficiencies up to 85% (Meerwarth 1935). The most common form of waterwheel built was the *breastshot* waterwheel, one form of which was the *Zuppinger* waterwheel shown in Figure 5. These wheels are a cross between the undershot and overshot waterwheel, being driven by both impulse and potential. The Zuppinger waterwheels were used for heads between 0.5 and 2m, with flow capacities not exceeding 1.2m^3/s per m width and efficiencies up to 73%(Müller 1939). These operating principles, impulse and potential, are clearly different to the RHPM, which is operated directly by the pressure of the water.

When compared to the Zuppinger waterwheel, the RHPM's operating principle allows for some significant design differences. The first of these is its small size relative to the head, with the upstream water level being above rather than below the axel height, reducing the machine's visual impact. Another is the large size of the blades of which there are relatively few; just 12 compared to 30 - 40. Being able to reduce the number of blades results in fewer losses detrimental to efficiency. The large size of the compartments between the blades, which fill 100% with water compared to the 60% of Zuppinger waterwheels (Muller 1939), allow a greater flow capacity per metre width of machine.

The RHPM extends from the water's surface down to the channel bed. This property should allow for improved natural sediment transport along the river when compared to Turbines and modern Zuppinger waterwheel installations. Turbines are normally designed to collect sediment upstream to prevent erosion of the blades and Zuppinger waterwheel installations require adjustable inlet gates to maintain a constant upstream water level. These act as barriers to flow resulting in a build-up of sediment upstream and prevent replenishment of sediment downstream. Similarly, the large open nature with which water enters the RHPM and the small number of blades may improve downstream fish passage conditions. This is because no large and sudden pressure changes take place and the chance of mechanical strike on small fish is reduced.

2.4 Model testing

The RHPM was hydraulically tested to ascertain its performance. This was done using a small scale model shown in Figure 6a. The model had a width of 0.245m, an outside diameter of 0.45m, and a hub diameter and blade length of 0.15m. Tests were conducted in a specially built flume of 2m length, 0.75m width, 0.4m depth and maximum flow rate of 25 l/sec.

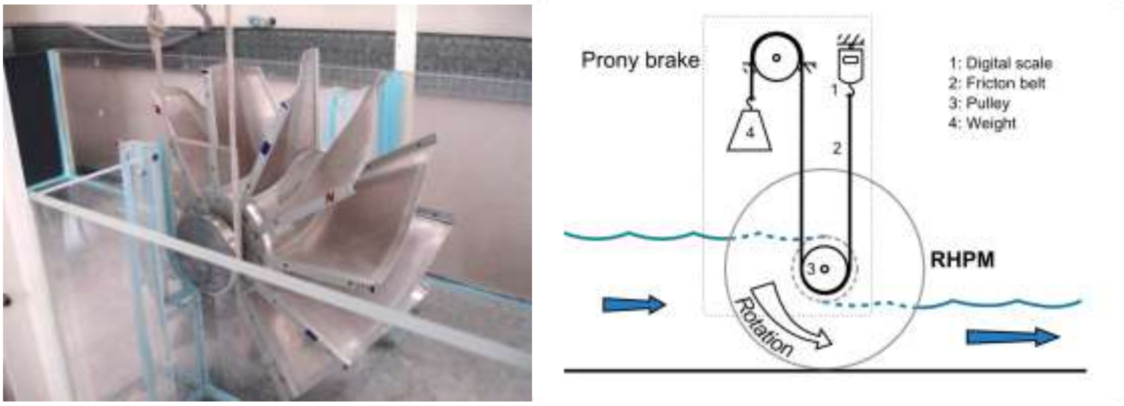


Figure 6: a) RHPM scale model, b) Prony brake power take off

The test series measured the flow rate, *Q*, power output, $P_{out\ measured}$, and efficiency, η, of the RHPM at several speeds of rotation ranging from stationary to maximum (freewheel at no load), whilst maintaining the upstream and downstream water depths to within 1mm to ensure a constant head.

The speed of the wheel was controlled using a ‘Prony Brake’. This is a traditional means of applying a load to a rotating shaft which also allows the power output of the shaft to be measured. Shown in Figure 6b, the Prony brake uses a weight and a counterweight (scale) of mass, m_{weight} and $m_{counterweight}$, and a friction belt to apply a torque to a pulley rotating with frequency, *f*. The Prony brake is used to calculate the output power, $P_{out\ measured}$, by multiplying the torque by the angular speed:

$$P_{out\ measured} = (m_{weight} - m_{counterweight})g \times r \times 2\pi \times f$$

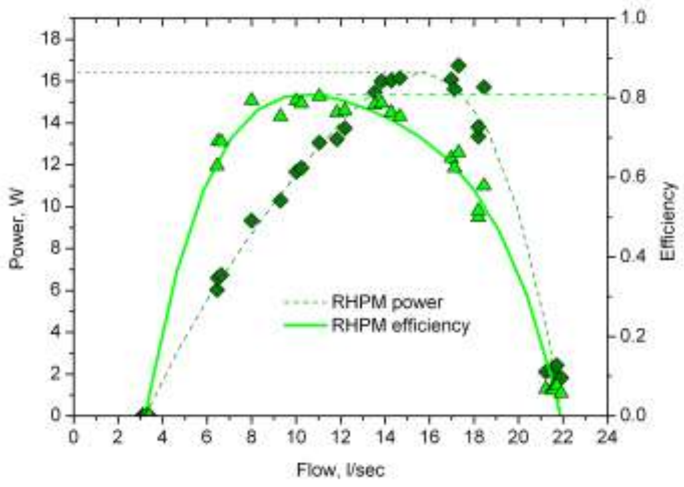
The flow rate was measured using a standard flow measurement weir and equations (Chanson, 2001):

$$q = \frac{2}{3} C\sqrt{2g(d_1 - \Delta z)^3} \qquad C = 0.611 + 0.08\frac{d_1 - \Delta z}{\Delta z}$$

The results of the model testing are shown in Figure 7a. It can be seen that the ‘RHPM power’ curve has a similar shape to that of the theory shown in Figure 4b, suggesting that the theory may be correct. The line does not intersect the axis at [0,0] as there was a constant leakage around the wheel of ~3 l/sec, driven by the pressure difference.

Figure 7a shows that the peak hydraulic efficiency is ~80%. The peak efficiency occurs at lower speeds of revolution and flow than the peak power output, P_{max}, which was 16.5W and occurred at 70% efficiency. The maximum acceptable flow rate, Q_{max}, can be taken as 18 l/sec, after which the efficiency and power output reduce significantly.

Assuming no scale effects, the Q_{max} and P_{max} of full scale installations have been estimated using the Froude scaling laws (Douglas, 2001), as shown in Figure 7b. The scaling maintains a head, hub and blade relationship of 1:1:1 as with the model. They suggest that for a 2m head, an RHPM could process 3.6m^3/s per m width of machine, which is ~300% that of a traditional Zuppinger waterwheel.



Head / Hub diameter / blade length, m	Q_{max}, m^3/s per m width	P_{max}, kW
0.5	0.5	1.4
1.0	1.3	7.7
1.5	2.3	21.3
2.0	3.6	43.7

Figure 7: a) RHPM scale model results, b) Full-scale estimates

3. CASE STUDY

A small case study is provided for a very low head hydropower site in the South of Germany. The site has a head of 0.9m, an average flow of 10m^3/s and a width restriction of 6m. Two reputable German manufacturers provided quotes for Zuppinger waterwheels for electricity generation, the average values of which are used to make a comparison with a RHPM installation, as shown in Figure 8. The quotes have been broken down into three cost groups:

- The wheel: The proposed Zuppinger waterwheels have a diameter and width of ~6m. They have 36 blades, each of which consist of wooden boards bolted to multiple curved and galvanised steel brackets. In comparison the RHPM only requires a diameter of 4.3m and a width of 5m. It would only require 12 blades and a central hub. Despite the RHPM requiring a greater quantity of steel, its smaller size (having a volume 40% that of the Zuppinger wheel), smaller quantity of parts and simple welded construction are expected to result in lower costs. Two scenarios are provided: the *best case* where the cost of the wheel is taken as 50% that of the Zuppinger waterwheel, and the *worst case* where the cost of the wheel is taken as 80% that of the Zuppinger wheel.
- The inlet gate: this component is required by the Zuppinger waterwheel to maintain a constant upstream water level. It is not required by the RHPM as the speed of rotation directly controls the flow rate and thus the water level.
- Common components and installation costs: These include the cost of the gearbox, generator, belts, control systems etc, and the costs of installation. They are applied directly to the RHPM from the Zuppinger waterwheel costs, as are the efficiencies of the gearbox, belt and generator.

Of importance *in this particular case study*, the RHPM with a hub of 0.9m and a blade length of 1.7m, has a flow capacity of 2m^3/s per m width. As a result, the full 10m^3/s flow at the site can be exploited, increasing the P_{max} by ~50% to 54kW when compared to the Zuppinger waterwheel installations which could only exploit ~8m^3/s of the available flow. With the estimated cost of the complete RHPM installation being between ~70% and ~80% of the Zuppinger waterwheel installation, the *specific cost* also improves, being between ~50% and ~60% of the Zuppinger waterwheel installation. This is the cost per kW of capacity installed, and at approximately 3000 €/kW the RHPM looks economically very attractive for very low head hydropower sites.

	Zuppinger quotes (averaged)	**RHPM, *best case***	**RHPM, *worst case***
Diameter, m	6.25	4.3	4.3
Width, m	6	5.0	5.0
Q_{max}, m^3/sec	7.9	10	10
$Q_{max,}$ m^3/sec per m width of wheel	**1.32**	**2.0**	**2.0**
Wheel efficiency, maximum, %	73	80	80
Gearbox / belts / generator efficiency, %	87	87	87
$P_{elecrical}$, kW	37	54	54
Wheel, €	94,000	47,000	75,200
Inlet, €	15,200	0	0
Common components and installation, €	92,300	92,300	92,300
Total before tax, €	**201,500**	**139,300**	**167,500**
Specific cost, € / kW installed	**5,450**	**2,650**	**3,150**

Figure 8: Case study comparing Zuppinger waterwheel and RHPM installations

4. CONCLUSION

The RHPM is a novel energy converter for very low heads below 5m. A plausible theory of operation has been proposed which suggests that it is driven directly by the pressure difference between two dissimilar depths of water either side of the installation. This is unlike any conventional waterwheel or turbine. Model tests showed that the machine has an efficiency up to 80%, and scaling of the model data suggests that flow capacities up to 3.6 m^3/s and powers of ~40kW per metre width of machine are achievable. A case study was conducted comparing the RHPM to a Zuppinger waterwheel installation and found that the larger flow capacity and relative simplicity of the machine could result in a 40% to 50% lower specific cost of around 3000 €/kW installed capacity. Such values would suggest that the RHPM could be economically attractive. Combined with its potential for improved sediment transport and fish passage, the RHPM could satisfy the FP7's demand for a new economically and ecologically acceptable technology suitable for very low heads less than 5m.

5. ACKNOWLEDGEMENTS

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