

Design and analysis of a portable spiral vortex hydro turbine for a Pico Hydro Power Plant

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Abstract. Pico Hydro Power Plant (PHPP) is a hydroelectric power plant with a scale below 5 kW. This technology is suitable to be applied to areas that have many rivers with sloping slopes. The PHPP applied in this research utilized the river flow and then flowing the water through a water channel with a slope angle around 10 degrees. Due to this sloping angle, it is necessary to modify the turbine intake to produce a more rapid water flow so that the turbine can rotate faster. The modification is made by designing and making a spiral vortex hydro turbine, where the intake is designed to resemble a snail house or a whistle to produce a spiral vortex to drive a turbine. The results show that the spiral vortex hydro turbine can produce faster turbine rotation, compared with a conventional water intake. The speed of the portable spiral vortex hydro turbine in this research can reach 90 rpm. Then, the turbine is coupled with a generator to produce electricity, through a pulley system. The faster the turbine rotation, the higher the generator output voltage. The highest output voltage of the generator is 27.5 Vdc at the speed of 293 rpm. In addition, the device is easy to move and maintain due to its portable design with a weight of 22 kg.

1. Introduction

The potential energy from water can be utilized as electrical energy through hydroelectric power plants. In Indonesia, the existence of rivers and freshwater lakes has an advantage as the initial capital for the development of this type of energy. In hydroelectric power plant systems, the utilization of water energy is based on the use of gravitational potential energy. This energy is used to drive a hydro turbine. Then, the turbine is connected to a generator to generate electricity.

The Pico Hydro Power Plant (PHPP) is a power plant with a scale below 5 kW [1]. In rural areas in Indonesia, there are adequate river flows for electricity generation at such a scale. It is hoped that by exploiting the available potential hydro energy, the need of electricity for the people in rural areas can be met.

This research aims to design and to make a portable spiral vortex hydro turbine for a pico-hydro power plant. The design of this equipment utilizes a modified flow of water into a spiral vortex to drive a hydro turbine. Furthermore, the hydro turbine will be coupled with a generator to produce electricity. The modification of water flow aims to produce a swifter water flow in order to produce a faster turbine rotation. In addition, the design of this tool is portable so that it makes the maintenance process of the turbine and its house becomes easier.



2. Pico hydro power plant

2.1. Definition of pico hydro power plant

The Pico Hydro Power Plant, in principle, is the same as other hydropower plants which is utilizing the potential hydro energy from river, waterfall, or even from irrigation channels. This water flow is used to drive a hydro turbine which is coupled to a generator to produce electricity.

Based on the output produced, Hydroelectric Power Plants can be distinguished into six forms, include [2]:

- Large-hydro: more than 100 MW
- Medium-hydro: between 15-100 MW
- Small-hydro: between 1 - 15 MW
- Mini-hydro: Power above 100 kW, but below 1 MW
- Micro-hydro: between 5kW - 100 kW
- Pico-hydro: output power is 100 W - 5kW

Based on the differences above, the Pico-Hydro hydroelectric power plant is a power plant that produces an electric power output of no more than 5 kW. This plant has several advantages, such as [3-5]:

- The manufacturing cost is relatively cheap. This is because the materials used do not require specific materials that are difficult to obtain. For example, the pico-hydro turbines can be made from the remaining scrap metal sold in the market / used metal.
- The manufacturing materials are relatively inexpensive because they are easy to find in the market, include generators, batteries, and turbines.
- This type of generation is environmentally friendly because it does not use fossil fuels so that the maintenance is not too complicated. This technology has a very little impact on nature.
- Its construction can be integrated with the construction of irrigation networks. The construction of the Pico Hydro power plant can also be used as irrigation by adding a water channel for irrigation.
- Its size is quite small, suitable for rural areas that have not been reached by the electricity grid.

2.2. The working principle of pico hydro power plants

The Pico Hydro Power Plant is a water way type of power plant that uses a water intake upstream of the river then flows the water downstream through a channel of water with a rather small gradient. This power plant also uses river flow directly by using reservoir ponds where the river water is flowed into ponds through open or closed channels, filtered in advance and accommodated in a pond that serves to precipitate sand and mud as well as reservoirs. The water from the pond is channeled through pipes which can rapidly rotate the turbine to generate electricity.

The power generated can be calculated based on the following formula [6]:

$$P = \rho \cdot Q \cdot h \cdot g \quad (1)$$

Where,

P = theoretical output power (watts)

ρ = fluid density (kg / m³)

Q = water discharge (m³ / s)

h = effective height (m)

g = gravitational force (m / s²)

From equation (1), the power produced is a product of the height of the fall and the discharge of water, therefore the capacity of hydropower generation depends on the effort to obtain a high water fall and a large discharge of water.

The amount of electric power before entering the turbine can be mathematically written as follows:

$$P_{in\ turbine} = \rho \times Q \times h \times g \quad (2)$$

While the turbine output power is as follows:

$$P_{out\ turbine} = \rho \times Q \times h \times g \times \eta_{turbine} \quad (3)$$

So, mathematically, the real power generated from the generator is:

$$P_{real} = \rho \times Q \times h \times g \times \eta_{turbine} \times \eta_{generator} \times \eta_{transmission} \quad (4)$$

Where:

$P_{in\ turbine}$ = input power to the turbine (kW).

$P_{out\ turbine}$ = output power of the turbine (kW).

P_{real} = actual power produced (kW).

ρ = fluid density (kg / m³).

Q = water discharge (m³ / s).

H = effective height (m)

g = gravitational force (m / s²)

$\eta_{turbine}$ = turbine efficiency

$\eta_{generator}$ = generator efficiency

$\eta_{transmission}$ = passing water efficiency

2.3. Cross-flow turbine

Hydro turbine has a role to convert hydro energy (potential energy, pressure and kinetic energy) into mechanical energy in the form of shaft rotation. The rotation of the turbine shaft will be changed by the generator into electric power. The turbine used in this thesis is a cross-flow turbine.

The cross-flow turbine is a hydro turbine of the type of action turbine (impulse turbine). The working principle of this turbine was first discovered by an Australian engineer named A.G.M. Michell in 1903. Then this turbine was developed and patented in West Germany by Prof. Donuts Banki so that this turbine is named Turbine Banki sometimes also called the Michell-Ossberger Turbine [7].

The use of Cross-flow Turbine types is more advantageous than the use of waterwheels or other types of micro hydro turbines. Using this turbine for the same power can save manufacturing costs for up to 50% of the use of waterwheels with the same material. This saving can be achieved because the size of the Cross-flow Turbine is smaller and more compact than a water wheel. The diameter of the water wheel is usually 2 meters up, but the diameter of the Cross-flow Turbine can be made only 20 cm so that the materials needed are far less, which is why it can be cheaper. Likewise the average efficiency of this turbine is higher than the efficiency of the waterwheel. The results of laboratory tests carried out by the West Germany Ossberger turbine plant concluded that the efficiency of waterwheels of the most superior type even reached only 70%, while the efficiency of the Cross-flow turbine reached 82% [7]. The high efficiency of the Cross-flow Turbine is due to the utilization of water energy in the turbine, which is done twice, the first is the collision energy of the water on the blades when the water starts to enter, and the second is the thrust of the water on the blades when the water will leave the runner [8]. This multi-level water works turns out to be advantageous in terms of its high effectiveness and simplicity in runner water removal systems.

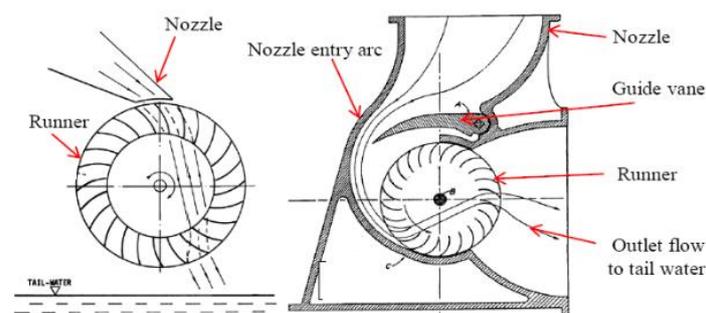


Figure 1. Cross-flow turbine parts [8].

3. Design of a hydro turbine with a pulley system

3.1. Turbine dimensions

Designing of a turbine has several aspects that must be considered, include runner, bearing, and pulley [9,10]. Runner is one of the main components of the turbine which works to produce rotation due to the impact or the push of strong water on the blade of the runner.

3.1.1. Turbine inlet water speed (C_1) [11]

$$C_1 = K_{C1}(2gH)^{1/2} \quad (5)$$

Where:

- C_1 : turbine inlet water speed (m/s)
 K_{C1} : coefficient of water velocity at the nozzle (0.98)
 g : Earth's gravitational acceleration (m/s²)
 H : height of falling water (m)

3.1.2. Turbine rotor inlet speed or tangential speed (U_1) [10]

$$U_1 = K_{U1} \cdot C_1 \cdot \cos \alpha$$

Where,

- U_1 : circumferential speed (m/s)
 K_{U1} : circumferential speed coefficient
 α : the angle of entry formed by absolute speed and tangential speed

3.1.3. Outside runner diameter (D_1) [11]

$$D_1 = \frac{U_1 \cdot 60}{\pi \cdot n} \quad (6)$$

$$D_2 = D_1 \times 0,66 \quad (7)$$

Where,

- D_1 : outside runner diameter (m)
 D_2 : inside runner diameter (m)
 n : turbine rotation (rpm)

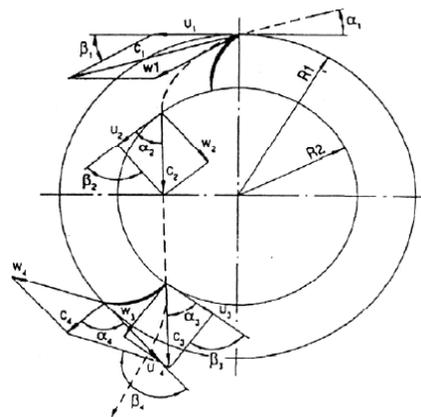


Figure 2. Cross-flow turbine parameters [12].

- W_1 : relative speed of water entering the turbine house
 C_1 : speed of water entering the turbine
 β_1 : the angle of velocity of water entering the outside of the runner
 U_1 : line speed (circumference)
 α_1 : the angle formed by absolute velocity and tangential
 W_2 : relative speed of water coming out at level I blade
 C_2 : speed of water coming out of the turbine

B_2 : the angle at which the water velocity exits on the outside of the runner
 U_2 : speed of the line (circumference) when the water comes out of the blade
 The parameters when water enters from the level II blade are C_3 , W_3 , α_3 , and U_3 . The parameters when the water comes out of the level II blade are, C_4 , W_4 , α_4 , and U_4 .

3.1.4. *Blade length design.* Blade length can be determined based on the formula [10]:

$$b = 0,006 \frac{nQ}{kH} \quad (8)$$

Where,

N : turbine rotation (rpm)
 Q : flow capacity (m³/s)
 K : coefficient of water burst thickness against runner diameter
 H : height of falling water (m)

3.1.5. *Arc length (LB).* In determining the length of the bow can be done in several steps, include:
 Calculating the value of C [10]:

$$C = \sqrt{R_1^2 + R_2^2 - 2R_1R_2 \cos(\beta_1\beta_2)} \quad (9)$$

Calculating ε :

$$\varepsilon = \sin^{-1} \left[\frac{R_2 \sin(\beta_1 + \beta_2)}{c} \right] \quad (10)$$

Calculating ζ :

$$\zeta = 180^\circ - (\beta_1 + \beta_2 + \varepsilon) \quad (11)$$

Calculating ϕ :

$$\phi = (\beta_1 + \beta_2) - (180^\circ - 2\zeta) \quad (12)$$

Calculating d :

$$d = \frac{R_1 \sin \theta}{2 \sin(180^\circ - \zeta)} \quad (13)$$

Calculating angle of complete blade (δ):

$$\delta = 180^\circ - 2(\beta_1 + \varepsilon) \quad (14)$$

Calculating the radius of curvature of the blade (rb):

$$rb = \frac{d}{\cos(\beta_1 + \varepsilon)} \quad (15)$$

Calculate the radius of curvature of a pitch (blade) for a blade (rp):

$$rp = \sqrt{rb^2 + R_1 - 2rbR_1 \cos \beta_1} \quad (16)$$

Calculate arc length (lb):

$$lb = 2\pi \cdot rb \left(\frac{\delta}{360^\circ} \right) \quad (17)$$

3.1.6. *Number of blades.* The number of blades can be obtained by the equation [13]:

$$Z = \frac{\pi D_1}{t} \quad (18)$$

Where, t is the distance between the outer blades [11]:

$$t = \frac{S_2}{\sin \beta_1} \quad (19)$$

$$S_2 = k \cdot D_1 \quad (20)$$

Where, k is a statute (0.075 - 0.10)

3.1.7. *The plate width.* By determining the plate width (t), the runner length is as follows [13]:

$$B = b + 2t \quad (21)$$

3.1.8. *The axis.* The pivot design is based on a combination of calculation of moment punter and power plan. The punter moment can be calculated by the formula [13]:

$$T = 9,74 \times 10^5 \frac{Pd}{n} \quad (22)$$

Where, Pd is the planned power (kW):

$$P_d = f_c \times P_T \quad (23)$$

Where,

F_C: correction factor

P_T: turbine output power

Shaft diameter can be calculated by the equation:

$$d_s = \sqrt[3]{\frac{5,1}{\tau a} \times Kt \times Cb \times T} \quad (24)$$

Where,

τa: allowable voltage (kg / mm²)

Kt: correction factor for twisting

Cb: flexural factor

T: moment of twisting

3.2. Bearing

In mechanical science, bearing is an element that functions to limit the relative motion between two or more engine components to always move in the desired direction. Bearings keep the shaft rotating about the axis of the shaft, or also keep a linear moving component to always be in its path.

Bearing is one part of the engine element that plays an important role because the function of the bearing is to support a shaft, so that the shaft can rotate without experiencing excessive friction. It must be strong enough to allow the shaft and other engine elements to work properly. Also, the bearing can be used to reduce the friction of rotating equipment on the shaft. Bearing is usually in a form of round shape.

One of the bearings that are often used and commonly found is the pillow block bearing type. Pillow block bearings are the base used to provide support for the rotating shaft with the help of compatible bearings & various accessories. Housing material for pillowcases is usually made of cast iron or cast steel.

3.3. Pulley system

Pulley system is a mechanism that consists of a wheel on a shaft or a rod that has a groove between two edges around it. A rope, cable, or belt is usually used in the pulley grooves to move power. Pulleys are used to change the direction of force used, continue rotational motion, or move heavy loads.

A pulley system with a belt consists of two or more pulleys that are connected using a belt. This system makes it possible to move power, torque, and speed, even if pulleys of different diameters can ease the work of moving heavy loads.

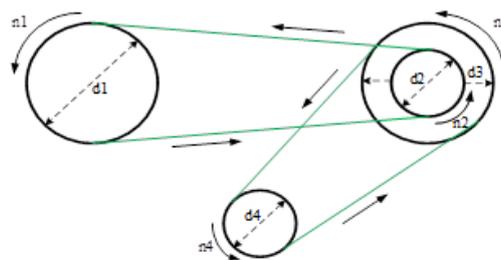


Figure 3. Pulley system [13].

V belt is the most commonly used transmission system because of its easy installation, economical price, besides it can produce large power at low voltage. The V belt is made of rubber and has a trapezoid shaped section that is wrapped around a V-shaped pulley groove. The V belt is divided into several types include the followings:

Standard types are marked with the letters A, B, C, D and E; Narrow-type that is marked with values 3V, 5V, and 8V; Light load types are marked with values 3L, 4L, and 5L. The speed ratio on the pulley is inversely proportional to its diameter, mathematically it can be written as follows [13]:

$$\frac{N_2}{N_1} = \frac{d_1}{d_2} \quad (25)$$

Where,

- N2 : pulley rotation driven (rpm)
- N1 : driving pulley rotation (rpm)
- d2 : diameter of pulleys driven (mm)
- d1 : diameter of pulleys driven (mm)

4. Results

4.1. Turbine

The cross-flow turbine in this research is manufactured using a 3x4 cm hollow iron box as a buffer. A solid round iron of 1 dim (= 1 inch) is used as a turbine shaft. The solid shaft was chosen because it is suitable for use and is not easily bent. A used oil barrel is utilized as a turbine house. This material is chosen because it is easy to find, easy to modify and the price is relatively cheap.

This turbine is designed to be simple and easy to disassemble, not easily clogged and easy to maintain. A bearing is placed to support the turbine shaft. Aside from being a turbine buffer, this bearing also facilitates turbine rotation. The type of bearing used is the pillow block. This bearing type is flexible in the middle and can follow changes in the motion of the turbine shaft.

4.2. Turbine blades

The blades used for this research have dimensions of 18 cm in width per blade, the iron tube size is 12 cm. The more cross-sectional area of the crossflow blade, the larger the torque and the crossflow blade is also light so the rotation is faster.

4.3. Pulley system

The transmission system used in the pico-hydro power generation system is the pulley system. The selection of this energy transmission system is based on a study of a previous generating system using a gear box, where the desired generator rotation is less than optimal. The pulley design in figure 4 is used.

By referring to the figure 4, the expected generator speed is 650 rpm, following the initial measurement results table, by modifying the percentage of incoming air intake.

Considering that n_2 dan n_3 connected to the same shaft,

$$n_2 = n_3$$

$$n_4 = \frac{n_1(d_1 \cdot d_3)}{(d_2 \cdot d_4)} = \frac{80(0,25 \cdot 0,25)}{(0,075 \cdot 0,075)} = 888,8 \text{ rpm}$$

For calculations using 1 level pulley with pulley size 25 cm and 0.75 cm

$$\frac{d_1}{d_2} = \frac{n_1}{n_2} = \frac{0,075}{0,25} = \frac{80}{n_2}$$

$$N2 = \frac{80 \times 0,25}{0,075} = 266,6 \text{ rpm}$$

From the results of the above calculation, the diameter of the pulleys used are 25 cm and 7.5 cm, respectively.

4.4. Turbine house and support

There are 2 designs tested in this research. The explanation can be seen in the description below.

4.4.1. Design no. 1

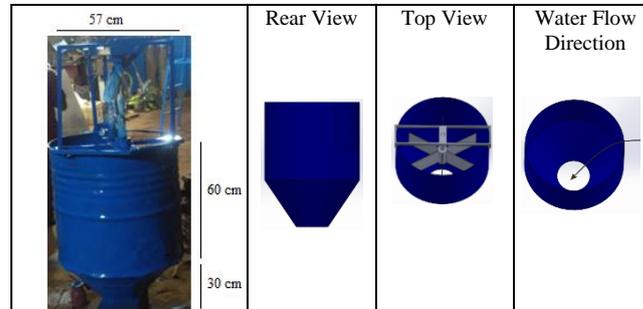


Figure 4. Design 1.

The turbine house design no. 1 is manufactured using used oil barrel with the dimensions of 57 cm in diameter, about 90 cm in height. At 30 cm above the bottom of the tube, a trapezoidal cone is formed with a 30-degree inclination. There is a drain in the middle with a diameter of 20 cm. The overall weight of the turbine and turbine house is around 23 kg.

The test results show that when water is thawed into the turbine house, the turbine does not rotate, or the turbine speed = 0 rpm. This is because water directly falls into the drain hole at the bottom of the turbine.

4.4.2. Design no. 2

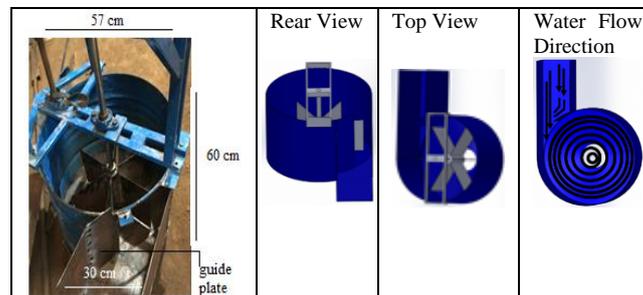


Figure 5. Design 2.

The design of turbine house number 2 is a modification of design number 1 by adding a water flow steering guide mounted on an iron channel. There is a drain in the middle with a diameter of 20 cm. The overall weight of the turbine and turbine house is around 22 kg.

The test results show that when water is thawed into the turbine house, the flowing water is directed to crash into the circular turbine house wall. So that a spiral whirlpool is formed immediately and the turbine rotates with a higher speed, which is around 90 rpm.

4.5. Turbine siting

The Turbine and its housing are placed exactly at the outputs of the drains that have been made, as shown in Figure 6.



Figure 6. Spiral vortex occurrence.

In figure 6a, it can be seen that the turbine house design, using design no. 2, where the design has a water channel and a drain plate, it can produce a spiral vortex of water flow.

This spiral water rotation occurs when the water is entering through the water channel, the flow is directed by the guide plate so that it will directly hit the walls of a circular turbine house. As a result, the flow of water will form a spiral vortex.

The installation of the turbine in the turbine house and its placement in the field can be seen in Figure 6b.

Furthermore, testing is carried out to determine the effect of water discharge on the turbine rotation. This is done by regulating the intake of air that enters the turbine house, with variations in the opening of the intake of water by 50%, 75% and 100%, as shown in table 1.

Table 1. Intake open and turbine speed.

Intake open	Turbine speed (rpm)
50%	86,9
75%	89,4
100%	90

From table 1 it can be seen that the greater the air intake opening, the faster the turbine rotation.

4.6. Power torque

To calculate the measured power torque value at a luggage meter, it needs to be multiplied by the radius of the pulley arm. So, the turbine torque value needs to be multiplied by the pulley radius arm of 11 cm = 0.11 m and for the generator torque multiplied by the pulley radius arm by 3 cm or 0.03m.

The water channel from the control tank is in the form of a trapezoid, so that the channel area is

$$\begin{aligned}
 L_{trapezoidal} &= \frac{1}{2}(AB + CD) \times AD \\
 &= \frac{1}{2} \times 0,9153 = 0,45765m^2 \\
 &= \frac{1}{2}(1,52 + 1,87) \times 0,27
 \end{aligned}$$

And the volume of the trapezoidal is:

$$\begin{aligned}
 V &= L_{trapezoidal} \times \text{water level} \\
 &= 0,45765 \times 0,18 = 0,082377m^3
 \end{aligned}$$

Therefore, the water debit is

$$Q = \frac{V}{t} = \frac{0,082377}{4,05} = 0,02034m^3/s$$



Figure 7. The trapezoidal shape of the water intake.

Annotation:

- Outside intake length = 1,87 m
- Inside intake length = 1,52 m
- Intake width = 0,27 m
- Intake height = 0,25 m
- Water level = 0,18 m

4.7. The generator

The generator used in this research is a DC generator with a Permanent Magnet in it. The generator has specification of: 48 V, 650 RPM, and a power of 550 watts.

The following results are obtained from the generator speed data after connecting pulleys, voltage and current obtained.

Table 2. Turbine speed vs generator speed.

Intake open	Turbine speed (rpm)		Generator speed (rpm)	
	Standalone	Connected to generator	Battery is not connected	Battery is connected
50%	86,9	73,8	264,5	121,5
75%	89,4	78,1	276,1	129,3
100%	90	83	293,3	146,5

Table 2 shows that the wider the intake opened, the faster the speed of the turbine, which also effects on the speed of the generator to become faster.

Table 3. Generator speed vs generator output.

Generator speed (rpm)		Generator output (DC Voltage-V)		Generator output (DC Current-A)
Battery is not connected	Battery is connected	Battery is not connected	Battery is connected	
264,5	121,5	25	11	0,25
276,1	129,3	25,5	11	0,33
293,3	146,5	27,5	11	0,41

According to the data from table 3, it can be seen that the increase of generator speed effects on the increase of the generator output.

5. Conclusions

The cross-flow turbine and the turbine house manufactured in this research are portable, easy to move because the overall weight is only 22 kg. The resulting design is also simple so as to facilitate device maintenance.

In addition, the turbine house can produce a spiral vortex water flow that can increase the rotational speed of the turbine, from 50 rpm to 90 rpm. The turbine rotational speed affects the generator rotation

which ultimately affects the generator output voltage. The output voltage of the generator can reach 27.5 Vdc at the speed of 293 rpm.

6. Future work

It is necessary to increase the size of the barrel so that when the water debit increases, it will not overflow. Moreover, the increase of water debit will increase the speed, the torque and the output of the generator as well.

Acknowledgements

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