Application of Elliptical Blade Shape to Enhance Power Generation of the Savonius Water Turbine

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Abstract. Sewerage pipelines found in the buildings can be used as a mechanical energy resource for small capacity hydrokinetic power plant. The utilization of energy resources can be generated by installing the savonius hydrokinetic turbine. Conventional turbine is designed with semi-circular blades able to generates its own performance, but is still relatively low. In this research, the savonius type elliptical blades are applied to enhance the turbine performance. This experimental observation are conducted to obtain the optimal number of blades, which is determined by the maximum power generated by the rotor. The number of blades are tested for 2, 3, and 4 blades with four differences of the water discharge. A single-stage horizontal axis savonius water turbine (HAWT) was installed in a 3 inches diameter pipelines. The results of the experiment show that at four numbers of the blade, obtained the optimal power of 4.251 Watts at a discharge of 5.826 x 10⁻³ m³/s with tip speed ratio (λ) 2.37 and the coefficient of power (Cp) 0.025.

1. Introduction

The drainage system of a building has the potential hydrokinetic energy that can be converted into electrical energy. The drainage system of a building contained a mechanical energy due to the movement of amount water mass based on gravity. The kinetic energy and potential energy due to the head will catch by savonius turbine in the drag force principle [1]. It is the reason why the turbine have to built with most appropriate design and high efficiency. Because the drag force principle, it needs a large and optimum surface area to capture the energy contained on the water flow. Higher torque can be conducted using a curved blade inside. The turbine can also receive all water-induced on the blade in all directions. Therefore, the turbine can rotate more easily and automatically when water flows relatively about the blade.

The performance improvements of the savonius turbine can be achieved by designing the optimum profile of the turbine blades. The conventional semi-circular savonius turbine blade profile has low efficiency and large static torque variations. The available literature reports that the twisted-slatted rotor shows better performance in terms of efficiency, initial and smooth capability compared to the one half-circle rotor blade [2]. Other researchers also conducted research with elliptical blades with variations of the arc angle. The results of the study gained that the elliptical shape with an arc angle (θ) of 47.5° was better 18.18% compared to previous research in a semicircular shape. The coefficient of power (Cp) 0.33 can be achieved at the tip speed ratio (λ) 0.8 [3].
The number of blades provides an important role in the performance of the savonius turbine depending on operating conditions. An increase in the number of turbine blades can increase the driving force from static to rotating conditions [4]. Other studies said that the performance of three blades is better than other number of blades. The performance of the turbine with three blades can produce the power coefficient of 0.234 at tip speed ratio of 1.783 and the water discharge of $5.751 \times 10^{-3} \text{m}^3\text{s}^{-1}$ [5]. Several studies show differences in concluding which blade number is optimal. It can be understood because the differences in operating condition of the turbine on these research. So, we can not judge and generalize that three blades is the most optimum design.

Based on the literature already studied, the development of the savonius turbine was needed to improve turbine performance. Experimental studies should be conducted by testing the shape of the elliptical turbine blades with a 47.5° arc angle and variations in the number of turbine blades. In this research, the aspect ratio ($\alpha$) of 0.7 is applied with 82.6 mm turbine height adjusted to the testing instrument and the diameter of the 118 mm turbine. This study uses the savonius turbine type horizontal axis water turbine (HAWT).

2. Experimental set-up

Figure 1 shows the schematic diagram of the test apparatus, which is used in the present work. The experiments using a horizontal axis savonius water turbine. The turbine is installed in a turbine house with one shaft as a focus. Both ends of the shaft are fitted bearing as bearings so that the axle rotation does not rub against the turbine house [6]. At the end of the inlet section of the water inlet to the turbine is given deflector to direct the water flow to the turbine blades. The data retrieval process is done by pumping the water on the bottom tank to be sucked using the pump to the upper tank and then flowing through the vertical pipe so that the water attacks turbine.

The performance results of the turbine are carried out through two steps of methods. First is the prony brake method and second is electrical method. Prony brake method is aimed to investigate and calculate the turbine performance based on torque produced. Besides, electrical method is aimed to calculate the power produced by generator based on the voltage and electric current. The mechanical power for the tested savonius rotor can be determined by measuring the rotor rotational and torque of the rotor shaft at a different value of water speed while the electrical power of the turbine is determined from the measurement of voltage and electric current of the generator. Power is obtained from the average value of the voltage and current measurements using multimeters for one minute observation. Figure 1 shows the experimental test in this research.

![Figure 1. Apparatus test [6]](image-url)
The present experimental investigation concerns the number of blades. The savonius turbine is made with an aspect ratio \((H/D)\) of 0.7 and an end plate ratio \((Do/D)\) of 1.1 [7,8]. The objective of the current paper is to adapt the elliptical blade shape that has been performed by alom et al. [9]. The design with the sectional cut angle at \(\theta = 47.5^\circ\) is chosen and applied to the current research. Figure 2 shows the dimension and pattern of the ellipse with the sectional cutting angle \(\theta\). The \(\theta\) is made by the line intersecting the major axis AA’ at M. The point M is at 54% of AO from O to get the required chord length \((d)\) of the blade.

Figure 2. Elliptical profile and turbine geometry [9]

Figure 3 shows the results of the turbine fabrication which perform in the current study. The turbine is made using the 3D printing method with polylactic acid (PLA) material. Two, three, and four blades with the shape of the elliptical blade are shown in Figure 3. The back of the blade is added reinforcing using resin and fiberglass. It is intended that the turbine does not experience damage when testing due to water pressure on the turbine. Then, Table 1 presents the detailed dimensions of the turbine.

(a)  
(b)  
(c)

Figure 3. Turbine of (a) two blades, (b) three blades, (c) four blades

| Parameters | Dimensions | Information |
|------------|------------|-------------|
| \(H\)     | 0.0826 m   | Height of Savonius water turbine |
| \(Do\)    | 0.1298 m   | End plate diameter |
| \(D\)     | 0.1180 m   | Overall rotor diameter |
| \(T\)     | 0.0030 m   | Thickness |
| \(\theta\) | 47.5\(^\circ\) | Cutting angle of the ellipse |
3. Analytical of performance

In this section, several parameters are presented to calculate the turbine performance and the electricity that can be produced. From the values of measured torque and rotational speed, the mechanical power defined in Watt

\[ P_m = T \omega \]  

where \( T \) is the mechanical torque from the turbine shaft, and \( \omega \) is the angular speed. The angular speed is obtained in rad/s by

\[ \omega = \frac{2 \pi n}{60} \]  

where \( n \) is the rotational speed from a shaft in rpm. The mechanical torque obtained in Nm by the following equation:

\[ T = F \cdot r \]  

where \( r \) is the pulley radius. The force acting the rotor defined in N by

\[ F = (m - s) \cdot g \]  

where \( m \) is the mass loaded on the prony brake, \( s \) is the spring balance based on measuring instrument, and \( g \) is the gravitational acceleration. The power coefficient determines from the following equation

\[ C_p = \frac{P_m}{P_w} \]  

where \( P_w \) is the power available from the water. The value calculated from the following equation

\[ P_w = \frac{1}{2} \rho A V^3 \]  

where \( \rho \) is the density of water in Kg/m\(^3\), \( A \) is the projected area for the rotor from the outlet of the pipeline in m\(^2\), and \( V \) is the water speed in m/s. The power coefficient defined by

\[ C_p = \frac{g \pi r n (m - s)}{15 \rho A V^3} \]  

The electrical power (Watt) from the turbine generator defined by

\[ P = V \cdot I \]  

where \( V \) is the voltage in volt, and \( I \) is current in Ampere. Finally, the coefficient of torque given by

\[ C_T = \frac{4 T}{\rho U^2 D^5 H} \]  

where \( U \) is the velocity from the water in m/s, \( D \) is the rotor diameter in m, and \( H \) is the height of the rotor in m. The tip speed ratio is given by

\[ \lambda = \frac{\omega D}{2 U} \]  

where \( D \) is the rotor diameter.

The power that can be produced by generator is calculated at one minute experiment with six data every ten seconds. This method is applied because of the hydropower fluctuation produced by the water falls. So, to calculate the power and performance, we use the following equation.
\[ P = \sum_{t=1}^{60} V_{tx} Y_{tx} \]  

(11)

where, \( t \) is the time in second. \( tx \) is time at every ten seconds, \( x = 10, 20, 30, 40, 50 \) and \( 60 \).

4. Result and discussion

This section will discuss the results of the turbine experiment that has been obtained with variations in the blades number and water discharge. Turbine testing is performed using four different discharge of water flow.

**Figure 4.** Tip speed ratio related to debit

The experiment result showed the highest tip speed ratio was achieved at the water discharge, \( u = 3.168 \times 10^{-3} \text{ m}^3\cdot\text{s}^{-1} \), with a value of tip speed ratio, \( \lambda = 3.86 \) on a turbine with four blades. Figure 4 shows the relationship between the \( \lambda \) of the turbine and the water discharge, \( u \), as the variation in the experimental research. Adding water discharge to the input causes a decrease in the value of tip speed ratio. The decrease in the value of tip speed ratio corresponds to the formula, where the value of tip speed ratio will be inversely proportional to the water flow rate.

**Figure 5.** Power generates by the turbine

Figure 5 shows the impact of discharge on the power generated. The total electric power is calculated depend on the value of electric current multiplied by the voltage produced by generator. The electric current and voltage are measured by multimeters. The total power is calculated based on equation 11.
for one minute. The experimental results showed that a second discharge, \( u = 5.826 \times 10^{-3} \text{ m}^3\text{s}^{-1} \) is the maximum power of all the turbine blade numbers. The turbine with two blades can generate higher electrical power, \( P = 3.0687 \) Watts compared to other operating point. The measurement using multimeter showed a voltage, \( V = 10.6 \text{ V} \) and electric current, \( I = 0.29 \text{ A} \) can be produced at rotational speed of turbine, \( n = 392.6 \text{ rpm} \). The 3-inch turbine can provide rotational speed, \( n = 445.23 \text{ rpm} \) with voltage, \( V = 12 \text{ V} \) voltage measurement value and an electric current, \( I = 0.33 \text{ A} \). The experiment showed the best results with a maximum power, \( P = 4.25 \text{ Watts} \) on a 4-inch turbine. The electrical power measurement shows the result, \( V = 12.6 \text{ V} \) and a current, \( I = 0.337 \text{ A} \) can be produced at rotational speed, \( n = 463.7 \text{ rpm} \). The increasing of the debit value is not equated with the increasing power value of the resulting electricity, because the turbine rotation is obstructed by the back pressure of the water so that the turbine cannot rotate optimally. The following data is shown in the measurement results using multimeters.

![Figure 6. The relationship rpm and power generates](image)

Figure 6 shows a graph of the relationship between the rpm of the turbine and turbine generated power. The highest rotational speed occurs at a discharge, \( u = 3.168 \times 10^{-3} \text{ m}^3\text{s}^{-1} \) with a power output, \( P = 4.2521 \) Watts. The turbine with 4 Sudu delivers the best performance in this study. The power will be directly proportional to the rpm of the turbine. The rotational speed on the third and fourth debits decreased due to the rotation of the turbines hindered back pressure from the air. The water discharge input crashed the blade not directly out of the housing but took a round of turbines. This leads to back pressure on the convex part of the turbine and inhibits the turbine rounds.

### Table 2. Measurement result

| Blades | \( u \) (m\(^3\)/s) | \( V \) (Volt) | \( I \) (Ampere) | \( n \) (rpm) | \( P \) (Watt) |
|--------|---------------------|----------------|----------------|-------------|--------------|
| 2      | 3.168 \cdot 10^{-3} | 6.70           | 0.220          | 316.10      | 1.4740       |
|        | 5.826 \cdot 10^{-3} | 10.60          | 0.290          | 392.60      | 3.0687       |
|        | 8.994 \cdot 10^{-3} | 8.61           | 0.250          | 348.35      | 2.1533       |
|        | 11.652 \cdot 10^{-3} | 8.71           | 0.248          | 327.00      | 2.1634       |
| 3      | 3.168 \cdot 10^{-3} | 8.92           | 0.273          | 373.52      | 2.4368       |
|        | 5.826 \cdot 10^{-3} | 12.00          | 0.330          | 445.23      | 3.9661       |
|        | 8.994 \cdot 10^{-3} | 9.34           | 0.277          | 401.17      | 2.5850       |
| 4      | 3.168 \cdot 10^{-3} | 9.63           | 0.292          | 376.98      | 2.8097       |
The power coefficient represents the actual strength the turbine can extract from the working fluid. Tip speed ratio is an important parameter to identify turbine performance. The tip speed ratio is defined as the ratio of the tangential speed at the blade tip with the actual speed of the fluid, which determines the optimum speed of the blade to transfer energy from water to generate power [9].

![Figure 7. The power coefficient $C_P$](image)

Figure 7 shows the relationship between tip speed ratio and the coefficient of power. Best performance is achieved in 3 blades turbines with maximum power coefficient, $C_P = 0.196$ and tip speed ratio, $\lambda = 3.56$ at $u = 3.168 \times 10^{-3}$ m/s. Whereas the highest tip speed ratio value, $\lambda = 3.85$ is obtained at four blades, the power coefficient value that can be achieved is $C_P = 0.190$ at $u = 3.168 \times 10^{-3}$ m/s. In general, the increment of the tip speed ratio value will be directly proportional to the increase in the value of the power coefficient on all turbines.

![Figure 8. The coefficient of torque](image)
Figure 8 shows the coefficient of maximum torque occurring in a turbine with three turbine blades, and discharge $3.168 \times 10^{-3} \text{ m}^3/\text{s}$. Torque is measured on all variations of the turbine blade. Each turbine is carried on torque measurements on all discharges. The coefficient of power increases with a further increase in the tip speed ratio.

5. Conclusion
The experiment conducted to turbine 2, 3, and 4 Sudu with a variation of fluid flow speed to obtain the highest electrical power. It can be concluded that a turbine with a total of 4 blades can produce the highest electrical power while the highest $C_T$ and $C_P$ values are obtained on the turbine with three blades. The discharge with a value of $3.168 \times 10^{-3} \text{ m}^3/\text{s}$ is the optimal discharge that can convert the turbine into electrical power. Larger debit will lower the power output that the turbine can convert into electrical power because the larger discharge is given, the turbine will be exposed to the backpressure the water in the turbine housing. The back pressure caused the rotation of the Turbines to decrease, and the resulting electric power would be reduced due to the turbine’s electrical power being proportional to the turbine rotation.

Nomenclature

| Symbol | Description |
|--------|-------------|
| $C_P$  | Power coefficient |
| $C_T$  | Torque coefficient |
| $d$    | Chord length (m) |
| $D$    | Diameter of the rotor (m) |
| $D_o$  | Endplate diameter (m) |
| $e$    | Overlap distance (m) |
| $F$    | Mechanical load applied to turbine shaft (N) |
| $H$    | Turbine height (m) |
| $n$    | Rotational speed of turbine (rpm) |
| $r$    | Radius of the turbine (m) |
| $P_{\text{available}}$ | Power available in water (W) |
| $P_{\text{turbine}}$ | Actual power produced by the turbine (W) |
| $T$    | Torque (Nm) |
| $u$    | Water velocity (m/s) |
| $v$    | Water velocity (m/s) |

Greek symbols

| Symbol | Description |
|--------|-------------|
| $\lambda$ | Tip speed ratio |
| $\omega$ | Rotational speed (rad/s$^{-1}$) |
| $\rho$ | Water density (kg/m$^3$) |
| $\theta$ | Sectional cutting angle |

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