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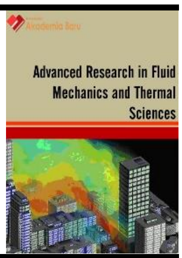

The Effect of the Ratio of Wheel Tangential Velocity and Upstream Water Velocity on the Performance of Undershot Waterwheels

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ABSTRACT

Pico hydro type undershot waterwheels are one of solutions to overcome energy crises in remote areas. The geometry of the wheels is based on the Betz limit concept: a wheel tangential velocity of one-third of the upstream water velocity. Although this concept has long been proposed, it has never been empirically demonstrated. The aim of this study was to identify the optimal ratio between the wheel tangential velocity (U) of undershot water wheels and the average upstream water velocity (V). The experimental work was done in a run of river conditions (irrigation) in remote areas with a discharge of 0.105 m^3/s. Two instruments measured power output: a tachometer (used to measure wheel rotational speed) and a force meter (used to measure torque) with accuracies of 0.05% and 0.1 kg, respectively. Testing variation was done 29 times by loading masses ranging from 0–56 kg. A peak efficiency of 24.31% was achieved with a mechanical power of 10.55 W, a wheel rotation of 2.26 rpm and a torque of 29.01 N·m. This peak efficiency occurred at a U/V ratio of 0.39 if using the Gaussian fit approach of 0.41. Thus, the recommended U value for designing the undershot waterwheel is $0.4V$. Furthermore, in the application of undershot waterwheels in independent power plants with a run of river conditions in remote areas, the installation of filter bars prior to the wheels is needed.

1. Introduction

The Indonesian electrification ratio is presently 98% [1]. This uneven electricity distribution is caused by difficult access due to the topography of mountainous and hilly areas, called “remote areas” [2]. The Indonesian electrification ratio target for 2025 is 100% [3]. Developing small-scale renewable energy power plants [4,5] is one of the strategies to achieve this target. In some developing countries, hydroelectric power plants with pico scales (< 5kW) are recommended for use in remote areas [5-7]. Furthermore, Indonesia has potential water energy with low head conditions

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(< 5 m) up to 19 GW [6]. However, the obstacle to implementing pico hydro technology in Indonesia is the abundance of garbage contained in its rivers [8-10]. One study reported that the undershot waterwheel, despite having low efficiency, has little effect on garbage [8].

Undershot waterwheels absorb water power through blades at their base [8]. They are a fairly old technology, but they underwent significant development around the end of the 20th century [8]. The key to the study of undershot waterwheels is characterization, such as the analysis of the optimal blade number [8], the ratio of the length of immersed blade to the blade diameter [11], blade shape [12], and empirical equations to determine the power available in the water channel [13].

This study divides its characterization into two sections: proposing empirical equations and studying hydraulic behaviour. The empirical equation adopted here for determining the optimal number of blades is the Pelton turbine empirical equation [8]. The disadvantage of the proposed equation is that all conditions result in eight blades [8]. The optimal wheel tangential velocity (*U*) turns out to be one-third of the average upstream water velocity, which is adopted from the Betz limit or Betz law [13]. This assumption produces maximum efficiency because the analytical results prove that the percentage of torque received with wheel rotation is optimal in this condition [13]. To discover the optimal parameters, the wheels' hydraulic behaviours are also a concern. A previous study found that immersed blade depth affects wheel performance [11] and that the optimal ratio of immersed blade depth to the wheel diameter is 0.4 [11]. The effects of water's kinetic energy on wheel performance has also been assessed [8], and analysis of variance (ANOVA) shows that it has no significant effect on wheel performance [8], indicating that undershot waterwheels absorb hydrodynamic force or water pressure energy [8,14]. w

Several studies have indicated that wheel rotation (n) is a parameter that determines the geometry of undershot waterwheels [8]. Fallible methods of determining optimal wheel rotation not only affect size but also performance. Although characterizations and hydraulic behaviour studies have been carried out, the proposed Betz limit ($U = 0.33V$) has not been demonstrated by experimental work (only mathematical analysis) [15]. This study's objective is to clarify whether $U = 0.33V$ is indeed the optimal parameter. Tests on a run of river conditions were carried out to find out the obstacles that might occur in the application of undershot waterwheel turbines as independent power plants in remote areas.

2. Methodology

An undershot waterwheel was tested on a run of river (irrigation) conditions. The wheel dimensions used were 2 m in diameter, 0.4 m in width, and 12 blades (Figure 1).

The power measured was mechanical power, which is a function of torque (τ) and angular velocity (ω). The friction force (F) was also measured using a Prony brake system with a pulley attached to the rotating shaft (Figure 1), a system adapted from a previous study [15]. The equipment set-up used to measure force (force meter in Figure 2) had an accuracy of 0.1 kg in the full-scale accuracy category. The friction force (F) produced was analysed using Eq. (1).

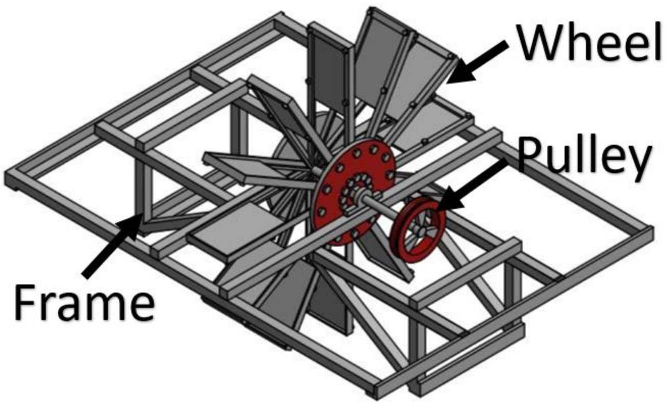

Fig. 1. Schematic of the undershot waterwheel

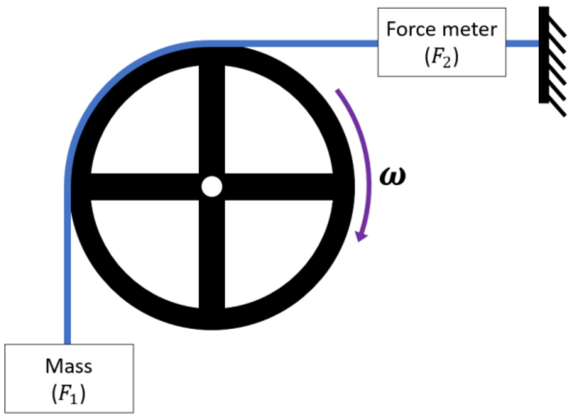

Fig. 2. Schematic of prony break

$$F = F_2 - F_1 \tag{1}$$

where F_2 is the measured force at force meter and F_1 is a given loading mass. The torque was calculated according to Eq. (2).

$$\tau = F \cdot r \tag{2}$$

where r is the radius of the pulley in Figure 2. The angular velocity (ω) is determined by wheel rotation (n). The wheel rotation (n) was measured using a non-contact tachometer with an accuracy of 0.05% in the reading accuracy category. The analysis to find out angular velocity (ω) used Eq. (3).

$$\omega = 2 \cdot n \cdot \pi/60 \tag{3}$$

Then, using Eq. (4), the mechanical power was discovered.

$$P_{mech} = \tau \cdot \omega \tag{4}$$

Efficiency is the ratio of mechanical power to potential power ($P_{mech}/P_{potential}$). $P_{potential}$ is a function of discharge (Q) and head (h). The discharge was measured using a rectangular weir (see Figure 3). Eq. (5) was used to calculate the available discharge.

$$Q = 1{,}84 \cdot H^{3/2} (L - 0{,}2\,H) \tag{5}$$

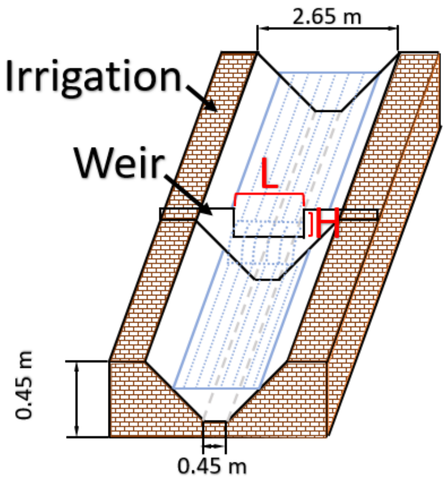

Fig. 3. Schematic of rectangular weir

where L is weir width and H is weir height. In this case, head (h) was approximated using the Bernoulli equation ($v^2 = 2 \cdot g \cdot h$). Water velocity (v) was measured using the float method. Finally, the efficiency was determined using Eq. (6).

$$\eta = (P_{mech}/P_{potential}) \cdot 100\% \quad (6)$$

3. Results and Discussions

3.1 Results

Table 1 shows the test results using the rectangular weir method (see Figure 3). The calculations using Eq. (5) show that the discharge (Q) available in irrigation is 0.105 m^3/s. From the measurement results using the float method, the water velocity (v) was 0.91 m/s. Using the Bernoulli equation, the velocity of the water (v) was 0.91 m/s, proportional to the head (h), 0.04 m.

Table 1
Measurement using rectangular method

Testing no	Wide weir, L	Head weir, H
1	0.45 m	0.28 m
2	0.45 m	0.28 m
3	0.45 m	0.27 m
4	0.45 m	0.27 m
5	0.45 m	0.28 m
6	0.45 m	0.27 m
Average	0.45 m	0.275 m

Thus, the potential power ($P_{potential}$) is the following

$$P_{potential} = 1000m^3/kg \cdot 0.105m^3/s \cdot 9.81m/s^2 \cdot 0.04m = 43.38\,Watt$$

The peak efficiency is simply the highest value obtained from multiplying torque (τ) and angular velocity (ω). The test was done 29 times – that is, with 29 samples – until the wheel stopped rotating. The given loading mass (F_1) ranged from 0–56 kg. Table 2 summarizes the measurement results.

Based on Table 2, the peak efficiency produced by the wheel was 24.31% with a mechanical power of 10.55 W, a wheel rotation (n) of 3.36 rpm and a torque of 29.01 N·m.

Table 2
Mechanical power measurement of undershot waterwheel

Samples	Wheel rotation, n	Torque, τ	Mechanics power, P_{mech}	Efficiency, η
1	7.00 rpm	0.00 N·m	0.00 W	0.00 %
2	6.46 rpm	3.43 N·m	2.32 W	5.36 %
3	6.72 rpm	6.22 N·m	4.37 W	10.08 %
4	6.00 rpm	9.96 N·m	6.26 W	14.42 %
5	5.83 rpm	11.91 N·m	7.28 W	16.78 %
6	5.60 rpm	12.81 N·m	7.51 W	17.31 %
7	5.46 rpm	13.84 N·m	7.90 W	18.22 %
8	5.32 rpm	14.42 N·m	8.03 W	18.51 %
9	5.19 rpm	15.00 N·m	8.15 W	18.78 %
10	5.06 rpm	16.03 N·m	8.50 W	19.59 %
11	4.88 rpm	16.86 N·m	8.62 W	19.88 %
12	4.77 rpm	18.03 N·m	9.01 W	20.77 %
13	4.62 rpm	18.54 N·m	8.96 W	20.66 %
14	4.52 rpm	18.58 N·m	8.78 W	20.25 %
15	4.42 rpm	18.85 N·m	8.73 W	20.12 %
16	4.29 rpm	19.47 N·m	8.74 W	20.14 %
17	4.20 rpm	20.22 N·m	8.89 W	20.50 %
18	4.12 rpm	21.25 N·m	9.17 W	21.13 %
19	4.00 rpm	22.15 N·m	9.28 W	21.38 %
20	3.93 rpm	22.70 N·m	9.33 W	21.50 %
21	3.85 rpm	23.24 N·m	9.38 W	21.62 %
22	3.75 rpm	24.21 N·m	9.51 W	21.91 %
23	3.63 rpm	25.85 N·m	9.81 W	22.62 %
24	3.59 rpm	27.02 N·m	10.16 W	23.42 %
25	3.53 rpm	28.33 N·m	10.47 W	24.13 %
26	3.36 rpm	29.70 N·m	10.45 W	24.09 %
27	3.36 rpm	29.97 N·m	10.55 W	24.31 %
28	3.28 rpm	29.01 N·m	9.97 W	22.98 %
29	0.00 rpm	27.47 N·m	0.00 W	0.00 %

3.2 Discussions

Non-dimensional analysis clearly interprets these results for reference and comparison to previous studies by verifying them against previous results and vice versa. Figure 4 is a non-dimensional graph of the ratio of wheel tangential velocity (U) and average upstream water velocity (V) against efficiency (η). Based on Figure 4, the peak (optimal) efficiency occurred at a ratio of U/V of 0.39, while the prediction using the Gaussian fit approach is 0.41. This finding indicates that the approach used in a previous study [16], which suggested a wheel tangential velocity of one-third the upstream water velocity, that is, $U = 0.33V$, is incorrect. Based on these results, the recommended U value for designing the undershot waterwheel is actually $0.4V$.

Pico hydro turbines are cost-effective when manufactured in the areas in which they will be implemented [17] because, when a crash occurs, the tools and materials needed for repair can be easily accessed. Based on this suggestion, the turbine was manufactured in the area to be used at a cost of USD 420. The turbine manufacturing process used standard welding workshop equipment, such as welding tools, rivet pliers, grinders, hacksaws, hammers, wrenches, screwdrivers, brushes and paint. Figure 5 shows the undershot waterwheel turbine that was manufactured.

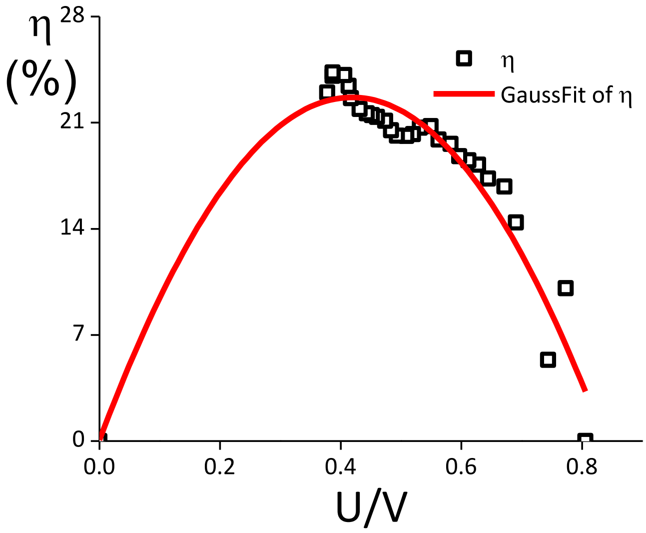

Fig. 4. Undershot waterwheel's mechanics efficiency

Fig. 5. Undershot waterwheel testing in irrigation

Based on the results of testing in a river (irrigation) in the village of Batu Roto, Bengkulu, Indonesia, the chief obstacle to turbine operation is flooding. The overflow of rain dense with garbage material, such as pieces of wood, can crush turbine blades (see Figure 6). Pico hydro turbines in Indonesia, such as undershot waterwheels, should use filters capable of blocking dense garbage.

(a) Side view (b) Front view

Fig. 6. The condition of blade of undershot waterwheel after being hit by wood

4. Conclusions

The peak efficiency of this study's undershot waterwheel occurred at a U/V ratio of 0.39 of 24%, while the prediction using the Gaussian fit approach is 0.41. Consequently, a U value of $0.4V$ is recommended, not the previously suggested value of $0.33V$. Furthermore, based on observations, the implementation of undershot waterwheels as independent power plants in remote areas must be accompanied by strong water filters to prevent waterwheel damage by heavy rubbish, such as wood.

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