Potential for using the floating body structure to increase the efficiency of a free stream energy converter

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Abstract: *The design of 'classic' floating or boat mills in the 18th and 19th Century typically separated the design of the floating structure from the waterwheel. These waterwheels were of undershot design with low efficiencies. Today there is a desire to extract energy from all renewable energy resources and consequently technologies for extracting kinetic energy from river and tidal currents is being developed. Most of these technologies are based on wind turbine designs which require water depths greater than 20m to be viable. The current tested concept combines the use of a waterwheel with the floating body to both to accelerate the flow and produce a head difference. This is achieved by using a duct type forms and separators. To date experiments have shown efficiencies of up to 90% based on the wheel width. The design has a shallow draft, the results demonstrate the applicability for both large rivers and sheltered tidal sites and the concept is expected to be appropriate for remote areas with limited electrical grid connections*

Keywords: *Free Stream Energy Converter, Boat Mill.*

1. INTRODUCTION

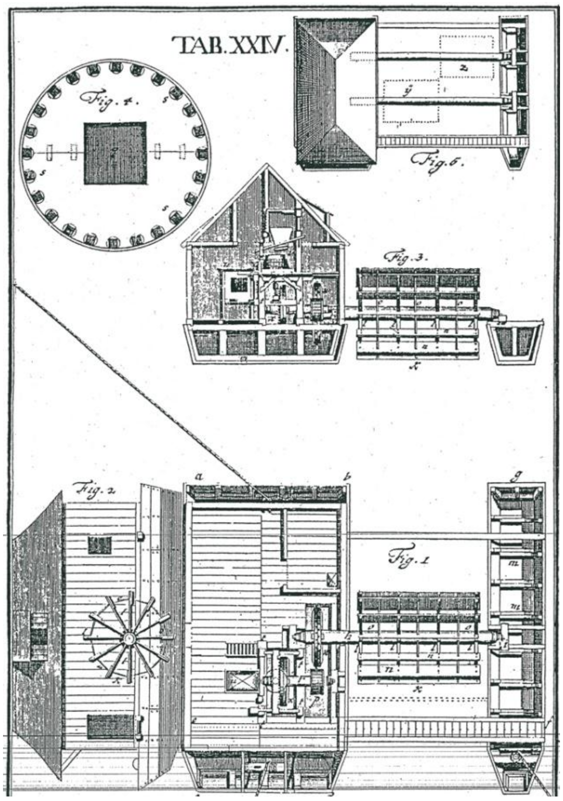
The Romans constructed floating mills as early as the 6th century. From Rome their use spread on the major rivers of Europe (Reynolds, 1983). Typical floating mills of the 18th and the early 19th century were designed to operate in strong river currents and normally consisted of a mill house in a boat and a float on the far side of the water wheel to stabilise the device. This typical layout is shown in Figure 1.a (Gräf D, 2006). These mills were common site on many large rivers throughout Europe and were often installed in close proximity as demonstrated in the artist's impression in Figure 1.b. During the industrial revolution these floating mills were the first mills to disappear due to the low power outputs and the interference with steam shipping and navigation. A few historic floating mills have been restored, for example a replica mill on the Mura river is shown in Figure 1.c. (Davorfiles, 2008).

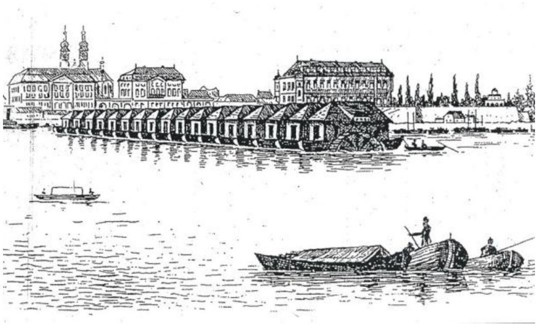
Today there is a new requirement to extract energy from renewable sources such as river and tidal currents. The work developed is based upon improving the classic designs, which separated the design of the wheel from the hull forms, to a design that uses the hull form to improve the performance of the wheel.

The work presented is a continuation of initial studies that have shown that a base plate between the hulls allows a hydrostatic pressure difference to develop across the water wheel. This significantly improves the performance. Page *et al.* (2009)'s qualitative results have also shown that the device efficiency can be further improved by the use of a separator at the stern.

This work forms a part of a wider FP7 energy project "Hydropower converters for very low head differences" (Müller, 2009; HYLOW, 2010) This research project aims to develop novel hydropower converters for very low head differences / pressure differences three segments of hydropower which are still hardly unused:

1. Hydropower with very low head differences between 0.5 and 2.5 m.
2. The energy of currents (river or tidal streams).
3. Small pressure differences in pipelines - (< 25 – 30 kPa).





(b) Drawing of floating mills at Cologne on the Rhine in 1856

(a) Layout of a typical floating mill, 1735

(c) Replica floating mill in still in operation on the Mura river in Croatia

Figure 1 Typical boat mill configurations

2. CHOICE OF MODEL GEOMETRY

Typical undershot water wheels were proven to have good design performance with a paddle immersion depth to diameter ratio of between 1:4 to 1:5 (Bresse, 1876). For the tests presented the wheel is designed a compromise between these undershot wheel as the new hydro static pressure wheel developed at Southampton University. (Senior *et al.* 2010) and a depth diameter ratio of 1:5 was chosen.

The hull form and layout is shown in the schematic in Figure 1.a. The bow section has a contraction region which is designed for maintain a constant flow velocity and a constriction which allows the development of a head in front of the turbine. The stern section also has an expansion section that is designed for the flow to exit at a shallower depth with a higher velocity.

In order for the design to also work in tidal estuaries it is preferable that the design is symmetrical so a large turning circle is not required. For the design to be cost effective choosing a hull form that has minimum length desirable due to material and fabrication costs.

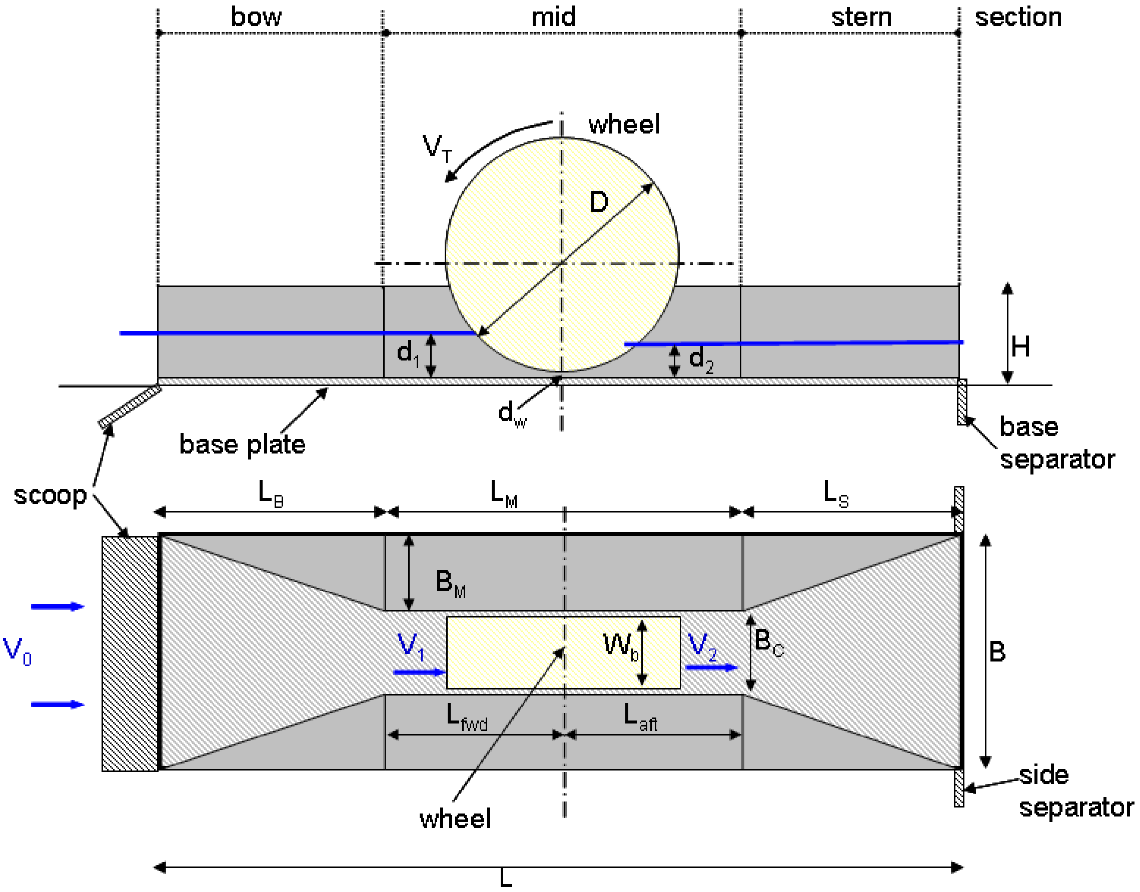


Figure 2 General schematic showing principle dimensions

Table 1 Principle model and test dimensions

Test	Scale	Value	Comment
Varied	Speed (V_0)	0.37 to 0.40m/s	The speed was held constant during each set of tests
All	Wheel clearance (d_w)	16 mm	
All	Beam (B)	420 mm	
All	Wheel breadth (W_b)	176 mm	Tolerance +/- 0.2 mm
All	Midsection beam (B_M)	120 mm	
All	Midsection length (L_M)	500 mm	
All	Wheel diameter (D)	500 mm	
All	Draft	100mm	External draft was set constant for all tests

3. TEST FACILITY, MODELS AND TESTS

3.1. Facility

The tests were performed in the circulating water channel at hydraulics laboratory of Technische Universität Braunschweig, Germany. The 30 m tilting flume has a width of 2 m and a maximum draft of 800mm. The test models were fixed rigidly in the tank about 20 m from the inlet in the centre. The flume was tilted (s = 0.0005) to ensure uniform flow conditions. The free stream velocity upstream of the model was measured by a Sontek ADV system. This was positioned a model width upstream and velocities were recorded with both the model wheel stationary and rotating.

3.2. Models

Details of the model geometry are shown in Figure 2 and the principle dimensions are presented in Table 1. The mid section is made of Acrylic to view the internal water depths. The bow and stern sections are made from foam and wood and are changeable to allow 45° and 26.6° inflow angles to be tested. Figure 3 shows a photograph of the model centred in the test tank with the 45° contraction and expansion sections. The model also has removable scoops to increase the effective inflow area and separator to generate a beneficial pressure drop downstream of the device.

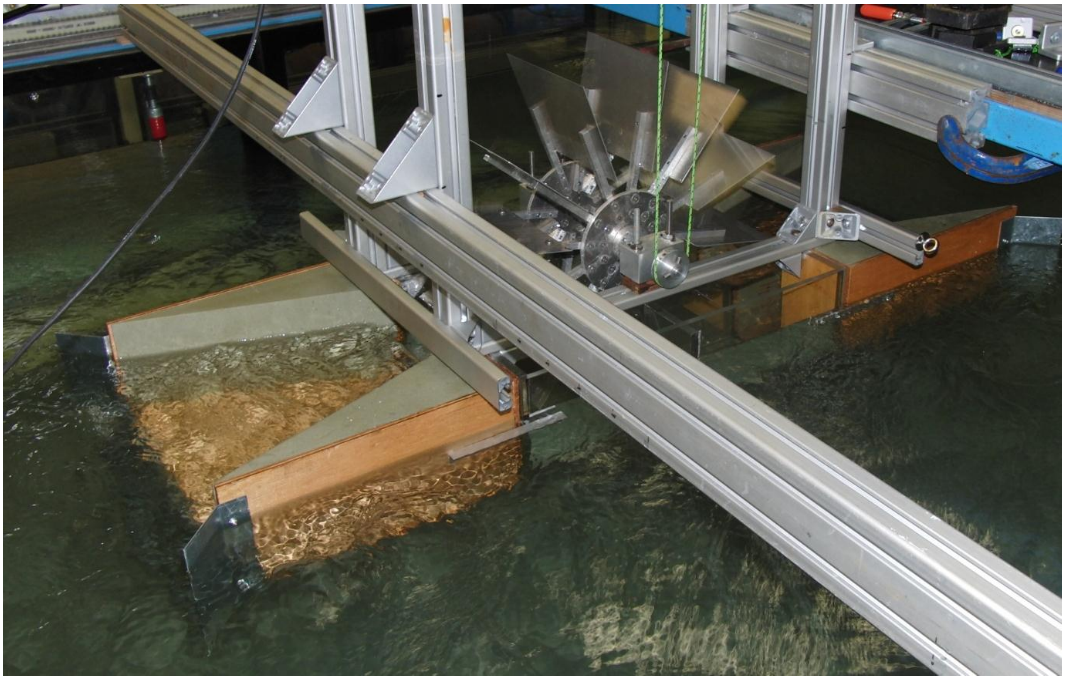


Figure 3 Setup in test tank with the wheel under load;
45° contraction and expansion sections and 90° separators;
Flume depth 600 mm and flow speed 0.40 m/s

3.3. Power takeoff

The wheel was mounted on stainless steel ball bearings with no seals to ensure low friction. The power take-off consisted of a *Prony*-brake, with a 46 mm diameter brake disk fitted onto the shaft. Tests were performed under a series static loads and the reaction force measured using a load cell.

3.4. Tests

The tests were performed at similar speed of 0.4m/s at a constant draft of 100mm to ensure similar Froude numbers inside the model and forces acting on the blade. Three series of tests were performed with three geometric changes, over a range of depths from 400mm to 700mm and series of separator & scoop combinations. For the depth tests the speed was held constant this corresponds to a small change in depth Froude number from 0.20 to 0.15. To insure no inherent friction from the previous test run was present the wheel was ran backwards before each test case. Data for each test case was acquired for a minimum of five revolutions.

4. DATA REDUCTION AND PRESENTAION

The results are presented in non-dimensional form to allow comparisons and predictions for full scale devices. The blade speed is presented as a blade tip ratio;

$$TSR = \frac{V_T}{V_0} \tag{1}$$

where V_T is the tip speed of the blade and V_0 is the free stream speed measured from the ADV as discussed in section 3.1.

The efficiency of the device is calculated from the hydrodynamic kinetic energy based on blade area and the wheel shaft power and is defined as;

$$\lambda = \frac{P_s}{0.5\rho\, A\, V_0^3} \tag{2}$$

where P_S is the shaft power, ρ is the water density and A is the blade area.

The effective blockage area including body, wheel and separators at depth of 400 mm is 13.7% and at depth of 700 mm is only 7.8%. No corrections were made for blockage in the presented results

Figures 4, 5 and 6 show the efficiencies derived from the experiments, including the geometric changes, the influence of separators and the effect of water depth.

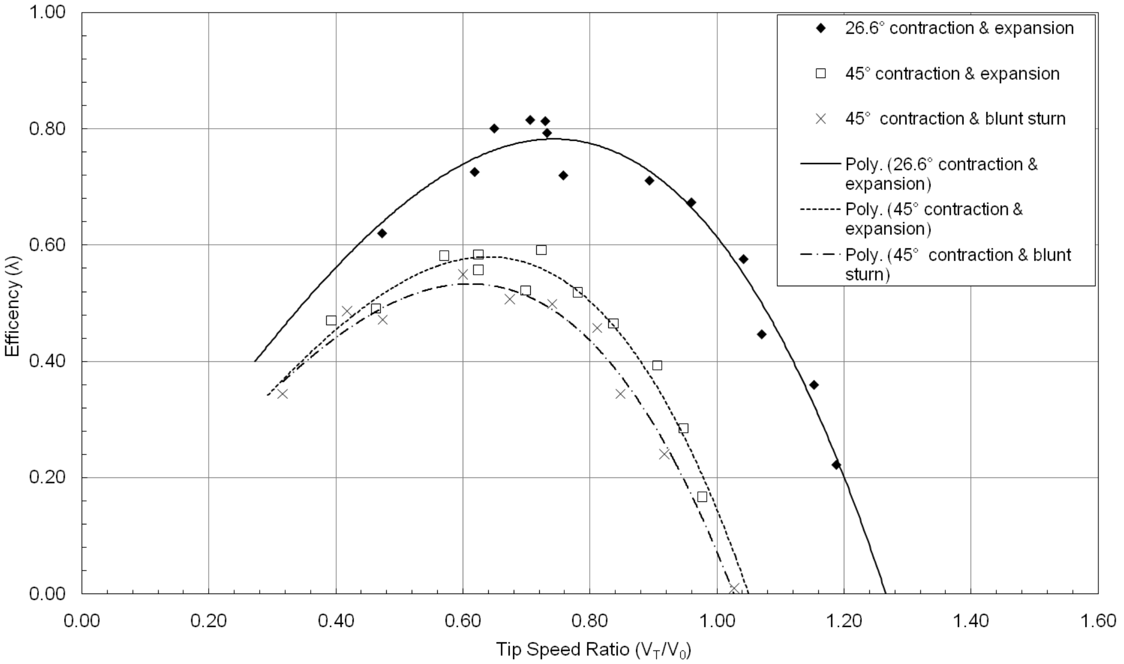


Figure 4 Comparison between 3 contraction and expansion shapes; 90° separator; flume depth of 600mm and speed 0.39 – 0.40 m/s.

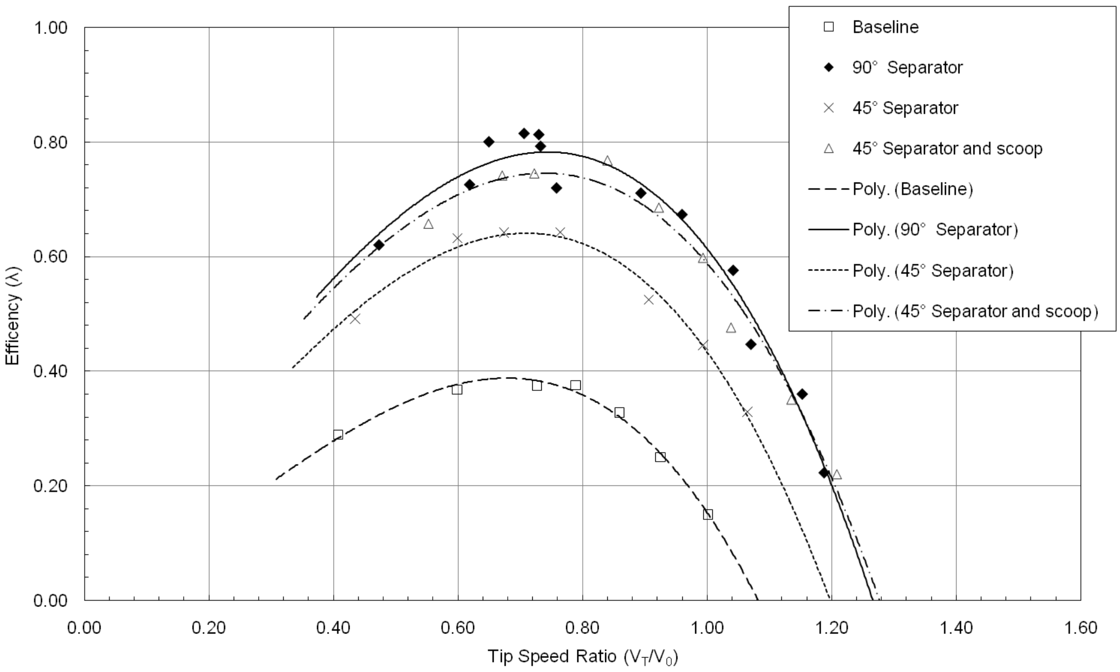


Figure 5 Effect of separator and scoop on the model;
26.6° expansion and contraction; flume depth 600mm and flow speed 0.36 – 0.38 m/s.

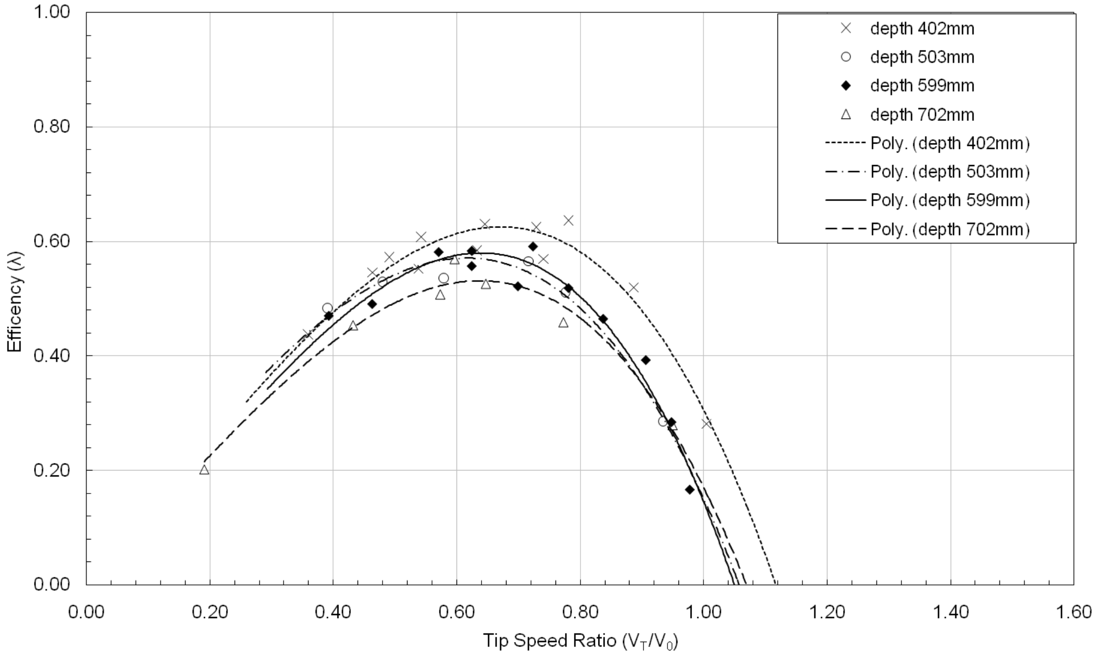


Figure 6 Effect of flume depth on the performance of model;
45° contraction and expansion with 90° separator; flow speed 0.38 - 0.39 m/s.

5. DISCUSSION OF RESULTS

5.1. Effect of bow and stern geometry

Figure 4 shows the influence of bow and stern geometry on the performance of the FSEC. The results clearly show that the 26.6° contraction ratio is favourable over the steeper 45° contraction with peak performance 40 % higher. This is probably due to larger separation and regions of recirculation reducing the effective entry width onto the wheel. The tests with a 45° inflow angle and a blunt stern demonstrate little change indicating that the expansion region is not critical.

5.2. Effect of separator and scoop

Figure 5 shows the influence of separator and scoop on the performance. When no separator was installed, there was noticeable backfilling inside the model which reduces performance. The addition of a 90° separator increases the amount of power generated by almost 100%. When the separator was installed the region of low pressure behind the device produces a localised reduction in the water level this reduces back filling. Consequently the head drop aft of the wheel is increased by a further 20%.

For the 45° this head drop is not as significant and the consequently the increase in performance is not so large. The inclusion of a scoop at front improves the performance almost that with the 90° separator. The scoop further increases the head in front of the wheel by about 10%, and is required if the design was bi-directional.

Table 2 presents the peak efficiencies based on blade area and maximum cross sectional area including separators.

Table 2 Effect of separator and scoop on the maximum efficiencies

Condition	**λ (blade area)**	**λ (maximum area)**
No Separator	41%	18%
90° Separator	87%	16%
45° Separator	70%	16%
45° Separator & scoop	81%	19%

5.3. Influence of depth

The effect of flume depth is demonstrated in Figure 6 with the 45° contraction ratio. The results demonstrate an increase in performance as the depth decreases. This is caused by the increase in blockage and the stronger effect of the separator due to the accelerated flow below the model. In some river situations small clearances between the model and the river base may be possible especially in low flow conditions. In this case the associated flow from the separator may cause local scour (Müller & Batten, 2009).

6. IMPLICATIONS AND CONCLUSIONS

The results have demonstrated that plausible efficiencies are possible for the relatively simple machine presented. The use of the separators and scoops can be a cost effective method of increasing the power output. Based on these and other model tests a 7.6m demonstrator has been developed and is being deployed as a part of the HYLOW project (Hadler & Broekel. (2010); Batten *et al.* (2011). This large scale model aims to demonstrate performance when scaled and prove stability. The model will also be used for studies on the effect of the machine on the fluvial environment (Weichbrodt *el al.* (2010).

Considering the model sizes and efficiencies, floating water wheels may not be a solution for large scale renewable energy production but due to their simplicity and low costs they may be a viable option for decentralised electricity generation in remote locations.

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