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## Investigation of the 16 Blades Pico Scale Breastshot Waterwheel Performance in Actual River Condition

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### ABSTRACT

Breastshot waterwheel are considered as one of solutions for electrification in remote areas in Indonesia. Since it has low investment and maintenance costs, as well as an uncomplicated manufacturing process. Analytically, the optimum performance of this turbine occurs at the ratio of tangential velocity of wheel with the upstream velocity of water is 0.25 -0.35 and numerically simulated the best efficiency is 62%. However, there is no experimental study for 16 blades of breastshot waterwheel in pico scale in actual river condition. The experiment is carried out in actual conditions with a discharge of 0.09708 m<sup>3</sup>/s and head 0.26 m. Based on results, the highest mechanical efficiency occurs at the ratio of tangential velocity of wheel with the upstream velocity of water is 0.83, while for electrical efficiency it was found at the 0.95. for U / C compared to the reference, the results are quite far from optimal and for efficiency the result is slightly lower at 45%.

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## 1. Introduction

In 2019, more 4.16 million peoples of Indonesian in remote areas did not have access to electricity [1]. Pico hydro suitable to provide electricity in remote areas that do not have access to electricity because Indonesia has hydropower potential up to 19 GW that spread on all provinces [2]. Furthermore, pico hydro has lower investment and operational costs compared to wind turbines and solar PV power plants [3]. Pico hydro is a green energy that exploits small streams to generate electricity under 5kW [4]. However, the problem faced in the use of pico hydro is river garbage such as twigs and plastic waste. River garbage makes the turbine cannot rotate properly [5]. Pico hydro type's waterwheel has a small effect on garbage [5]. Thus, pico hydroplants equipped with a waterwheel are one of the right solutions as a power plant for remote areas in Indonesia. Many researches have been made to optimize waterwheel at pico scale.

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Breastshot waterwheel are considered as one type of waterwheel suitable for remote areas in Indonesia [6]. Breastshot waterwheel are effective to be applied for low head conditions (<5m) [5]. Furthermore, breastshot waterwheel as an independent power plant in remote areas, exhibit several advantages: ease in irrigation construction, environmentally friendly, easily accessible manufacturing materials, relatively low investment costs and does not require complicated maintenance [7].

Many researches have been made to optimize the performance of breastshot waterwheel. Fundamental analytical has been done to get optimal geometry [8,9]. Analytical calculations were developed to identify the optimal form with the investment costs for installing waterwheels in remote areas [10,11]. The Computational fluid dynamics (CFD) method is used to analyse the shape of the blade and found the circle shape is the best [12]. The number of blades and the flow discharge of water are examined to get the relationship between these two things with the generated power and show that both factors affect the generated power [5]. The effect of variation blade height with inlet height on pico scale waterwheel is analysed using computational fluid dynamics (CFD) and found  $h/L$  has significant influence on waterwheel performance [13]. Also found the best turbulence model for CFD simulation for pico hydro waterwheel is standard transitional SST turbulence model [14].

Based on literatures, a significant parameter affecting the performance of the waterwheel are tangential velocity and inflow velocity [15]. The tangential velocity of turbine ( $U$ ) is initial parameter determined where this will affect the diameter ( $D$ ) size. The ratio of design tangential speed and theoretical velocity (based on energy line difference) should be between 0.2 and 0.35 (Sagebien wheel) [16]. This study conducted using a 16 blades breastshot turbine in the actual river conditions, aims to identify and compare the ratio between tangential velocity with upstream velocity of water and the highest electrical and mechanical generated power efficiency of breastshot waterwheel with previous study.

## 2. Methodology

### 2.1 Analytic and Measurement Method

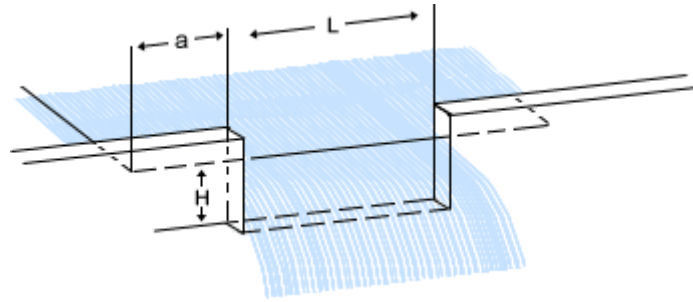
Water discharge ( $Q$ ) and head ( $h$ ) were measured to determine potential power ( $P_{avai}$ ) available on the river. Available power ( $P_{avai}$ ) is calculated using Eq. (1).

$$P_{avai} = \rho \cdot g \cdot Q \cdot h \quad (1)$$

For  $h$  was measured using length meter, while  $Q$  is measured using the weir method. The shape of the weir used is a rectangular weir. Eq. (2) is used to calculate the  $Q$  [17]. The measurement scheme is shown in Figure 1.

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

where  $L$  is the length of the weir,  $a$  is weir side length and  $H$  is the height of water surface.



**Fig. 1.** Rectangular weir

To find mechanical power, the parameters that need to be measured is angular velocity ( $\omega$ ) and torque ( $\tau$ ) (see Eq. (3)).

$$P_{mech} = \tau \cdot \omega \quad (3)$$

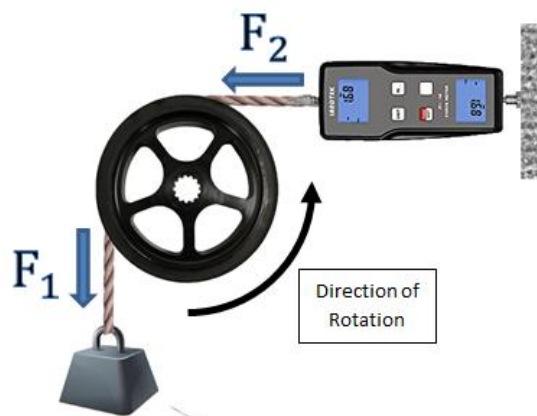
The torque ( $\tau$ ) is calculated using force ( $F$ ). The force ( $F$ ) is measured using the Prony brake. The Prony brake scheme can be seen in Figure 2. The force ( $F$ ) generated by the wheel can be calculated using Eq. (4).

$$F = F_2 - F_1 \quad (4)$$

where  $F_1$  is a varying mass load, the mass load is given by adding a load of 2 kg in stages until the breastshot waterwheel stopped, in this study, the wheel stops at mass load of 60 kg;  $F_2$  is the reading result from a force meter. The force meter was used has uncertainty 0.1 g with category reading. The result in force meter is still in kilogram (kg), so we need multiply it with gravity to get force value, the gravity value used is  $9.81 \text{ m/s}^2$ . After getting the force ( $F$ ) value, the torque ( $\tau$ ) calculated using Eq. (5).

$$\tau = F \cdot r \quad (5)$$

where  $r$  is the pulley radius.



**Fig. 2.** The Prony brake scheme

Angular velocity ( $\omega$ ) can be calculated using Eq. (6).

$$\omega = 2 \cdot \pi \cdot n / 60 \quad (6)$$

where  $n$  is the rotational speed (rpm) of wheel. The  $n$  measured using commercial tachometer with uncertainty of 0.05 RPM with category full scale.

To find electrical power, the parameters that need to be measured is the voltage ( $V$ ) and current ( $I$ ). Electrical power can be calculated using Eq. (7). Commercial multimeters with direct current (dc) specifications are used to measure the voltage ( $V$ ) and current ( $I$ ) generated by a DC generator. The commercial multimeter was used has uncertainty 0.7% for voltage and 2.2% for current with category full scale.

$$P_{elec} = V \cdot I \quad (7)$$

Electrical power measurements are done by connecting the generator with a load of 10 W ( $12V_{dc}$ ) lamps. The lamps are installed in stages from 0 to 11 units (12 variations).

Thus, calculation of mechanical and electrical efficiency is done using Eq. (8) and Eq. (9).

$$\eta_{mech} = (P_{mech}/P_{avai}) \cdot 100\% \quad (8)$$

$$\eta_{elec} = (P_{elec}/P_{avai}) \cdot 100\% \quad (9)$$

To know the tangential velocity of wheel ( $U$ ) using Eq. (10).

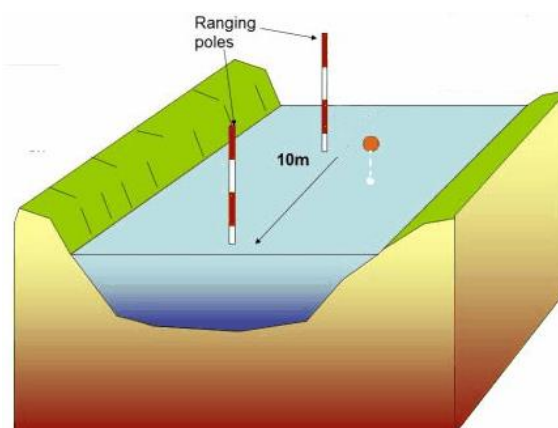
$$U = \frac{n}{60} \cdot D \quad (10)$$

where  $D$  is the diameter of the wheel.

Measurement of Upstream velocity of water ( $C_1$ ) is done by the buoy method, with two measurement poles within 10 meters. A buoy with a ballast is passed from the first measurement point to the second measurement point and then the travel time is recorded using a stopwatch. Five experiments were carried out and an average velocity was taken. The measurement scheme is shown in Figure 3. Upstream velocity of water ( $C_1$ ) can be calculated using Eq. (11).

$$C_1 = l/t \quad (11)$$

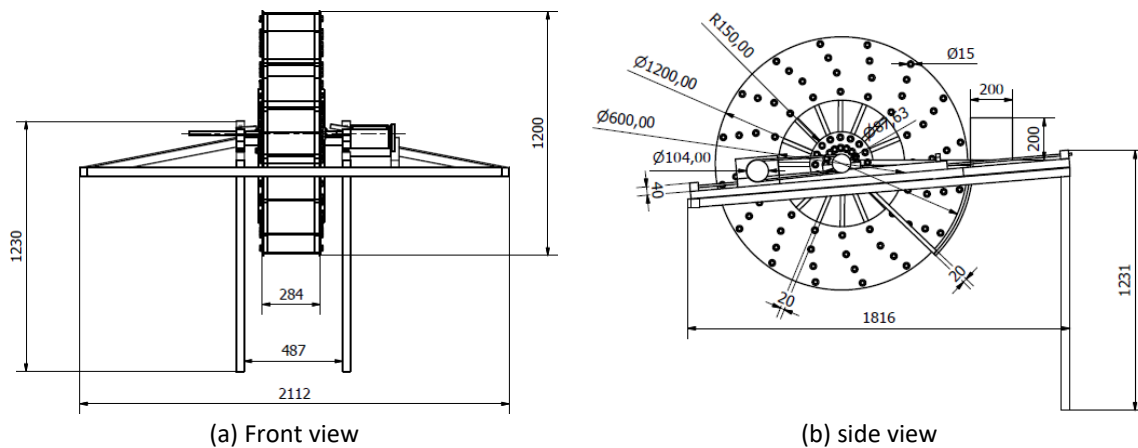
where  $l$  is distance between two poles,  $t$  is times.



**Fig. 3.** Upstream river velocity measurement using buoy method

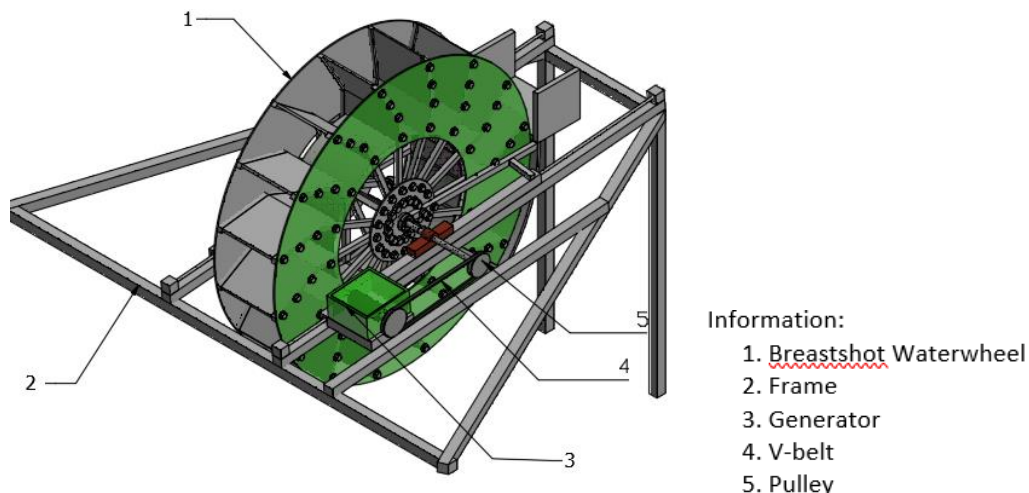
## 2.2 Breastshot Waterwheel Design

Breastshot waterwheel with 16 buckets were used with a diameter of 1.2 meters. The detailed dimensions of the breastshot waterwheel are shown in Figure 4(a) and Figure 4(b). The weight of the waterwheel is 26kg, the material uses a 0.2mm steel plate. 16 blades were chosen because of lower manufacturing costs.



**Fig. 4.** Breastshot waterwheel detailed dimension

The breastshot waterwheel holder scheme is shown in Figure 5.



**Fig. 5.** Isometry view of the breastshot waterwheel

## 3. Results and Discussions

### 3.1 Potential Power of Water

The results of the measurements of water discharge ( $Q$ ) in river using the rectangular weir method are shown in Table 1.

Based on data in Table 1 and calculation using Eq. (2), the water discharge ( $Q$ ) in river is  $0.09708 \text{ m}^3/\text{s}$ . In the results obtained, the average of head ( $h$ ) is 0.26 m. So, the potential power of water is 246.7 Watt.

And from the measurements using buoy method, the average upstream velocity of water ( $C_1$ ) is 0.909 m/s.

**Table 1**

River discharge measurement result using rectangular weir method

Number of testing	Water height, $H$
1	0.27 m
2	0.26 m
3	0.25 m
4	0.25 m
5	0.26 m
Average	0.26 m

### 3.2 Performance of Breastshot Waterwheel

To find out the mechanical power of the breastshot waterwheel, the test was carried out 30 times from a mass load of 0 kg to 60 kg. Based on measurements, the torque ( $\tau$ ) increases when adding load over 48 kg but the wheel rotation ( $n$ ) decreases. Table 2 are the results of these measurements. Based on Table 2, the highest efficiency mechanics ( $\eta_{mech}$ ) of the breastshot waterwheel is 45.72% ( $P_{mech}$  of 112.79 Watt) at wheel rotation ( $n$ ) of 13.8 rpm with a torque of 78.01 N·m.

**Table 2**

Mechanical power test summary

Testing no.	Wheel rotation, $n$	Torque, $\tau$	Tangential Velocity ( $U$ ), $m/s$	Mechanical power, $P_{mech}$	Mechanic efficiency, $\eta_{mech}$
1	40.90 rpm	0.00 N·m	2.57	0.00 Watt	0.00 %
2	39.10 rpm	11.48 N·m	2.45	46.98 Watt	18.98 %
3	37.12 rpm	17.57 N·m	2.33	68.27 Watt	27.57 %
4	35.20 rpm	21.45 N·m	2.21	79.04 Watt	31.92 %
5	33.30 rpm	24.47 N·m	2.09	85.29 Watt	34.45 %
...	...	...	...	...	...
23	14.86 rpm	71.11 N·m	0.93	110.70 Watt	44.87 %
24	14.34 rpm	73.91 N·m	0.90	111.04 Watt	45.01 %
25	13.8 rpm	78.01 N·m	0.86	112.79 Watt	45.72 %
26	13.26 rpm	77.69 N·m	0.83	107.92 Watt	43.74 %
27	12.8 rpm	77.58 N·m	0.80	104.04 Watt	42.17 %
...	...	...	...	...	...
31	0.00 rpm	76.92 N·m	0	0.00 Watt	0.00 %

The results of electrical power measurements are shown in Table 3. Based on Table 3, the more load is added, the more electricity is generated. Voltage ( $V$ ) increasing when adding a lamp load up to 10, but more than 10 the resulting current ( $I$ ) will be significantly reduced. Consequently, the reduced current ( $I$ ) causes the electric power generated to decrease. The highest electrical efficiency ( $\eta_{elec}$ ) of 4.61% is achieved with 10 lamp loads with a voltage of 34.48  $V_{dc}$  and a current ( $I$ ) of 0.33 A.

**Table 3**  
 Electrical power test summary

Load no.	Voltage, $V$	Current, $I$	Generator rotation, $n_{gen}$	Wheel rotation, $n$	Electric power, $P_{elec}$	Electric efficiency, $\eta_{elec}$
0	70.10 $V_{dc}$	0.00 A	1084.00 rpm	40.9 rpm	0.00 Watt	0.00 %
1	7.45 $V_{dc}$	0.55 A	959.90 rpm	36.2 rpm	4.10 Watt	1.66 %
2	9.60 $V_{dc}$	0.44 A	902.20 rpm	34.0 rpm	4.22 Watt	1.71 %
3	15.07 $V_{dc}$	0.39 A	823.90 rpm	31.0 rpm	5.88 Watt	2.38 %
4	21.89 $V_{dc}$	0.36 A	757.30 rpm	28.5 rpm	7.88 Watt	3.19 %
5	25.76 $V_{dc}$	0.34 A	697.00 rpm	26.2 rpm	8.76 Watt	3.55 %
6	24.52 $V_{dc}$	0.37 A	606.10 rpm	22.8 rpm	9.07 Watt	3.68 %
7	27.65 $V_{dc}$	0.35 A	528.80 rpm	19.9 rpm	9.68 Watt	3.92 %
8	32.32 $V_{dc}$	0.34 A	478.80 rpm	18.0 rpm	10.99 Watt	4.45 %
9	31.50 $V_{dc}$	0.34 A	416.70 rpm	15.7 rpm	10.71 Watt	4.34 %
10	34.48 $V_{dc}$	0.33 A	321.10 rpm	12.1 rpm	11.38 Watt	4.61 %
11	41.60 $V_{dc}$	0.27 A	274.00 rpm	10.3 rpm	11.23 Watt	4.55 %

### 3.3 Discussions

Comparison of experimental results with previous studies conducted by Quaranta *et al.*, [5] in Table 4.

**Table 4**  
 Comparison with previous study for 16 blades breastshot by Quaranta

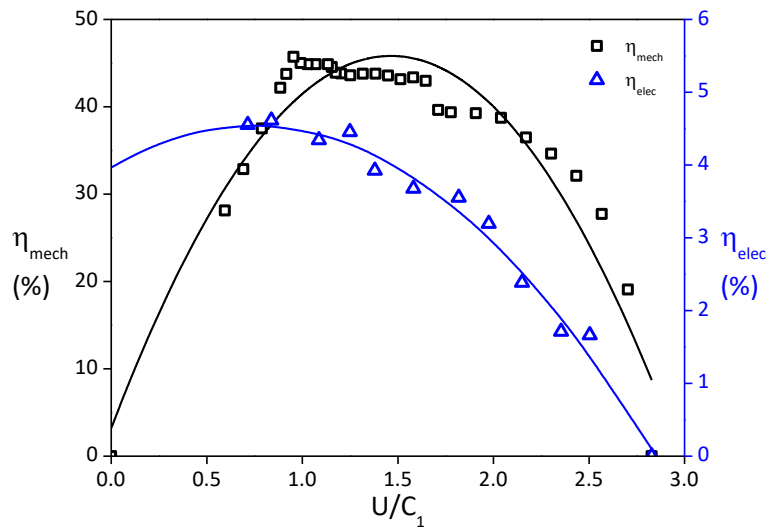
No	$Q, m^3/s$	$\frac{H}{D}$	Torque, $Nm$	$N, \frac{Rad}{s}$	efficiency, $\eta_{16}$
1	0.05	0.197	160	0.78	62 %
2	0.06	0.218	199	0.79	58 %
3	0.07	0.248	216	0.89	53 %
4	0.097	0.216	76.92	1.43	45 %

In this comparison, this study has smaller efficiency results, seen from Table 4, with the same number of blades, increasing the number of discharges will reduce efficiency. In this study the torque obtained is smaller because the smaller diameter can be seen from the Head per Diameter ( $H / D$ ) and in actual conditions in the river there are many streams of water that are not completely captured by the turbine due to poor channel design.

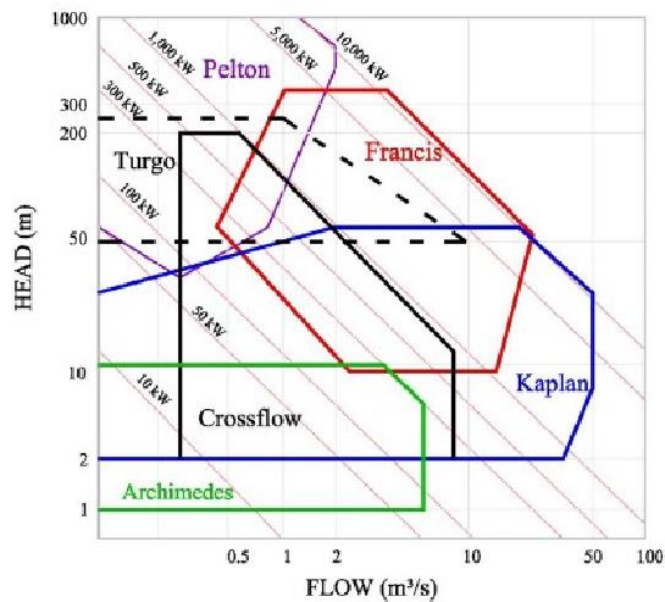
Figure 6 show the relationship between the ratio of tangential velocity of wheel ( $U$ ) and the upstream velocity of water ( $C_1$ ) to the mechanical and electrical efficiency of the breastshot waterwheel. Based on Figure 6, the highest  $\eta_{mech}$  occurs at the  $U/C_1$  of 0.83, while for  $\eta_{elec}$  it was found at the  $U/C_1$  of 0.95.

The  $U/C_1$  results are quite different from Sagebien's, which is around 0.25-0.33, the shape of the breastshot turbine is not optimal for capturing energy efficiently under very small discharge and head conditions, so it is not recommended to use breastshot turbine in river flow conditions that have discharge and small head, from the turbine selection graph (Figure 7) the best turbine in this condition is Archimedes [16].

Although the efficiency results are relatively low, breastshot waterwheel technology is easily understood and easily manufactured by people in remote areas of Indonesia.



**Fig. 6.** Relationship of  $U/C_1$  to  $\eta_{mech}$  and  $\eta_{elec}$  of the breastshot waterwheel



**Fig. 7.** Turbine Selection, Head vs Flowrate



**Fig. 8.** Experiment documentation



#### 4. Conclusions

Based on the results, the performance of 16 blades breastshot waterwheel in discharge of  $0.09708 \text{ m}^3/\text{s}$  and head of 0.26 m were: for the highest  $\eta_{mech}$  occurs at the  $U/C_1$  of 0.83, while for  $\eta_{elec}$  it was found at the  $U/C_1$  of 0.95. and has a mechanical efficiency of 45%, slightly lower compared to studies conducted by Quaranta *et al.*, [5]. Can be concluded from the comparison result, increasing the discharge with same number of blades (16 blades) causes reduction in performance efficiency and it is proven that the breastshot waterwheel does not produce optimal efficiency at a discharge below  $0.1 \text{ m}^3/\text{s}$  and the head below  $1\text{m}$ . In further studies it is recommended to be able to test different number of blades with more discharge and head variations.

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