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# Performance of Undershot Water Wheel with Bowl-shaped Blades Model

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**Abstract.** Water power is a type of power obtained from the force created by flowing water. Energy created from flowing water can be harnessed as a form of mechanical energy that can be utilized to generate electricity. Undershot water wheels have been extensively used to take advantage of the water flowing from rivers or waterfalls. This research was conducted by using water turbines with bowl-shaped blades made of iron and acrylic. The diameter of the turbines was 30 cm, and the diameter of the blades was 9 cm. Four, six, and eight blades were used in the three water turbines for this research. The blades were discharged and loaded to turn the turbine to generate force. The results of the study showed that the highest efficiency ($\eta$ = 74.22%) was found in the six-blade turbine with a discharge of 0.01228 $m^3$/s. It can be concluded that water turbines with bowl-shaped blades can be used as an alternative energy in small-scale electric generators.

*Keywords:* Blades; Efficiency; Energy; Undershot; Water wheels

## 1. Introduction

The need for energy is increasing, especially in developing nations or areas. Appropriate generation of energy must be achieved to fulfill this increasing need. In Indonesia, the supply of energy still mostly relies on power plants that are run on fossil fuels, such as coal, oil, and natural gases (Altan and Atigan, 2008; Borg et al., 2014). These fuels are available only in limited amounts and will run out one day, while the demand for electricity continues to grow. Therefore, present energy consumption is shifting toward the use of renewable energy resources available in nature, including hydroelectric, wind, and solar energy, among others. This is because renewable energy sources are easily available and can be recycled, unlike fossil fuels, such as petroleum and coal (Saha et al., 2008; Singh and Ahmed, 2013).

A hydropower plant converts the energy of harnessed flowing water into mechanical and electrical energy. Hydroelectric energy is mostly generated by water mills (water wheels) or turbines in a waterfall or a river or stream (Denny, 2004; Khan et al., 2009; Sule et al., 2013; Sule et al., 2014). In a hydropower design evolution, the kind of turbine to be selected is decided by several specifications that depend on the conditions in the wished location (Budihardjo et al., 2015; Warjito et al., 2017).

Water the wheels are built with different shapes of plates. Bowl-shaped (i.e., half-sphere) plates have one of the highest drag coefficient values (1.42), especially in

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comparison to spherical plates (drag coefficient of 0.47). The greater the value of the drag coefficient, the greater the ability to harness the power of rushing water (Pujol and Montoro, 2010; Tjiu et al., 2015). The bowl shape can create a flowing stream of fluid when placed inside a generator (Deendarlianto et al., 2015).

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Although there are many works on different types of low-flow wheels with various blade models, there are no studies on bowl-shaped blades, which can achieve 50% efficiency (Denny, 2004). The bowl-shaped blades model is more effective than other shapes because the momentum on the surface of the blade exposed to water produces high water pressure. However, it needs to be studied in more depth the resulting performance related to the number of blades using the same diameter and bowl size.

### *1.1. Type of Water Wheel*

Water wheels can be broadly classified into three groups depending on the way in which water moves the water wheel. The three groups are as follows: (a) based purely on the gravity of the water; (b) based partially on the gravity of the water and partially on the flow of the water; and (c) based purely on the impulse of the water. In addition, there are three types of water wheels based on how the water is utilized: overshot wheel, breastshot wheel, and undershot wheel (Muller and Kauppert, 2003).

First, in the overshot wheel, water is inserted into the blade (bucket) at the top of the wheel. This type of water wheel uses only the gravity of water to operate. Basically, there is a small amount of force from the flow of the water into the bucket. Water from the top surface, begins to move through the sluice gate, which can be opened in a predetermined way (Warjito et al., 2017). Gravity pushes the blade down and makes the wheel rotate. When the blade approaches the bottom of the wheel, the water gradually begins to decrease. The advantages of using an overshot wheel are that it does not require heavy flow because the gravity of the water falling into the blade causes the water wheel to spin, it has a simple construction, and it is easy to maintain.

Second, in the breastshot wheel, water enters the blade at the center of the wheel (i.e., breast). The wheel is driven by a combination of gravity and the force of the water (Pujol and Montoro, 2010). Water flows from the top of the wheel (head race) into the blade through a number of channels, which are opened and closed through a rack and pinion mechanism and are designed to avoid changes in the flow. The bucket moves downward due to the gravity of the water and turns the wheel.

Third, in the undershot wheel, waterwheel activate when flowing water hits the bottom of the blade, which will rotate the wheel on its axis. This type of wheel is suitable for installation in a shallow, flat area where the water flows opposite to the direction of the blade in order to turn the wheel (Muller and Kauppert, 2003).

## 2. Methodology

### *2.1. Experimental Setup*

The installation testing involved a water reservoir, centrifugal pump, reservoir, installed pipe, installed duct, water wheel with bowl-shaped blades, lams circuits, a belt, a dynamo, and a digital tachometer (Asahi DT-2235) with a range of 40–50,000 rpm and accuracy of ±0.05%. All measurement devices were calibrated before the experiment.

*2.2. Experimental Procedures*

The performance of the water wheel was calculated by measuring the parameters of the primary speed of the water, debit, shaft rotation, and torque in the axle on the water (which was measured by varying the load on the water wheel axle, as shown in Figure 1 and 2).

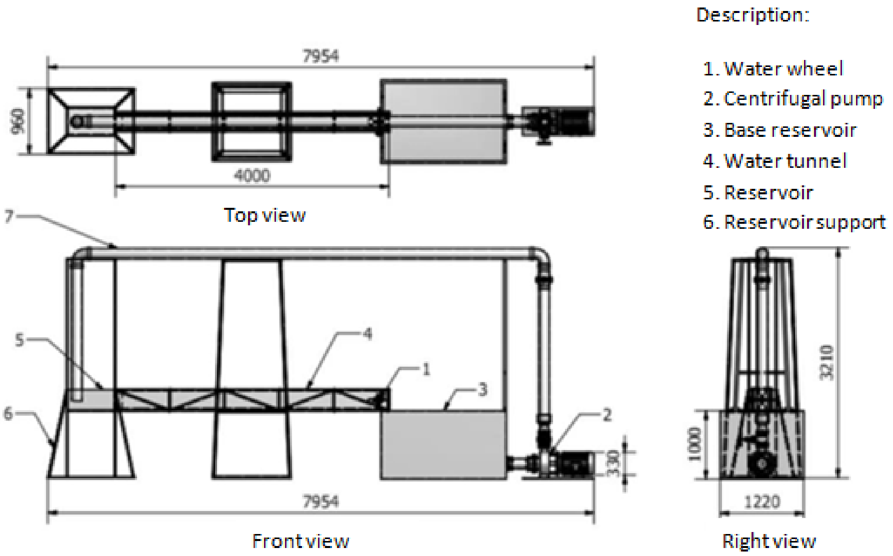


**Figure 1** Scheme and dimensions of experimental installation

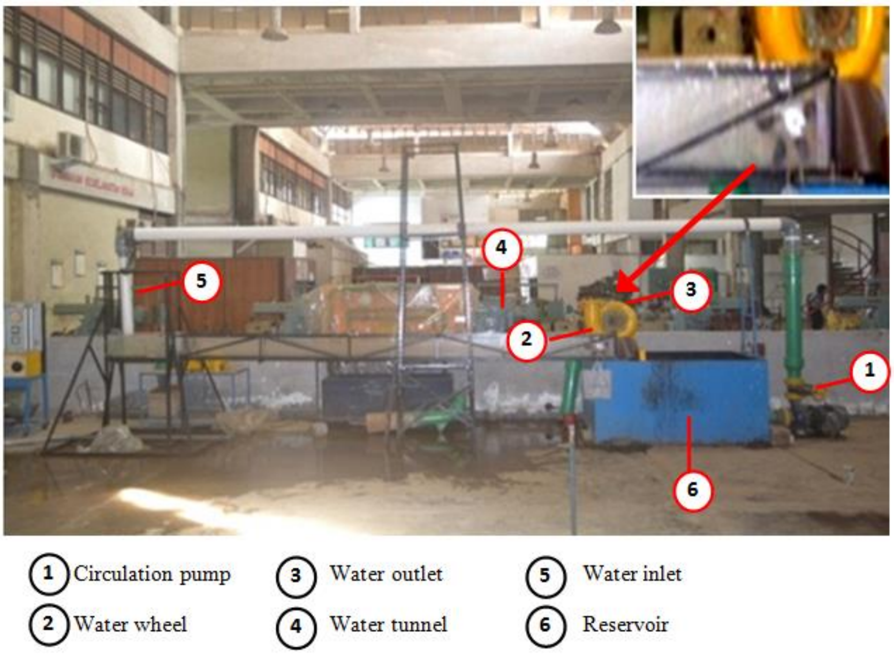


**Figure 2** Experimental setup

In this experiment, the loading on the shaft and debit was varied. Tests are carried out with loads from zero to maximum, which causes the shaft to slow down and finally stop. After that, the test results were calculated and analyzed by creating a table of efficiency with respect to debit and with respect to the number of blades. In the experiments, four, six, or eight blades were used to determine which number of blades is the best under the same flow rate conditions. The radius of the concave surface of the bowl was equal to the radius of the circle for each number of blades. The scheme of the water wheels with four, six, and eight blades are shown in Figures 3 and 4.

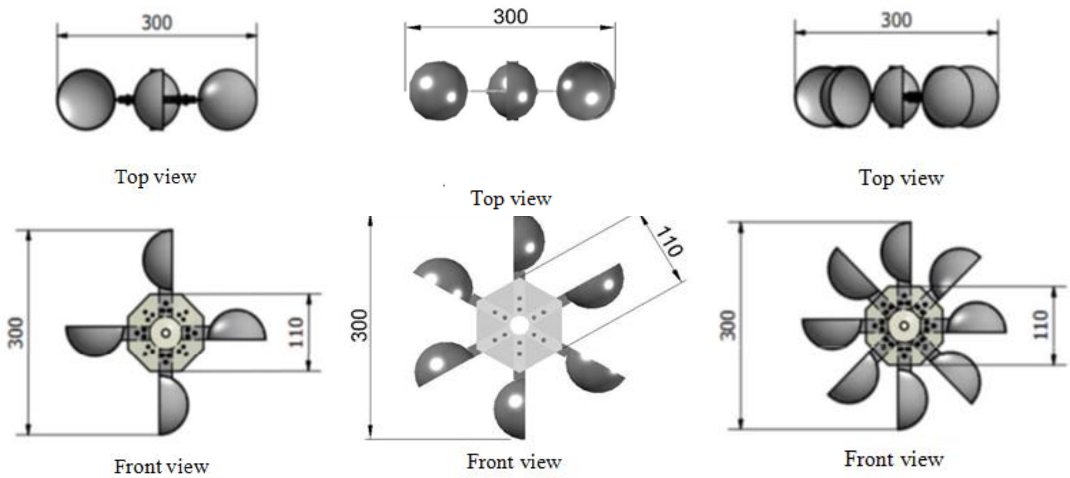


**Figure 3** Schematic of water wheels with four, six, and eight bowl-shaped blades

**Figure 4** Variations of bowl-shaped blades

## 3. Results and Discussion

The ideal water power differs based on the water debit. Water discharge starts from 0.01089 $m^3/s$ ($Q_1$) and then becomes 0.01156 $m^3/s$ ($Q_2$) and finally 0.01228 $m^3/s$ ($Q_3$). The higher the water discharge, the higher the ideal water power, in accordance with the following formula (Denny, 2004; Pujol and Montoro, 2010; Tevata and Inprasit, 2011; Sule et al., 2013):

$$\begin{aligned} P_{water} &= ½\times\rho\times Q\times v^2 \\ &= ½\times\rho\times A\times v^3 \end{aligned} \quad (1)$$

where $P_{water}$ is the water power (Watt), $Q$ is the water volume flow rate ($m^3/s$), $A$ is the cross-sectional area of the blade hit by water ($m^2$), and $v$ is the velocity (m/s).

When weight is added to the turbine, friction will be created between the weight and the rope connected to the weight, creating torque according to the following formula:

$$\begin{aligned} T &= F\times r_k \\ &= m\times g\times r_k \end{aligned} \quad (2)$$

where $T$ is the torque (N.m), $m$ is the mass of the weight (kg), $g$ is the gravitational force (9.81 m/s$^2$), $r_k$ is the radius of the weight wheel.

The efficiency/turbine performance and shaft power are calculated as follows:

$$P = T \times \omega \quad (3)$$

$$\omega = 2\pi n/60 \quad (4)$$

where $P$ is the power (W), and $\omega$ is the angular velocity (rad/s).
The water wheel installation efficiency is calculated as follows:

$$\eta_{ins} = P/P_{water} * 100\% \quad (5)$$

where $\eta_{ins}$ is the Efficiency of water wheel (%).

The relationship between torque and loading tends to be directly proportional, meaning that the greater the loading, the greater the torque. Any loading placed on the water wheel will reduce the rotation of the shaft of the water wheel. This happens because the brake on the shaft, which results in shaft rotation, is gradually reduced until there is no rotation. The water wheel produces power because it can offset the given torque. When the load is removed, the water wheel will not produce power (turbines spin fast because there is no braking force on the shaft). From the graph that forms the parabolic curve, there is a maximum value for the water wheel power. Figures 5, 6, and 7 compare the performance of the water wheel ($\eta$) with rotation (n) with a different number of blades and debit values.

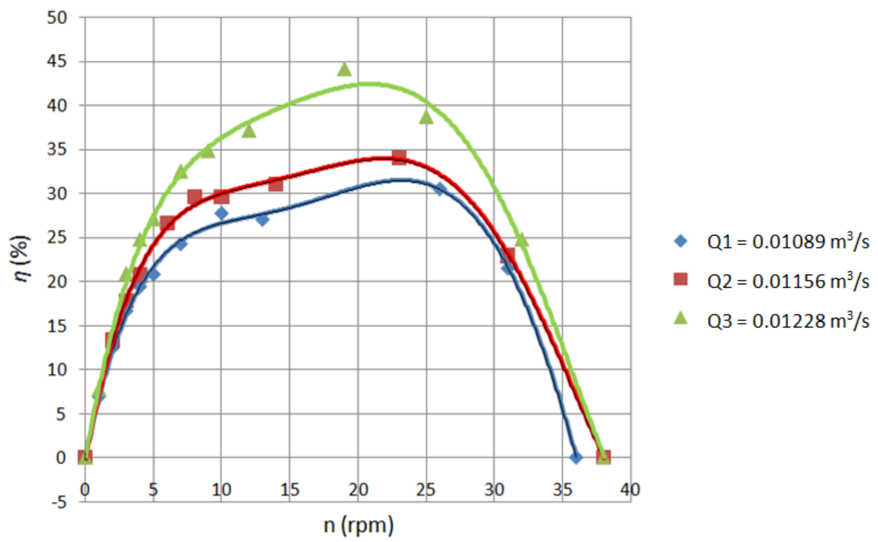


**Figure 5** Graph of power and rotation for a four-blade water wheel with various discharges

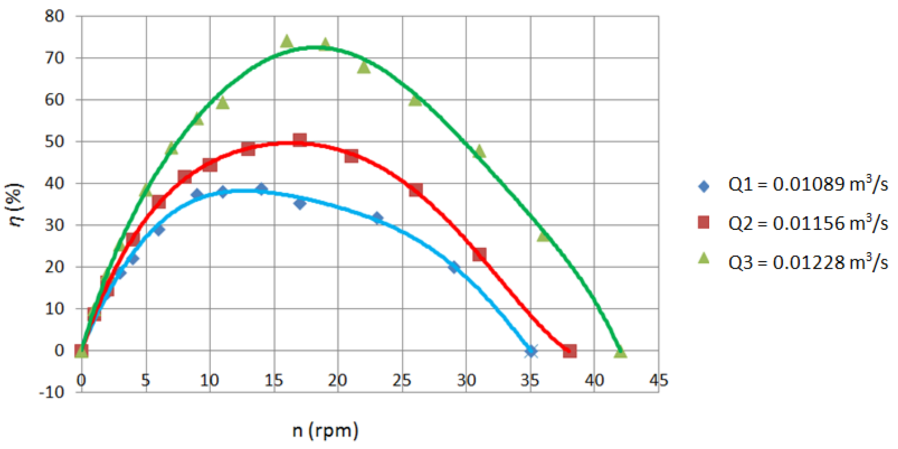


**Figure 6** Graph of power and rotation for a six-blade water wheel with various discharges

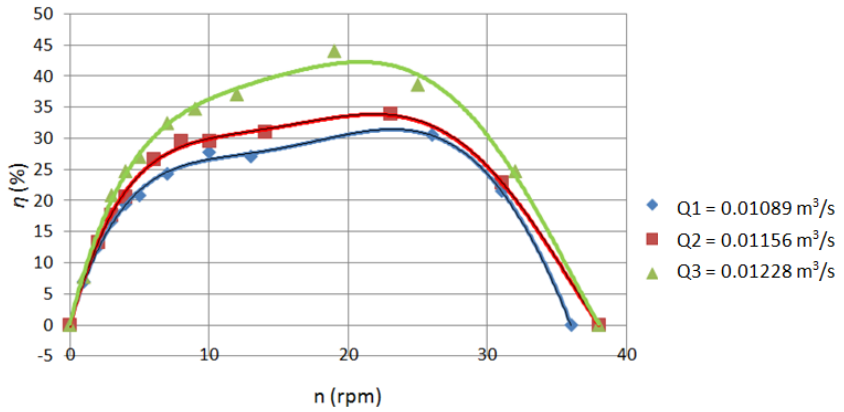


**Figure 7** Graph of power to rotation for an eight-blade water wheel with various discharges

The data testing and processing for a water turbine with a bowl-shaped blade model provided the performance results. The relation between torque and weight tends to be directly proportional; the more weight, the greater the torque. Adding loads to the water turbine will reduce axis rotation. It occurs due to braking on the shaft, which gradually reduces rotation until rotation stops. Turbines generate power because turbines can compensate for torque. When the load has not been given, torque equals zero, and the water wheel will not produce power. Conversely, at the maximum load, where the turbine will stop spinning, energy generation will be lost. Table 1 shows the rotation and torque produced from each load (interval 0.05 kg) on the six-blade water wheel for debit $Q_3$.

**Table 1** Rotation and torque for a six-blade water turbine with discharges $Q_3$

| No. | Q ($m^3/s$) | Load (kg) | N (rpm) | T (Nm) |
|---|---|---|---|---|
| 1 | 0.01228 | 0 | 58 | 0 |
| 2 | | 0.05 | 44 | 0.0126 |
| 3 | | 0.10 | 33 | 0.0253 |
| 4 | | 0.15 | 20 | 0.0379 |
| 5 | | 0.20 | 16 | 0.0505 |
| 6 | | 0.25 | 12 | 0.6320 |
| 7 | | 0.30 | 5 | 0.0758 |
| 8 | | 0.35 | 3 | 0.0884 |
| 9 | | 0.40 | 1 | 0.1010 |
| 10 | | 0.45 | 0 | 0.1137 |

Table 2 shows that the four-blade turbine generates maximum power for every increase in discharge. This can be seen from the parabolic graph, which shows the highest and lowest points. The power generated by the six-blade turbine is inversely proportional to the increase of discharge. For the eight-blade turbine, the highest power is inversely related to the discharge.

The results show that the maximum efficiency ($\eta$) is directly proportional to the maximum turbine power ($P_{wheel}$). Table 3 shows that the highest efficiency (74.22%) is achieved by the six-blade turbine. This turbine is more efficient since the impact of the water is more precise than for the four- and eight-blade turbines. Moreover, the large circular wheel using 6 of bowl-shaped blades attached around its periphery that slowly turns as the flow of water pours over or underneath it producing lots of mechanical torque to drive auxiliary machinery than using four and eight bowl-shaped blades.

**Table 2** Maximum power generated by turbines with different numbers of blades and different water discharges

| No. | Number of water wheel blades | Q ($m^3/s$) | Load (kg) | n (rpm) | Output power (Watt) |
|---|---|---|---|---|---|
| 1 | | 0.01089 | 0.25 | 14 | 0.09254 |
| 2 | 4 | 0.01156 | 0.40 | 18 | 0.19037 |
| 3 | | 0.01228 | 0.25 | 24 | 0.15864 |
| 4 | | 0.01089 | 0.50 | 19 | 0.25118 |
| 5 | 6 | 0.01156 | 0.40 | 19 | 0.20094 |
| 6 | | 0.01228 | 0.20 | 31 | 0.16393 |
| 7 | | 0.01089 | 0.10 | 39 | 0.10311 |
| 8 | 8 | 0.01156 | 0.10 | 38 | 0.10047 |
| 9 | | 0.01228 | 0.10 | 33 | 0.08725 |

**Table 3** Efficiency for various blade numbers

| No | Number of blades | Volume ($m^3/s$) | Loads (kg) | Rotating wheel (rpm) | Efficiency maximum (%) |
|---|---|---|---|---|---|
| 1 | 4 | 0.01156 | 0.6 | 11 | 40.77 |
| 2 | 6 | 0.01228 | 0.8 | 11 | 74.22 |
| 3 | 8 | 0.01089 | 0.25 | 13 | 21.87 |

Figure 8 presents the relation between maximum efficiency of the water turbines ($\eta$) and rotating wheel n for all types of turbines (4, 6, and 8 blades). Figure 8 shows the turbine efficiency with the different number of blades associated with turbine rotation. From the graph, it can be seen that the efficiency increases with the turbine rotation, until it reaches a maximum at 20 rpm, then decreases further.

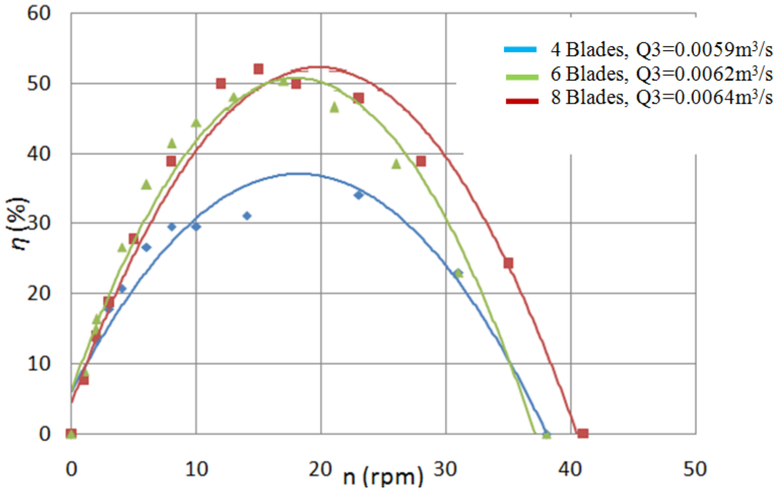


**Figure 8** Efficiency performance of rotating water wheels with different numbers of blades

Figure 9 shows the relation between maximum water turbine efficiency ($\eta$) and maximum water turbine power ($P_{wheel}$) with a rotating wheel (n) on the six-blade turbine with $Q_3$ = 0.0062 $m^3/s$ (the turbine with the highest efficiency).

The results of all experiments show that the six-blade turbine is better than the four and eight blade models. It is the case for several reasons, including the fact that the eight-blade turbine does not have good efficiency because each blade does not optimally harness the potential water power. When the blades enter the water or are faced with rushing water, each blade blocks the water flow for the following blades. Moreover, when there are six blades, three blades are under pressure due to the flow of water (i.e., water velocity), so the performance is better under constant flow rate conditions.

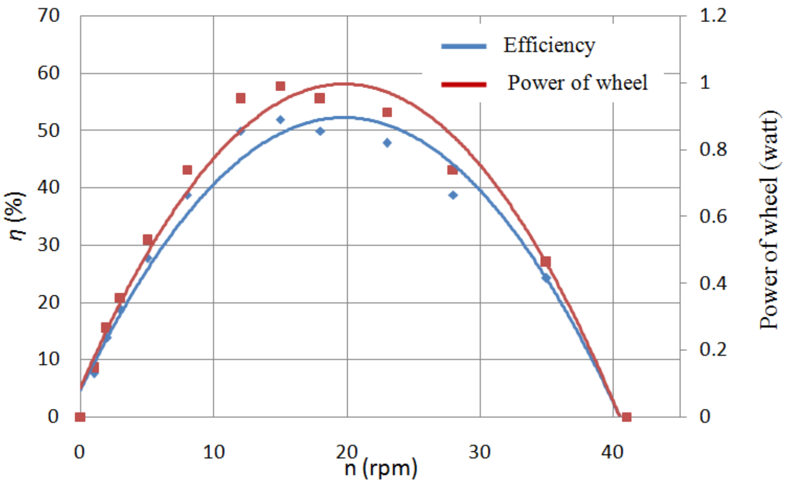


**Figure 9** Efficiency performance and power of the six-blade water wheel when rotating

The four-blade turbine has the potential to increase power, but each blade faces the maximum opposing force due to its bowl-shaped profile. Water can be optimally harnessed when the shape and number of blades create the least opposing force. When a blade first hits the water, the maximum potential water power is achieved, and the following blade can receive the potential water power not harnessed by the first blade, and so on.

## 4. Conclusions

The research results demonstrate that of the turbines with various numbers of blades, the six-blade model has the highest efficiency ($\eta$): 74.22% for discharge of 0.01228 $m^3/s$. The maximum efficiency, $\eta$, is directly proportional to the maximum turbine power (power of wheel) and that maximum power occurs when maximum efficiency is reached. The deviation of the test results from the ideal line on the graph is due to the opposing pressure of the current flow on the bowl-shaped blades (i.e., flow turbulence).

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