View metadata, citation and similar papers at core.ac.uk
brought to you by CORE
provided by Hydraulic Engineering Repository

HENRY
Hydraulic Engineering Repository

Ein Service der Bundesanstalt für Wasserbau

Conference Paper, Published Version

Müller, Gerald; Jenkins, R.; Batten, W. M. J.

Potential, performance limits and environmental effects of floating water mills

Verfügbar unter/Available at: https://hdl.handle.net/20.500.11970/99708

Vorgeschlagene Zitierweise/Suggested citation:
Müller, Gerald; Jenkins, R.; Batten, W. M. J. (2010): Potential, performance limits and environmental effects of floating water mills. In: Dittrich, Andreas; Koll, Katinka; Aberle, Jochen; Geisenhainer, Peter (Hg.): River Flow 2010. Karlsruhe: Bundesanstalt für Wasserbau. S. 707-712.

Standardnutzungsbedingungen/Terms of Use:

Die Dokumente in HENRY stehen unter der Creative Commons Lizenz CC BY 4.0, sofern keine abweichenden Nutzungsbedingungen getroffen wurden. Damit ist sowohl die kommerzielle Nutzung als auch das Teilen, die Weiterbearbeitung und Speicherung erlaubt. Das Verwenden und das Bearbeiten stehen unter der Bedingung der Namensnennung. Im Einzelfall kann eine restriktivere Lizenz gelten; dann gelten abweichend von den obigen Nutzungsbedingungen die in der dort genannten Lizenz gewährten Nutzungsrechte.

Documents in HENRY are made available under the Creative Commons License CC BY 4.0, if no other license is applicable. Under CC BY 4.0 commercial use and sharing, remixing, transforming, and building upon the material of the work is permitted. In some cases a different, more restrictive license may apply; if applicable the terms of the restrictive license will be binding.

River Flow 2010 - Dittrich, Koll, Aberle & Geisenhainer (eds) - © 2010 Bundesanstalt für Wasserbau ISBN 978-3-939230-00-7

Potential, performance limits and environmental effects of floating water mills

G. Müller, R. Jenkins & W.M.J. Batten

University of Southampton, School of Civil Engineering and the Environment, Highfield, Southampton SO17 1BJ, UK, Tel. 0044 2380 592442.

ABSTRACT: The energy of river currents has been employed to power floating mills since antiquity. Due to their low power outputs, the floating or boat mills however disappeared completely in the late 19th century. There is a strong desire today to exploit the renewable energy of river and tidal currents which led to numerous suggestions to again employ water wheel-type floating mills for electricity production. Most of the proposed new schemes however suffer from the lack of either theoretical or experimental data to indicate their performance potential, its limits and the effects on the river environment. An ongoing research program at Southampton University aims to develop a theoretical background, and to determine performance characteristics of floating water wheels. 'Classic' water wheel configurations were investigated experimentally and improvements were developed, increasing the efficiency from 25% to 42%. The effects of these water wheels on the river environments were assessed experimentally. Very recent developments, which allow the utilization of more efficient energy conversion mechanisms, are presented briefly. The general conclusions were that the performance potential of simple floating water wheels is limited, whilst the environmental effects are small. However, due to their low investment costs, floating water wheels are probably interesting machines for decentralized energy production in large rivers and may therefore find a more widespread application in the near future.

Keywords: Floating mills, Water wheels, Renewable energy, Environmental effects

1 INTRODUCTION

Floating mills were first recorded in Rome in 540 AD when *Belisarius* had them built during *Vitibes's* siege of Rome. They usually consisted of a mill boat, which contains the mill's machinery, and a water wheel which is usually supported by the boat on one, and an additional float on the other side. Sometimes, floating mills were built with two symmetrical floating bodies, often with conically shaped bows to guide the water into the wheel, or with a central boat and two wheels on each side, Reynolds (1981). Fig. 1 shows a drawing of a typical floating mill of the 18th century. From the Middle Ages onwards, floating mills were built in Europe and in Cologne/Germany, there were 17 floating mills in operation as late as 1856, Fig. 2a. The mills were tied to a bridge and arranged in one row. On the river Elbe, floating mills only ceased operation in 1911, Gräf (2007). Floating mills were often installed in areas of rapid flow, with flow velocities of up to 3.2 m/s, Müller (1939). The main reasons for their disappearance were the comparatively low power output, and the interference with shipping.

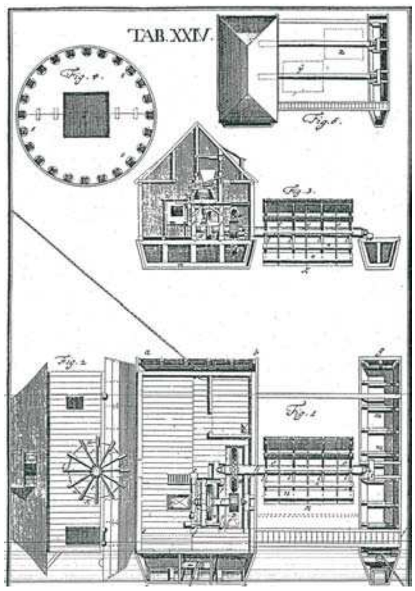

Fig. 1: Typical floating mill, 1735 (Ernst, 1805)

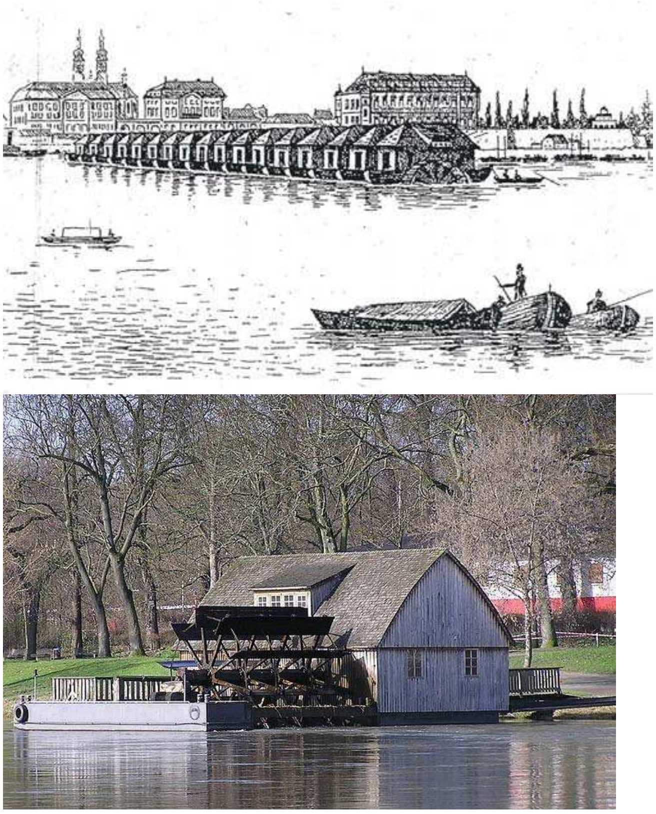

Fig. 2: Typical floating mills (a) Floating mills at Cologne / Rhine, 1856 (b) Replica mill (Rhine, 2008)

The wheels of floating mills usually had a diameter of 4 to 5 m, with six to twelve blades of 0.5 to 0.7 m depth which were submerged by 0.4 to 0.5 m, and widths of 2 to 6 m, e.g. Bresse (1869), Weisbach (1883). For the tangential velocity of the wheel, a value of 0.4 of the velocity of the river current is recommended as a compromise between a slight reduction in power and a faster speed of rotation of the wheel, which reduced the gearing requirements. *Weisbach* also gives a design method and theoretical efficiencies as a function of the number of blades of 0.265 for eight, and 0.428 for 16 blades. In his book he mentions full scale measurements from *Bossut*, who found efficiencies of 0.384 for a wheel with 24 blades.

2 CURRENT SITUATION

Today there are again floating mills built very occasionally either as replicas of historical mills, see the mill designed by Brüdern (2007), or to generate hydropower from the river current. The wish to exploit renewable energy sources has generated a renewed interest in this ancient technology, since floating mills have a number of practical advantages such as easy constructability and subsequently low costs, automatic adjustment to the water level and constant power generation. A large number of patents has been issued on variations of the theme, and several development projects are currently ongoing, Fig. 3. Very little actual engineering information is however available for these projects.

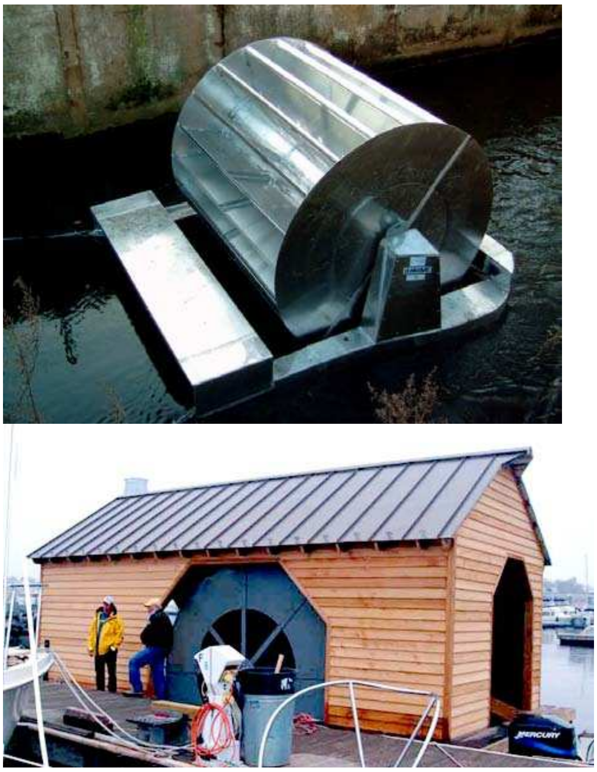

Fig. 3: Current research and development projects (a) Floating water wheel model, www.flusstrom.de, (b) Floating mill in Baltimore/ USA, (www.waterwheelfactory.com)

Although the energy contained in water currents of typical velocities in rivers is comparatively small, floating water wheels have the potential to provide a simple technology for decentralized power generation in larger and large rivers e.g. for application in developing countries. From this point of view a further research into this ancient technology appears to be justified. The kinetic power P_{kin} of a fluid of area A can be determined as a function of the flow velocity v_0:

$$P_{kin} = A \cdot \rho \cdot \frac{v_0^3}{2} \qquad (1)$$

Since the kinetic power is a function of the velocity cubed, it increases significantly as v_0 increases. In real terms however, typical flow velocities in rivers range from 1 to 3 m/s so that the kinetic power for one square meter ranges from 0.5 to 13.5 kW/m². Power densities are therefore quite low. The theory of floating mills, e.g. Morin (1864), assumes the blades to be fully submerged, infinitely long rectangular plates with a drag factor of $C_D = 2.0$. With a blade area A, a flow velocity v_0 and a blade velocity v_1 the power P generated can then be described as:

$$P = A \cdot C_D \cdot \frac{\rho}{2} \left(v_0 - v_1 \right)^2 \cdot v_1 \qquad (2)$$

The power reaches a maximum at $v_0 = v_1 / 3$, with an efficiency $\eta = 8/27$ or 0.296. For a typical blade area of $A = 0.5 \times 5 = 2.5$ m², the theoretical power is given in Fig. 4 as a function of the flow velocity. The graph indicates that in order to achieve significant power output, flow velocities of 2 m/s and more are required.

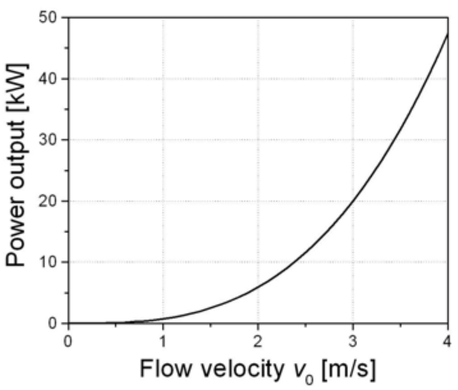

Fig. 4: Theoretical power for $A = 2.5$ m²

For the design, diameters of $D = 3.5$ to 6 m were recommended with 8 to 12 blades and blade depths b of $b = D/8$ to $D/10$, Bresse (1876) or Müller (1939). These values are however empirical. Weisbach (1883) developed a formula to take account of the number of submerged blades z_1, and gives the efficiency as

$$\eta = \frac{16}{81} \cdot z_1 \tag{3}$$

which however is only valid if the number of blades is not large. i.e.

$$z_1 < \frac{v_0}{v_0 - v_1} \tag{4}$$

Weisbach however assumed *Borda's* theory for momentum to be correct; today *Parent's* theory is generally accepted which gives a slightly increased theoretical efficiency of $\eta = 24/81$. In *Weisbach's* book this difference is compensated by optimistic values for the number of submerged blades. Blockage effects due to the proximity of the river bed and losses are not considered, and the effect of blade angle is recognized but not quantified. Despite the fact that several research and development projects in the area of floating water wheels are currently ongoing, little or no progress in theoretical work has been reported since the 1880's.

3 EXPERIMENTAL PROGRAMME

3.1 *Experimental set-up*

In order to investigate the performance of a water wheel in deep water, a series of experiments was conducted at Southampton University. The aims were to determine converter characteristics as a function of the blade number and to assess possible environmental effects. A 500 mm diameter wheel was built which could accommodate either 8, 12 or 24 blades. The wheel consisted of two 450 mm diameter Perspex disks; the blades had a width of a = 250 mm, and a depth of b = 50 mm whereby half the blade depth was fitted into slots machined into the Perspex disks. The width of the blade is assumed to produce near 2D flow conditions, so that the drag factor of the blade can be taken to approach $C_D = 2.0$. The power take-off consisted of a *Prony*-brake, with a 46 mm diameter brake disk fitted onto the shaft.

Tests were conducted in the 12 m long, 0.3 m wide and 0.4 m deep continuous flow tank with a constant water depth of 215 mm, and flow velocities of 0.2 to 0.59 m/s. Assuming a scale of 1:10, this corresponds to full scale flow velocities of 0.8 to 1.9 m/s and therefore the lower range of operational velocities for floating mills. The flow velocities were determined as the free wheeling velocity of the wheel.

In addition, flow visualization experiments were conducted in order to assess the flow velocities underneath the wheel since the possibility of wheel induced bed erosion appears to be the most important potential environmental effect of such a technology. The experiments were conducted by inserting neutrally buoyant particles (expanded polystyrene, $d = 0.5 – 0.8$ mm) upstream into the flow in the centre section of the canal. A Casio EX-F1 camera capable of recording 60 fps at 6 MB was located at 1 m distance from the side of the channel. Lighting was provided by an overhead photographic light.

3.2 *Blockage and wall effects*

The blades of the wheel model described in the previous section had a submerged depth of 50 mm for a water depth of 215 mm, giving a ratio of blade to water area of 0.2. The experimental set-up constitutes a 2D-flow situation with limited depth, resulting in blockage effects which increase the power output and which need to be addressed to make the results more generally applicable. Bahaj et al. (2007) gave power correction factors for tests with continuous flow situations for tidal turbines (i.e. without a free surface) as a function of the blockage area ratio, Fig. 5. Since the pressure increase in a free surface situation expresses itself as a rise in water level, it is assumed that these theoretically derived factors are applicable here.

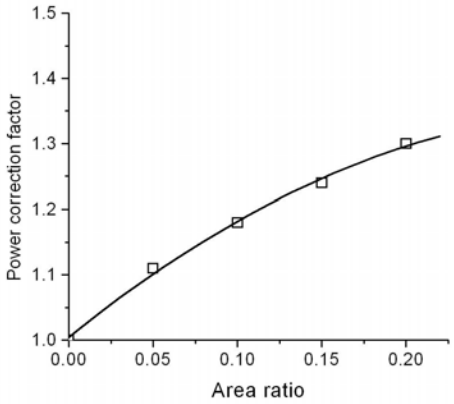

Fig. 5: Effect of blockage ratio on power output (after Bahaj et al., 2007)

Wall effects also need to be considered. The wheel blades have a width of 250 mm inside of the 300 mm wide channel. This means that effects of the immediate wall vicinity on the wheel are reduced. Since the free wheel velocity of the wheel, i.e. the average velocity over the wheel width, is employed as the effective velocity measurement the authors consider further wall effects to be included in the analysis.

4 EXPERIMENTAL RESULTS

4.1 *Performance characteristics*

Initially, measurements were conducted with three different flow rates. It was however found that the friction brake led to unsteady movement of the wheel for very low velocities of less than 6 rpm. Only the experiments with flow velocities between 0.56 and 0.59 m/s are therefore reported. In order to take account of blockage effects caused by the limited water depth, the experimental results were reduced by a factor of 1.3 for a blockage ratio of 0. 2, according to Fig. 5, in order to generate values representative for a situation where the river bed has no influence on the measured power. The efficiencies for three different blade numbers, and flow velocities ranging from 0.56 to 0.59 m/s are shown in Fig. 6a. It can be seen that efficiencies increase with increasing blade number as Eq. (3) suggests. Efficiencies range from 25% for 8 blades, to 42% for 24 blades.

The results for eight blades (one blade in contact with the water) are within the range expected from simple momentum theory. The maximum efficiencies occur for a velocity ratio of v_1 / v_0 = 0.4 to 0.55, confirming the observations reported by various authors (e.g. Weisbach, 1883). There is a difference from Eq. (2), where the maximum occurs for a velocity ratio of v_1 / v_0 = 1/3. The number of blades in contact with the water apparently affects the momentum exchange in a way similar to the Pelton turbine, e.g. Becker & Piltz (1995)

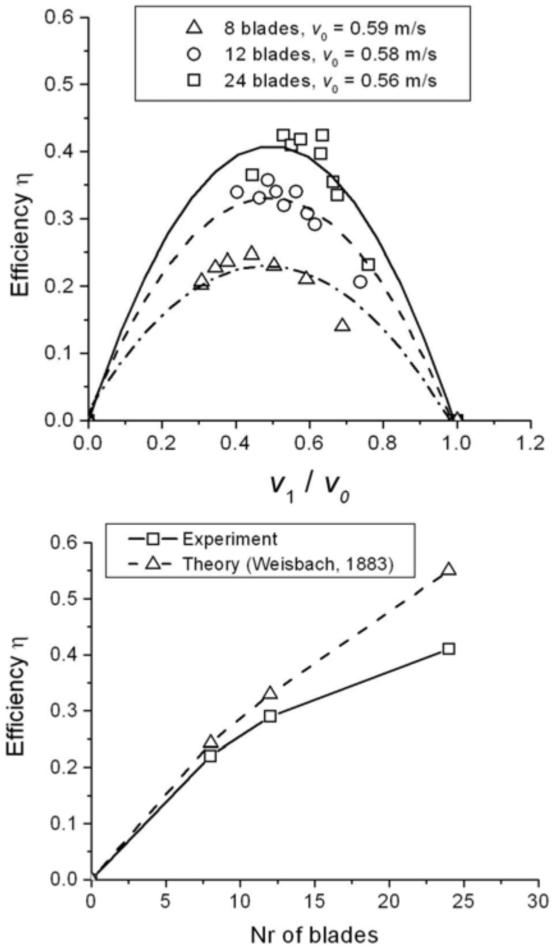

Fig. 6: Efficiency as function of blade number, Blockage reduction factor f_b = 1.3, (a) Efficiency as function of velocity ratio v_1 / v_0 , (b) Experimental and theoretical efficiency

In Fig. 6b the maximum efficiencies from the experiments and the theoretical values from Eq. (3) are given as a function of the blade number. It can be seen that *Weisbach*'s formula gives a reasonable estimate for the effect of blade numbers.

4.2 *Scaling*

The tests were conducted at a scale of approximately 1:10. The effectiveness of a water wheel depends largely on the drag forces exerted on each blade, which are a function of the Reynolds-number. At model scale, a flow velocity of 0.56 m/s results in a Reynolds-number of $Re = 2.8 \times 10^4$, at full scale (with a flow velocity of 1.8 m/s) this increases to $Re = 9 \times 10^5$. The drag factor for rectangular plates is however constant for $10^4 < Re < 10^6$, Crowe et al. (2001) so that scale effects can be assumed to be negligible. In addition, the experiments constituted a near 2D flow situation.

When scaling the geometry up to full scale, this can only be replicated when the blade aspect ratio (width to depth ratio) *a/b* is larger than 10. For a scale of 1:10 this requires blade widths of 5 to 6 m.

4.3 *Environmental effects*

In the historical literature, very little is said about effects of floating mills on the environment except that the mill owners often attempted to accelerate the flow – and their mill's power – locally e.g. by fascines put into the river. This of course caused difficulties with shipping. Some books, e.g. Weisbach (1883) mention a localized deepening of the river bed without giving any specifics. Most negative effects reported focus on interference with shipping, the use of illegal means to accelerate the flow locally and arguments between mill owners regarding their respective locations.

The potential effect of the accelerated flow on the river bed was considered as the most important environmental effect of a floating water wheel installation. The flow visualization experiments were conducted in order to assess the flow field below the water wheel. Fig. 7 shows a typical example (12 blades, maximum efficiency).

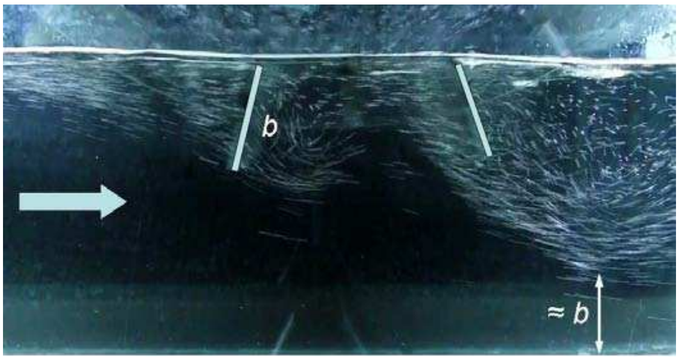

Fig. 7: Visualisation of flow underneath wheel (12 blades, $v_1 = 0.58$ m/s, $v_1 / v_0 =$ 0.5)

A small vortex forms behind the first blade in contact with the water and, quite surprisingly, a large vortex of diameter of approximately 3*b* develops downstream of the wheel. Velocities below the vortex are still larger than the free stream velocity so that probably water depths of 4*b* or more should be present if any effect on the river bed is to be avoided.

The main danger to aquatic life perceived to be generated by floating water wheels is blade strike on fish. This could only happen in the surface layer when a blade enters the water, since the blades are otherwise visible and moving with only one third of the velocity of the flow. Currently, a blade strike model is under development at Southampton University. Since however even the entry velocity of the blade is significantly lower than the velocity of the water, current opinion holds that the danger created by blade strike is low.

5 OTHER DEVELOPMENTS

There are a number of other developments in the area of floating water current converters, ranging from classic water wheels to horizontal axis wheel designs which employ flexible blades and/or guiding side skirts, and to vertical axis designs employing either *Darrieux*-type rotors or a set of guide vanes which divert the current from the half of the rotor which moves against the current, see e.g. the overview in NRC (2006). Most of the converters described utilize proprietary technology and although prototypes of various designs and conversion mechanisms were built, practically no performance data is available and often not even a theory exists which would allow to assess the development potential of the proposed converter.

Some projects attempt to utilize the effect of a surrounding duct in order to increase the power generation, e.g. Ponta and Dutt (2000). The idea is to create a low pressure zone downstream of the duct by inducing flow separation and vortex formation. This leads to a local acceleration of the flow, and in addition energy conversion principles which yield higher efficiencies than those of the simple impulse wheel such as turbines can be employed, see e.g. NRC (2006). Although there are far reaching claims with regard to efficiency and cost-effectiveness, none of the proposed converters has as yet provided reliable performance data so that the conclusion about the claimed performance characteristics remains unclear.

6 DISCUSSION

The principal reason for the disappearance of floating mills was the low power production; this still holds. Modern engineering design can only improve this situation to some extent. An increase in blade number from eight to 24 generates an efficiency increase from 25% to 42%. Further small increases of up to 10% to 46% appear possible by increasing the drag factor of the blades to 2.3 with a U-shaped cross section and side disks to ensure 2D flow conditions. If the water depth is less than 4*b*, further increases can be expected; these will however probably be balanced by a local erosion of the river bed. In combination with the low energy density of typical river flows, it appears that floating horizontal axis water wheels cannot be expected to contribute even marginally to the production of renewable energy.

There are however advantages of the technology for today's environment; namely the low environmental impact and the possibility to generate electricity and/or mechanical power with comparatively low costs for decentralized energy production e.g. in developing countries or in remote locations. The latter application in non-regulated rivers with areas of fast flows looks potentially interesting. The simplicity of the technology, combined with low investment and local construction and maintenance could point to this area of application. The principal disadvantages of floating mills are the low efficiencies, and the slow speed of rotation. At full scale, rotational speeds would probably range from 4 to 6 rpm, and a wheel of 10m width with blade depths of 1 m could produce a mechanical power of 32.8 kW in a flow velocity of 2.5 m/s. This appears to be rather low for such a large installation. The low power output has led to several assumptions how this problem can be overcome. Often it is suggested to create a channel between the buoyancy bodies of a floating mill e.g. with vertical plates to accelerate the flow and give increased performance. Experiments conducted at Southampton University however indicated that this effect is not large; the water chooses the path of the least resistance around the assembly (water wheel and floating bodies).

It appears that for the application in industrialized countries with many users in rivers, and especially shipping as a major mode of transport, floating mills have probably disappeared forever.

7 CONCLUSIONS

Floating mills are today often suggested to exploit the energy of river currents. An investigation of the historical literature on this topic was conducted in combination with an experimental program and an overview of ongoing research and development projects. The aim was to assess the development potential of floating water wheels. The following conclusions were drawn:

- Theory suggests that efficiencies and power output of floating water wheels for typical flow velocities are low.
- The theoretical maximum efficiency assumed today of 29.6% can be improved by increasing the number of blades.
- Experimental efficiencies reached 25% for eight and 42% for 24 blades.
- The environmental effects are probably minimal; flow visualization tests showed that a large trailing vortex develops which may generate local erosion of the river bed.

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 decentralized electricity generation in developing countries or remote locations.

REFERENCES

Bahaj A.S., Molland A.F., Chaplin J.R. and Batten W.M.J. 2007. Power and thrust measurements of marine current turbines under various hydrodynamic flow conditions in a cavitation tunnel and a towing tank. Renewable Energy. Vol. 32, Issue3. 407-426.

Becker E. and Piltz E. 1995. Übungen zur technischen Strömungslehre. Teubner Studienbücher Mechanik, B.G. Teubner, Stuttgart.

Bresse J.A.C. 2003. Water wheels or hydraulic motors. unchanged reprint of the 1876 ed. from University Press of the Pacific, Honolulu.

Brüdern W. 2008. Wie man Wasserräder baut (How to build water wheels, in German). Selbstverlag.

Crowe C.T., Roberson J.A. and Elger D.F. 2001. Engineering Fluid Mechanics. J. Wiley & Sons, New York.

Ernst H. 1805. Anleitung zum praktischen Mühlenbau. Leipzig.

Gräf D. 2006. Boat Mills in Europe from Early Medieval to Modern Times. Veröffentlichungen des Landesamtes für Archäologie mit Landesmuseum für Vorgeschichte, Band 51 / Bibliotheca Molinologica, Volume 19.

Morin, A. 1864. Aide-Mémoire de Mécanique Pratique. 5th Ed., Librarie de L. Hachette et Cie, Boul. St. Germain.

Müller G., Denchfield S., Marth R. and Shelmerdine R. 2007. Stream wheels for applications in shallow and deep water. *Proc. 32nd IAHR Congress*, Venice, Theme C2c, Paper 291.

Müller W. 1939. Die Wasserräder (The water wheels, in German), unchanged reprint, Moritz Schäfer Verlag, Detmold / Germany.

Natural Resources Canada (NRC). 2006. Technology Evaluation of Existing and Emerging Technologies of Water Current Turbines for River Applications. Report # NRCan-06-01071.

Ponta, F. and Dutt, G.S. 2000. An improved vertical axis water-current turbine incorporating a channeling device. *Renewable Energy*. 20. 223-241.

Reynolds T.S.. 1983. Stronger than a hundred men. John Hopkins University Press, Baltimore/US.

Weisbach J., Die Statik der Bauwerke und die Mechanik der Umtriebsmaschinen, Zweiter Teil, Ingenieur- und Maschinenmechanik. Zweite Abteilung ‚Die Mechanik der Umtriebsmaschinen', 5. Auflage, Vieweg & Sohn, Braunschweig/Germany, 1883.

ACKNOWLEDGEMENTS

The research leading to these results has received funding from the European Community's Seventh Framework Programme (FP7/2007-2013) under grant agreement n° 212423.