Optimization of the Water Volume in the Buckets of Pico Hydro Overshot Waterwheel by Analytical Method

Budiarso1, Dendy Adanta1*, Warjito1, A I Siswantara, Pradhana Saputra1 and Reza Dianofitra1
1Department of Mechanical Engineering, Faculty of Engineering, Universitas Indonesia, Kampus Baru UI Depok 16424, Indonesia

E-mail: dendyadanta@ymail.com

Abstract. Rapid economic and population growth in Indonesia lead to increased energy consumption, including electricity needs. Pico hydro is considered as the right solution because the cost of investment and operational cost are fairly low. Additionally, Indonesia has many remote areas with high hydro-energy potential. The overshot waterwheel is one of technology that is suitable to be applied in remote areas due to ease of operation and maintenance. This study attempts to optimize bucket dimensions with the available conditions. In addition, the optimization also has a good impact on the amount of generated power because all available energy is utilized maximally. Analytical method is used to evaluate the volume of water contained in bucket overshot waterwheel. In general, there are two stages performed. First, calculation of the volume of water contained in each active bucket is done. If the amount total of water contained is less than the available discharge in active bucket, recalculation at the width of the wheel is done. Second, calculation of the torque of each active bucket is done to determine the power output. As the result, the mechanical power generated from the waterwheel is 305 Watts with the efficiency value of 28%.

1. Introduction
Rapid economic and population growth in Indonesia lead to increased energy consumption, including electricity needs. Electrical energy development that is more efficient at a lower cost becomes vital since energy resource’s price tend to increase whilst its availability was limited. Meanwhile, Indonesia is a developing country where electricity supply is not evenly distributed in the entire region even though electricity is the primary need of everyone [1].

Construction of hydroelectric power (hydropower) is one of the potential electricity supply solution for developing countries such as Indonesia in which some areas, including remote areas, have rich water energy potential. The remote areas in Indonesia have several characteristics, such as the lack of infrastructure, clean water, inadequate electricity, irrigation, education, economy, and low productivity [2]. In designing hydroelectric power generation, the selection of water turbine technology should be considered as each turbine has its specifications. There are at least two parameters that are usually used in determining the type of turbine to be used namely head and flow rate [4].
Selection of the type of water turbine can be seen on the graph that describes the characteristics of relation between flow rate (m$^3$/s) and high net fall (m) in order to get the type of turbine that is appropriate and suitable to the site conditions of turbines as shown in fig. 1 [4]. The experimental site used is at Salam Lake UI with head is 2.7 m and discharge 0.041 m$^3$/s.

![Figure 1. Flow rate vs Head [4]](image)

From the information obtained in figure 1 the type of turbine that is suitable to be used is in Salam Lake is overshot waterwheel. The overshot waterwheel is a hydroelectric power plant that utilizes the gravity of water to rotate the shaft [5].

Although overshot is a fairly old technology, very few studies that examine the overshot waterwheel are available. There are at least four studies that discuss overshot turbines. Euren and Weyer (2005) identified suitable irrigation for overshot and undershot waterwheel [7]. Aryo (2012) used overshot to generate electricity at very low head condition, 25 cm [8]. Capecchi (2013) tells the origin of the overshot waterwheel used in the 18th century [6]. Wibawa et.al. (2014) designed an overshot turbine that will be used for electrification in the village of Bendosari Malang Regency Indonesia [9].

There are several advantages of using overshot waterwheel as a power plant in remote areas in Indonesia such as ease of operation, maintenance and maintenance and the low cost of investment costs are not too high. This is because the river conditions in Indonesia contain a lot of garbage in the form of dried leaves from trees, household waste and others that may interfere with the turbine’s operation. To prevent such interference, this study attempts to optimize bucket dimensions with the conditions available so that garbage does not have a significant effect on the turbine. In addition, the optimization also has a good impact in increasing the amount of generated power.

2. Methodology
The method that is used to design the overshot waterwheel is the analytical and numerical method, by specifying the dimensions in accordance with the provisions of the flow rate and the height. Analytical method also includes stating the mass and the volume of water contained in each active blade. Then, ascertaining the rpm, torque, and the power of the waterwheel is done to know the center mass point on each active bucket.

2.1. Waterwheel design analytic
Water condition at Salam Lake Universitas Indonesia with head ($H$) is 1.15 m and discharge ($Q$) is 0.041 m$^3$/s. So, available hydro dynamic power = 1090 N
2.1.1. Flow velocity

\[ V = \sqrt{2gh} \]  

(1)

2.1.2. Peripheral speed of the waterwheel

\[ U_1 = \frac{V_1 \cos \alpha_1}{2} \]  

(2)

2.1.3. Waterwheel rotation

\[ n = \frac{60 U_1}{\pi D_1} \]  

(3)

2.1.4. Tip speed channel

The tip speed channel can be obtained using the open channel hydraulics equation

\[ h_1 + \frac{\alpha V_1}{2g} + z_1 = h_2 + \frac{\alpha V_2}{2g} + z_2 \]  

(4)

\[ R = \frac{A}{p} \]  

(5)

\[ V = \frac{1}{n} R^{\frac{3}{2}} S^2 \]  

(6)

flowrate on channel

\[ Q = A.V \]  

(7)

2.1.5. Dimension

Outer diameter

\[ D = \frac{1000 N 2}{\rho \cdot g \cdot Q \cdot \eta} \]  

(8)

On the outer diameter, the obtained results is divided by 7, so that the waterwheel diameter will be smaller and can be installed at Salam lake UI.

Inner diameter

Planned \( t/R_0 = 0,15 \) (0,05 < \( t/R_0 < 0,25 \)), with:

\[ t = R_0 - R_0 \]  

(9)

and,

\[ 0,15R_0 = R_0 - R_1 \]

\[ R_1 = R_0 - 0,15 R_0 \]

\[ 0,15R_0 = R_0 - R_1 \]

\[ R_1 = 0,85 R_0 \]

\[ R_0 + 0,85 R_0 = \frac{1,03}{2} \]

\[ R_0 = 0,515m \]

Thus:

\[ R_1 = 0,85R_0 \]

\[ R_1 = 0,43m \]

Then the value taken is

\[ R_1 = 0,43m; D_1 = 0,875m \]

2.1.6. The bucket design
It is known that the optimum blade shape is the shape of flat bottomed, where the bottom of the blade-shaped is radial to the axis of the shaft with \(1/4\) length from annulus width \([10]\).

\[
\begin{align*}
\frac{R_0}{\sin \beta} &= \frac{h + R_1}{\sin \alpha} = \frac{h'}{\sin \theta} \\
\sin \alpha &= \frac{R_0}{\sin \beta (h + R_1)} \\
\theta &= 180^\circ - \beta - \alpha \\
h' &= \frac{D_0 \sin \theta}{\sin 115^\circ}
\end{align*}
\]  

(10)  

(11)  

(12)  

(13)

Overall length

\[ s = h' + h \]  

(14)

Design of the bucket can be seen on figure 2:

Figure 2. Bucket design \([10]\)

Number of buckets:

\[ z = \frac{\pi D_0 \sin \beta'}{a \cdot s + t'} \]  

(15)

Active buckets:

\[ i = \frac{N(rps)}{rpm} \cdot z \]  

(16)

Distance between the bucket on outer side:

\[ z_o' = \frac{D_0 \pi}{z} \]  

(17)

Distance between the bucket on inner side:

\[ z_i' = \frac{D_1 \pi}{z} \]  

(18)

The result of all the calculation above can be seen on table 1.

| Table 1. Design summary |
|-------------------------|
| Description | Value | Unit |
| \(V\)            | 4,75  | m/s  |
| \(U_1\)          | 1,43  | m/s  |
| \(n\)            | 28    | RPM  |
| \(Q\)            | 0,19  | m³/s |
| \(D_0\)          | 1,03  | m    |
| \(D_1\)          | 0,87  | m    |
| \(b\)            | 0,80  | m    |
|       |       |
|-------|-------|
| \(a\) | 53.1  |
| \(\theta\) | 11.87 |
| \(h'\) | 11.43 |
| \(s\) | 11.30 |
| \(z\) | 25    |
| \(i\) | 11.67 |
| \(z_{o}'\) | 13    |
| \(z_{l}'\) | 11    |

degree (\(^\circ\))
cm

After obtaining the design results of the calculation, the visualization of 2D and 3D can be seen in fig. 3.

The table above shows the dimensions of the waterwheel design.

**Figure 3.** a. overshot waterwheel design, b. side view of the 2D overshot waterwheel

### 2.2 Optimization of volume

To get the value of power and torque, the calculation is done by determining the buckets volume and the centroid points for each bucket.

#### 2.2.1. Volume of each bucket

To get the volume and mass on a bucket, the calculation is performed by dividing the area into several areas. For example the bucket number 1 on fig. 3. It is divided into three areas, namely there are two triangles and one rectangle. After the surface of each component is obtained, they are multiplied by the width of the bucket itself. Therefore we obtained the volume and mass of water in the bucket number 1. Overshot waterwheel should be able to accommodate the discharge of produced water per second. Then we got 80 cm width to accommodate a flow of 0.041 m\(^3\)/s. with assuming the initial calculation of 40 cm to get an area of each bucket.
Table 2. Area of triangle 1 of bucket number 1

| Description               | Value   | Unit  |
|---------------------------|---------|-------|
| ½ x base x height         | 55.38   | cm$^3$|
| area x width of bucket    | 4430.4  | cm$^3$|
| convert cm$^3$ to m$^3$   | 0.0044304| m$^3$|
| Convert to mass           | 4.4304  | kg    |

Table 3. Area of triangle 2 of bucket number 1

| Description               | Value   | Unit  |
|---------------------------|---------|-------|
| ½ x base x height         | 27.69   | cm$^3$|
| area x width of bucket    | 2215.2  | cm$^3$|
| convert cm$^3$ to m$^3$   | 0.0022152| m$^3$|
| Convert to mass           | 2.2152  | kg    |

Table 4. Area of rectangle of bucket number 1

| Description               | Value   | Unit  |
|---------------------------|---------|-------|
| ½ x base x height         | 18.9    | cm$^3$|
| area x width of bucket    | 1512    | cm$^3$|
| convert cm$^3$ to m$^3$   | 0.001512| m$^3$|
| Convert to mass           | 1.512   | kg    |

Total Mass on bucket 1 = 8,1576 kg.
The total area of bucket 1 = 8157.6 cm$^3$/s. If the amount total of water contained is less than the available discharge in active bucket, recalculation is done at the width of the wheel.

2.2.2. Center point of mass
Center point of mass is calculated to determine the torque of each active bucket. After the total torque of each active bucket is known, then we may get the value of the power output. This
calculation applies to all active bucket. For the example on bucket number 1:

Weight percentage on bucket number 1:
\[ I_1, I_2, I_3 = A_{\text{triangle}} \times \text{total area} \] (19)

Mass each surface on bucket number 1:
\[ w_1, w_2, w_3 = \text{Total volume (kg)} \times \text{weight percentage} \] (20)

![Figure 5. Each center point of surfaces on bucket number 1](image)

\[
x_G = \frac{\sum w_i x_i}{\sum w_i} = \frac{w_1 x_1 + w_2 x_2 + w_3 x_3 + \ldots}{w_1 + w_2 + w_3 + \ldots}
\]

\[
x_G = \frac{g(m_1 x_1 + m_2 x_2 + m_3 x_3 + \ldots)}{g(m_1 + m_2 + m_3 + \ldots)} = \frac{\sum m_i x_i}{\sum m_i}
\] (21)

The same calculation applies to y axis:
\[
y_G = \frac{m_1 y_1 + m_2 y_2 + m_3 y_3 + \ldots}{m_1 + m_2 + m_3 + \ldots} = \frac{\sum m_i y_i}{\sum m_i}
\] (22)

After the \( x_G \) and \( y_G \) is known, then we can get the center point of mass on the bucket 1. Which is the \( \beta \) and radius from center point of waterwheel to center point of the bucket and is known with 86.64° and 468 mm distance.

### 3. Results and Discussion

On the center of mass calculation, we can get point coordinates \((x, y)\) on the bucket 1 itself \( (x_G = 79.8 \text{ and } y_G = 54.8) \), and with a length of 468 mm radius and at an angle of 86.64° \( (\cos 86.64° = 0.0586) \) from center point of the wheel to the center point of bucket 1.

Torque on bucket 1 can be determine by:
\[
\tau = \cos \beta \times \text{length of mass} \times g \times \text{total mass}
\] (23)

\[ \tau = 0.0586 \times 0.468 \times 9.81 \times 8,1576 = 2,194 \text{ Nm} \]

The same calculation applies to all other active buckets and the optimum result is can be seen in table 5:

| Description | Value | Unit |
|-------------|-------|------|
|             |       |      |
Total Torque = 104 Nm.

After all the torque from each bucket are known, the power output can be calculated by:

\[ P_{\text{output}} = \tau_{\text{total}} \times \text{rotation} \]  
\[ P = 104 \, \text{Nm} \times 2.93 \, \text{rad/s} = 305 \, \text{Watts} \]

From the result of the power output and torque that is known, then the efficiency can be obtained by:

\[ \eta = \frac{P_{\text{output}}}{P_{\text{hydro}}} \]  
\[ \eta = \frac{305}{1090} = 28\% \]

**Table 6. Analytical result**

| Description        | Value | Unit |
|--------------------|-------|------|
| Torque             | 104   | Nm   |
| Power              | 305   | Watts|
| Efficiency         | 28    | %    |
| Bucket active      | 8     | -    |
| Bucket volume      | 40.28 | cm³  |

### 4. Conclusion

The result of investigation by using analytical method got maximum performance of overshot water wheel at head 1.15 meters and discharge 0.041 m³/s, which resulted in 305 Watt with wheel width 0.8 meters and has mechanical efficiency equal to 28%. The volume of water in the bucket is the most in bucket number 1 because the bucket arm leads to the vertical axis of the wheel while the largest torque is on bucket number 5 because it has the longest force arm.

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