The effect of bucket number on breastshot waterwheel performance

Warjito¹, Dendy Adanta¹,², Budiarso¹ and Aji P Prakoso¹

¹ Department of Mechanical Engineering, Faculty of Engineering, Universitas Indonesia, Kampus Baru UI Depok 16424, Indonesia

E-mail: dendyadanta@ymail.com

Abstract. More than 17% of people in remote areas of Indonesia still do not have electricity. With the abundance of water potential in Indonesia, hydro pico is considered as the right solution because it has cheap investment and operational cost. The breastshot waterwheel is a suitable turbine that can be applied because it does not affect the garbage in the water. Characteristic of the breastshot waterwheel especially effect of bucket number on performance have been study in this paper. CFD method is used to evaluate the flow field and explain the effect of the number of buckets on the waterwheel performance qualitatively. The turbulent model used is k-ε. Simulations were performed with the number of buckets 11, 12, 13, 14 and 15. Analysis using ANOVA block design explains that there is a relationship between the number of buckets to the generated power (F₀ > Fₜₐ₉ₐₙ). From the analysis, the wheel with the number of bucket 13 produces more stable power than other buckets. This is because the shape of the radial blade is not so steeply upward that the weight energy of water and kinetic energy can be utilized maximally.

1. Introduction
Water turbines with hydro-pico scale (<5 kiloWatt) are suitable for remote areas in Indonesia. Pico hydro is considered suitable because it has the cheapest investment and operational cost when compared with wind turbine and solar PV[1]. Therefore, some developing countries use hydro pico for electrification in remote areas such as Cameroon, Nepal, Laos, Rwanda, Honduras, Bolivia and Peru[1–6].

Indonesia has abundant water energy potential. However, there are major constraints for the utilization of hydro pico in Indonesia, namely garbage. The previous work shows that the garbage caused the turbine blade stuck so that the turbine can not operate. Waterwheel overshot, breastshot and undershot are seen as one turbine that has little effect on the garbage contained in water. This is because the shape of the bucket or blade is larger than the existing garbage.

The difference between the three types of waterwheels lies in the type of energy transferred to the wheel through the blade or bucket. The overshot waterwheel is a hydroelectric power plant that utilizes the gravity of water to rotate the shaft[7]. The undershot waterwheel is a hydroelectric power station that utilizes the compressive energy and boost of water that is transferred through the blade to

² Author to whom any correspondence should be addressed.
rotate the shaft[8]. While breastshot waterwheel is a hydroelectric power station that utilizes kinetic energy and weight water to rotate the wheel through the bucket[9].

Due to the available head of 1.5 meters and with a flow rate of 41 l/s, the breastshot waterwheel is considered to be very suitable for application. Many studies have been done to improve breastshot waterwheel performance for maximizing kinetic energy and weight water. Muller and Wolter (2004) observed water velocity on the upstream and downstream sides to find out the loses that occur on the breastshot waterwheel [10]. TevataanndImprasit (2011) designed breastshot waterwheel using non-dimensional parameters, Paddle number and immersed radius ratio [11]. Paddle number is a comparison of water velocity and wheel speed. Paudel etal. (2012) to modify the bucket by making the bucket flexible so as not to kill the biota that lives in the water [12]. Yelguntwar et al. (2014) determines the relationship of water velocity and wheel to the resulting power[13]. Emanuele Quaranta&Revelli (2016) determine the type of energy transferred to the bucket breastshot to easier improve performance[14], by 2017, engineering is done by flowing water directly to the bucket for reducing loses[15].

There are many parameters that influence the performance of breastshot waterwheel including are the number of bucket, wheel width, bucket shape and outer and inner diameter ratio. Bucket shape is very influential in the energy transfer process that occurs in the breastshot because the bucket is the place of the energy transfer process. On the other hand, the number of buckets is a function of the bucket form. To know the effect of bucket quantity on the breastshot waterwheel, an analysis was done by using CFD.

This study aims to evaluate the amount of bucket wheel to be used, to study the behavior of unexpected conditions and to know the relation of the number of buckets to the bucket shape. The CFD method is chosen because it is cheaper and can clearly describe the flow field which can not be done by another method[16].

2. Configure the dimension of breastshot waterwheel

Breastshot waterwheel design begins with determining wheel speed rotation after known rotation speed will be known size parameters of the wheel design to be used[17]. Bucket breastshot waterwheel schematic drawing can be seen in figure 1:

![Figure 1. Bucket breastshot waterwheel scheme](image-url)

Wheel rotation speed is the main parameter that must be set. The rotational speed \( n \) has an inverse relationship with the width of the mill \( (w) \). So to determine the value of \( w \) is done iteration with the value of \( n \) between 2-20 RPM. Equation 1 is used to determine the value of \( w \) and the value of \( n \)[17]:

\[
w = \frac{4060}{\pi(D_o^2 - D_i^2)}n\]

The next step, determine the size of the outer diameter \( (D) \) of the wheel[17]. To determine the value of \( D \) used the equation 2:

\[D = 2H\]
Where $H$ is the head. The basic difference between breastshot, undershot and overshot is that the diameter of the breastshot turbine wheel should be twice from the available $H$, this is because the waterwheel breastshot absorbs the water energy through the center of the wheel[17].

To determine the magnitude of the annulus width ($t$), the best efficiency of waterwheel has a ratio value of $t/R_o=0.23$ [18]. Determining the angular length of the road ($s$), the length of the radial side blade ($h$) and the width or length of line B to C ($h'$) using equation 3[17]:

$$\frac{R_o}{\sin \beta} = \frac{(h+R_i)}{\sin \alpha} = \frac{h'}{\sin \theta}$$

(3)

$$\sin \alpha = \frac{\sin \beta (h+R_i)}{R_o}$$

(4)

$$\theta = 180^\circ - \beta - \alpha$$

(5)

for ($s$) is:

$$s = h' + h$$

(6)

Number of bucket using equation 7 [19]:

$$z = \frac{\pi D_o \sin \beta'}{(a.s)+t_r}$$

(7)

$\beta' = 180 - \beta$, $t'$is the thickness of the iron plate to be used planned (3 mm) and $a$ is the obesity channel between the blades (1/2.5)[17].

3. Method

To design the wheel, the boundary conditions used is 1.5 meters, flow rate of 41 l/s (derived from laboratory conditions), wheel rotational speed of 7.5 RPM, gravity 9.81 m/s$^2$, and density of 1000 kg/m$^3$. The results of the calculations performed by using the previously described equations obtain the value of the width of the ($w$) 0.36 - 0.03 meters wheel with a wheel speed of between ($n$) 2 - 22 RPM. The wider the wheel the lower the speed of the turbine, and vice versa. So it takes the ideal width to be used. Wheel width determination is done by averaging the results obtained and then the average value is used to determine the value of rotation speed to be used [20]. Furthermore, the outer diameter of 3 meters is measured, while for inside diameter is 2.15 meters, the width of the wheel is 10 cm, the length of the radial road blade is 0.11 meters, the outer side of the outer blade is between 0.61 - 0.55 meters and the number of buckets used 11-15.

Computational method in this study is using CFD software. Computational method is done to see waterwheel performance. The boundary conditions given in the computational method are inlet velocity is 1.25 m /s, acceleration gravity is -9.81 m/s$^2$, rotational speed 5, 7.5 and 10 RPM. The flow is assumed to be turbulent. The turbulent model used is k-$\varepsilon$. k-$\varepsilon$ k-$\varepsilon$ can be used to predict the turbulent flow that occurs in the breastshot waterwheel[16]. In the computation method also consider the mesh independency to optimize the number of mesh used. Mesh independency is performed on one of the buckets, which in turn, the optimized number of mesh is applied to the number of other buckets. Furthermore, to save computational power, 2D assumptions were used in this study. The flow chart of the method can be seen in figure 2.

There are two data of simulation result which will be analyzed that is torque (power) and contour velocity. Torque (power) is used to determine the relationship of bucket number with power using ANAVO block design. Prior to analysis using ANOVA block design, Chauvenet’s criteria were used as a reference for data filtering (power). While the speed contour is used to see whether the kinetic energy and water weight is absorbed by the bucket. In addition, visual contours are also used to determine the number of buckets recommended for use.
4. Result and discussion
ANOVA blocking design is used to determine the relation of the number of buckets with power. Furthermore, Stability of power generated is used as base parameter to determine the ideal number of bucket, so that when the wheel is implemented the turbine can still operate even though the discharge decreases suddenly.

4.1. Statistic analysis
The grid independence process is performed to verify the number of mesh. This process is done by continuously reducing the mesh size, so the level of accuracy of the solving process in the simulation will increase. The grid independency process starts with medium mesh size, then fine mesh, followed by $\frac{1}{2}$ size of fine mesh size. To identify the grid independence result, tested at a point, the test is done by using pressure variable at the point (2.7,0,0) or after the water passes through the wheel. for more details please note figure 3 and table 1.

From the grid independency results, all simulations are performed on mesh number $\frac{1}{2}$ times the number of mesh fine. This number is chosen because when compared with the higher number of mesh (fine) has a smaller difference of 1.3% when compared with the lower mesh (medium) is 4%.

Each wheel with different RPM values is simulated per time step of 0.005 seconds for 4 seconds and with ten simulations. It is necessary to obtain the distribution of data, whether there are samples that are not in the normal distribution. Filtering the data obtained from the simulation results is done using Chauvenet's criterion. Filtering data is used to know the data obtained, what if a data has local standard deviation value $((x_i - \bar{x})/\text{std} dev)$ is greater than the value of Chauvenet's criteria ($t$) with the sample value of ten ($N=10$) is 1.96, then the data obtained must be eliminated because it exceeds the threshold of Chauvenet's criteria [21].

| Description       | Mesh size |
|-------------------|-----------|
|                   | Medium    | $\frac{1}{2}$ Fine | Fine       |
| No. of nodes      | 2540      | 3650              | 8496       |
| No. of elements   | 2172      | 3185              | 7748       |
| Pressure (Pa)     | 358.77    | 361.3             | 373.83     |

To determine whether there is a correlation to the number of buckets on the generated power, the analysis is done using ANOVA Blocking Analysis. ANOVA Blocking is chosen because the number
of buckets and rotational speed can be controlled[22]. Table 2 is a summary of the results of the analysis using ANOVA Block Design:

| Source of variation | Sum of square | df | Mean square | F0 |
|---------------------|---------------|----|-------------|----|
| SSTreatment         | 73147.72      | 4.00 | 18286.93    | 22.44 |
| SSblock             | 12074.34      | 2.00 | 6037.17     |     |
| SSE                 | 6518.56       | 8.00 | 814.82      |     |
| SSTotal             | 91740.62      | 14.00 |             |     |

\[ F_{0.01,4,8} = 7.59 \]. This explains that the value \( F_0 > F_{0.01,4,8} \) which means that \( H_0 \) rejected. This means that statistically proven that there is influence of the number of bucket breastshot waterwheel to the power to be generated by the turbine.

4.2. Computational result
The results of the data obtained from the simulation found that the highest power value obtained by the wheel with the number of bucket 11. This is because the volume of water accommodated by the bucket is much more than the other bucket. However, the percentage decrease or increase in power when the rotational speed decreases or increases, the least changed is the wheel with the number of bucket 13. This is presumably because the distance between buckets is relatively stable so that the water entering into the bucket is more stable. In the wheel with the number of bucket 15, the absorbed power is lower than the other bucket due to the small angle of the blade (\( \beta \)) so that the kinetic energy of water is not maximally utilized (see figure 5). The data of simulation result can be seen in figure 4.

Figure 4 and figure 5 describes both quantitatively and qualitatively the wheel with the number of bucket 11 is the bucket that has the highest efficiency and power. Technically the bucket with the number of bucket 11 is the best bucket but when viewed more clearly, bucket 13 is a bucket that is slightly affected when turbine rotation decreases and increases as result is stable generated torque. This is very advantageous when the wheel is implemented, this condition will extend the life of the generator to be used because the rotation and torque are relatively stable. Such as, when there is rain that causes the discharge increase significantly, this reduces the risk of over-round generator and also when the generator's rotation and torque decreases suddenly, the generator can still generate power because the required rotation of the generator remains met.

![Figure 4](image_url)

**Figure 4.** a. Graph of the bucket number relation to power, b. Graph of non-dimensional efficiency and power.
Figure 5. Water volume contour accommodated in wheel with 13 buckets.

4.3. Discussion
The breastshot waterwheel performance is influenced by the number of buckets because the waterwheel breastshot utilizes weight energy and kinetic energy. To maximize energy absorption, the bucket breastshot design of a minimum value of $\beta$ is $112.5^\circ$. This is because when the $\beta$ angle is too high it will block the access of water entering into the bucket thus causing the kinetic energy not to be maximally utilized.

Simulation results obtained similarly to this research was conducted by Quaranta and Revelli (2015). Quaranta and Revelli (2015) discussed the effect of the floodgates on wheel performance. Quaranta and Revelli explained that the smaller the water gate the higher the water velocity resulting in increased kinetic energy, increased kinetic energy impact on minimizing the water filling time in the bucket thereby increasing the torque and getting a positive effect on the performance of the wheel[23].

Research conducted by Helmizar (2016) indicated different result. Helmizar (2016) explains that the number of buckets does not contribute significantly to the performance of the turbine, in the case of 12 buckets obtaining torque of 0.97 Nm, while with buckets of 6 obtaining a torque of 0.91 Nm[9]. This is alleged because of the different forms of bucket used, Helmizar uses a curvature-shaped bucket that leads upwards, causing the kinetic energy of water not maximally utilized yet.

5. Conclusion
The results of the investigation using ANOVA block design explains that there is a relationship between the number of buckets used with the power to be generated ($F_0 > F_{0.01,4.8}$). This is because the angle of the bucket arm greatly affects the absorption of kinetic energy contained in water. The bucket breastshot design is recommended not to create a bucket shape with a value of $\beta$ below $112.5^\circ$ due to the bucket sleeve shape ($h'$) pointing upward, the outer side shape of the upwardly highway blade that will cause the kinetic energy of the water can not be absorbed maximally because it is blocked by bucket arm.

Bucket number 13 is a bucket that is slightly affected when turbine rotation decreases and increases as result is stable generated torque. Thus it can be concluded that for head of 2.71 meters and flow rate of 41 l/s the number of bucket 13 is recommended to use.

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