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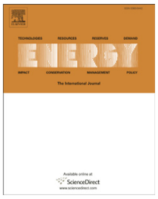

Performance characteristics, power losses and mechanical power estimation for a breastshot water wheel

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ABSTRACT

Breastshot water wheels were in widespread use in the Nineteenth and Early Twentieth century for the production of energy; although they represent an economic, efficient and sustainable technology, only a small amount of research has been paid to water wheels nowadays, in particular to the breastshot ones.

In this work a theoretical approach is adopted to estimate the different kinds of power losses occurring inside a breastshot water wheel, in order to predict its mechanical output power. The theoretical results are then validated with experimental results on a physical steel model. The characteristics experimental curves of the wheel are also illustrated, reporting the wheel efficiency and output power versus the flowrate, stream and wheel velocity.

The average estimated error between the experimental and the estimated theoretical output power is 9%, which is much lower than that calculated using some past formulations found in literature. The theoretical results show that the big power losses are the dissipation of the stream kinetic energy against the blades and the hydraulic losses in the headrace, after the passage through the sluice gate; therefore, a better design of the inlet and blades geometry may improve the efficiency of the wheel.

1. Introduction

In the last few decades the energy demand has increased. From statistics of 2013 [1], it appears that only 8% of the world consumed energy is generated from renewable sources and 92% from non-renewable sources. In Italy, 28% of the consumed energy came from renewable sources, divided as follows: 15.0% hydropower, 1.8% geothermal energy, 4.6% wind energy and 6.5% solar energy [2].

In particular, pico-micro hydropower, is developing more and more, due to its simple technology, sustainability and short payback periods (UNIDO, the USA Organization for the Industrial Development, defines as pico-micro hydropower the hydroelectric plants corresponding to installed power lower than 5 KW and 100 KW, respectively). For pico-micro hydropower generation, an important opportunity is represented by the restoration of the ancient water wheels, which were in widespread use until the end of the Nineteenth century, when they were replaced by turbines.

The earliest water wheel had a vertical axle and it required no gearing mechanism to transmit power to the millstone. The first kind with an horizontal axle was the undershot water wheel (it was already described by Vitruvius in 27 BC), where the water passed below the axle and, impinging on the blades, transferred its kinetic energy to the wheel (if the water weight is not exploited, they are also sometimes called stream wheels [3]). Water wheels were later analyzed by many engineers and scientists, including Da Vinci, Bernoulli, Smeaton and Borda [4,5]. In 1704 Antoine Parent published his theory on jets, which limited the hydraulic efficiency of all water wheels to just 14.8%. Since his analysis was mathematically incorrect and not applicable to all types of water wheels, the undershot water wheel was incorrectly preferred over the others, due to the fact that it was the simplest to construct. In 1759 John Smeaton published experimental data, demonstrating the bigger efficiency of the overshot wheel over the efficiency of the undershot one [5]: in overshot water wheels the potential energy of the water is exploited, which is represented by the water weight. In the Nineteenth century, in order to achieve high efficiencies also in sites with heads unsuitable for overshot wheels, breastshot wheels were introduced: the water entered at about the same height of the rotation axle and the potential energy generated the main driving torque for the wheel. At the same time, further work was developing in order to improve the efficiency of water wheels for very low heads. The french engineer Poncelet noticed that the potential

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energy of the slow flowing water in small rivers was appreciably larger than the kinetic energy, and designed the first wheel for very low head differences; it employed the kinetic and part of the potential energy. The french engineer Sagebien developed later an undershot wheel which used the potential energy only, improving significantly its efficiency. The most efficient shape for undershot and breastshot wheels was finally developed by the swiss hydraulic engineer Zuppinger and patented in 1883; it consisted in “backwards” inclined and curved blades, and in a weir type inflow [6].

By the time, theories and manufacturing methods of water wheels improved [6–13]; at the end of the Nineteenth century, the most developed technology took a significant leap into the turbine and the development of the classical water wheels ceased. Then, with the rapid diffusion of the electric motors between 1940 and 1950, the production of water wheels ceased definitively. Nowadays, thanks to a new sensibility to smart and clean technologies, some companies are specializing in the manufacture of water wheels [4].

The use of water wheels for the production of mechanical and electrical energy should not be considered bygone; in sites where hydraulic heads of a pair of meters are available (Table 1), water wheels represent a suitable technology, mainly in developing countries for local fabrication. Their technology is simpler over that of the turbines, the environmental impact is lower, the payback periods are faster and there is less public resistance to their installation, as they are considered not out of place in the countryside. If they are well designed, water wheels can reach a high and constant efficiency for a wide range of external conditions, but, turning at slow rotation speeds (6–10 rpm), they need high gearbox for generating alternate electricity.

However, few model experiments have been carried out on water wheels nowadays (most of the experimental information is ancient of hundred years) and there is still much uncertainty about their best working conditions and geometric design. In the recent years, undershot and overshot wheels have been more studied than breastshot ones [3,6,14–17] and only a little design and performance information is known about breastshot wheels. A literature review shows that one of the most advanced design method was developed by the German engineer Carl von Bach at the end of the Nineteenth century [6,8,18].

In order to fill the gap of information on breastshot water wheels, the present work aims to the theoretical estimation of the power losses occurring in breastshot water wheels, for the prediction of their mechanical output power and efficiency. In Sec. 2 the general theory for the calculation of the output power and efficiency of breastshot water wheels is reported, and in Sec. 2.1 the different kinds of power losses occurring in breastshot water wheels are detailed illustrated. Thanks to the detailed overview on power losses done in Sec. 2.1, in Sec. 3 some past theoretical models, found through a literature review, are reported and interpreted, highlighting their lower accuracy with respect to that of the presented model. Experimental and theoretical results are reported in Sec. 5. The theoretical results are validated through experimental analyses on a physical model and the experimental characteristic curves of the wheel are shown (Sec. 5.1). The unknown impact coefficient is then quantified by an optimization process between the theory and the experimental results (Sec. 5.2), in order to estimate the impact power loss during the filling process.

Table 1
The best water wheels working conditions [4]. Overshot water wheels are the most efficient and they work well with small flowrates and big heads, while undershot water wheels are more suitable in sites with small heads and high flowrates. The operative conditions of breastshot wheels are intermediate between the previous ones.

Type	Head [m]	Flow [$m^3/s \cdot m$]	Power [kW/m]	Efficiency [%]
Early Undershot	0.5–2.5	0.5–1.2	0.7–5	35–40
Breastshot	1.5–4	0.35–0.65	4–20	60–70
Overshot	2.5–10	0.1–0.2	2–18	70–90

2. General theory

The breastshot water wheel in Fig. 1 is considered; the diameter of the wheel is D, the width is b, the number of blades is n_b and the angular distance between two blades is $\beta = 2\pi/n_b$. The angle θ is the angular position of each bucket gravity center respect to the horizontal and the wheel turns a rotational velocity ω. The wheel is installed inside an open channel, where a sluice gate increases the water depth in the conveying channel and accelerates the water flow in the headrace. In the conveying channel the stream velocity is v_u and v_c is the contracted velocity after the sluice gate. The stream enters into the wheel at velocity v_e and moves then with the buckets at a velocity which is function of ω; at the tailrace, the water velocity is v_d. We suppose the flow field in the wheel and in the channels to be one-dimensional and the water in the buckets to be at rest.

The gross head available for the wheel depends on the geometric and hydraulic boundary conditions and it is expressible by:

$$H_{gr} = (H_U - H_D) = \left[\left(z_u + h_u + \frac{v_u^2}{2g}\right) - \left(z_d + h_d + \frac{v_d^2}{2g}\right)\right] \tag{1}$$

where H_U is the energy head before the sluice gate, H_D the downstream one (that at the tailrace) and $H_{gr} = H_U - H_D$ the upstream-downstream difference of energy head. The generic head H_x is the sum of the bed channel elevation z_x, the water depth h_x and the kinetic term $v_x^2/2g$, where $g = 9.81$ m/s^2 is the acceleration of gravity.

The input power for the laboratory hydroelectric plant is

$$P_{gr} = \rho g \cdot Q_{gr} \cdot H_{gr} \tag{2}$$

where Q_{gr} is the total flowrate and $\rho = 1000$ Kg/m^3 is the density of the water.

In general, the net head H_{net} available for the wheel is lower than the gross head H_{gr}, as a consequence of the friction bed in the headrace and changes in the channel geometry, which may determine local energy losses. For example, when the conveying channel is larger than the width of the sluice gate, lateral stream contractions may arise in the headrace, determining an increase in vorticity, friction bed and turbulence, as it occurs in the examined case. We call these power losses as L_c; their effect is to reduce the energy head from H_U to H_e, where H_e is the flow energy head just before the wheel (see Sec. 2.1.1).

Therefore, the net head available to the wheel is:

$$H_{net} = H_{gr} - (H_U - H_e) = H_e - H_D \tag{3}$$

and, considering also possible volumetric losses in the headrace, the input power P_{net} for the wheel is calculated by:

$$P_{net} = \rho g \cdot Q \cdot H_{net} \tag{4}$$

where $Q = Q_{gr} - Q_U$ and Q_U is the discharge lost before the wheel, through leakages and slits. We call this volumetric power loss L_{Q_U} (see Sec. 2.1.4).

The mechanical output power P_{out} at the wheel axle is still lower than P_{net}, because different *power losses* occur in the wheel and not the entirety of P_{net} is exploitable as useful work (Fig. 1). Four main