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Development of Portable Pico Hydro Power Plant for Low Head Applications Using Cross-Flow Turbine

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Abstract

Portable hydroelectric power plants today are typically designed as hobbyist toys and lack optimization for specific performance needs. The purpose of this research is to develop a portable Pico Hydro Power Plant (PHPP) using a cross-flow turbine type utilizing a very low head of less than 3 m, with a target output electric power of 20 W which is sufficient for lighting or charging laptops and smartphones for activities in remote areas. Previous research produced a prototype of a portable PHPP with a cross-flow type. However, many obstacles were still encountered during manufacturing, installation, and testing because the prototype construction was made using a 3D printing process. The development carried out in this research includes changes to the turbine housing, nozzle, outlet, bearing housing placement, and turbine runner. The resulting PHPP has advantages in simplicity in the manufacturing process, installation, and operation. In this research, a fluid flow simulation was also carried out to investigate the distribution of pressure, speed, and flow patterns in the turbine. Based on experiments or tests carried out at a head of 2.3 m, it shows that the electrical output power had met the output target of 20.5 W with a turbine efficiency of 39.6%. Referring to the results of the experiment and flow simulation, show that the prototype still has the potential to improve its efficiency and can still be developed further, especially in the shape of the nozzle and runner.

Keywords:
Portable PHPP; cross-flow; electrical power; turbine efficiency

1 Introduction

Energy is a primary need that continues to increase along with technological advances and increasing human demographics [1][2]. Electrical energy is one of the important energy sources used along with the increase in national electricity consumption in Indonesia which has reached 120,000 GWh [3]. Electrical energy plays an important role in human life [4][5], most of the electrical energy used is generated from power plants that use oil and coal, which are non-renewable and contribute to environmental pollution. [6]. Based on Presidential Regulation of the of Indonesia Number 22 of 2017 concerning the National Energy General Plan, the clause therein states that the priority is the use of a renewable energy mix with a minimum target of 23% in 2025 and a minimum target of 31% in 2050 [7]. One of the popular new renewable energies is hydroelectric power [8] as one of the solutions to accelerate the achievement of the set targets [9].

Hydroelectric power plants generally utilize the potential energy of water upstream or reservoirs such as reservoirs, lakes, and dams that have a higher position or head into kinetic energy of water flow and are then converted into mechanical shaft power and electrical output power [10]. The rotating turbine blades function to convert the kinetic energy of the water flow into mechanical energy [2]. Turbines connected to the shaft are able to transmit rotation to the generator unit to produce electrical energy. Hydroelectric power plants can be grouped based on the power produced [11], one of them is pico hydro commonly known as Pico Hydro Power Plant (PHPP) [12]. PHPP produces less than 5 kW of power [13] and the construction, installation, and operation of this turbine are simpler and more practical. [14].

Nature adventure activities are becoming increasingly popular among the public, especially among young people [15]. This activity offers many benefits, one of which is a green environment which has been proven to reduce fatigue, and mental exhaustion and increase concentration [16]. In nature activities, equipment that requires electrical energy is often needed, such as charging gadgets, power banks, flashlights, lamps, etc. Estimated power requirements during a staycation in glamping with an average capacity of four people, for one day requires around 120 WH of electrical energy. The absence of electrical resources in remote areas makes Portable PHPP a solution to provide electrical energy needs by utilizing the potential of low head water energy [17].

Water turbines convert the kinetic energy of water into rotational energy and then into electrical energy using a generator unit [18]. Water turbines are divided into two types according to the method used by the water turbine to convert water energy into rotational energy impulse turbines and reaction turbines [19]. Impulse water turbines can convert all available water energy, including potential energy, pressure energy, and velocity energy, into kinetic energy to produce momentum in the turbine and rotational energy [20]. Pelton turbine and cross-flow turbine are two types of impulse turbines. A reaction turbine is a type of water turbine that uses all the energy of the water flowing through the guide nozzle to produce a reaction on the rotor blades [20]. Francis turbines and propeller turbines are two types of reaction turbines [21].

The Banki turbine, also known as a cross-flow turbine, is suitable for operations with low water head and small water flow [22]. Cross-flow turbines can be used in PHPP systems that utilize water energy at low waterfall heights (heads) and also low flow rates [23]. Cross-flow Turbine is a type of impulse turbine. The water jet comes from a nozzle that enters the turbine through the path blades and can convert kinetic energy into mechanical energy. The water flow entering the turbine from above energizes the blades, then enters the inside of the turbine and exits at the bottom [24].

Hydroelectric power plants that are currently being developed generally use water sources with heads of more than 3 meters, whereas in Indonesia there are quite a lot of hydro energy sources with heads of less than 3 meters that have the potential to be used as portable pico hydropower plants (PHPP). PHPPs available on the market today are generally in the form of toys for hobbyists and have not been designed with specific performance objectives [25].

A portable PHPP prototype with a cross-flow turbine was created in 2021 and designed to produce 12 W of electrical power with a required discharge of 0.00437 m^3/s or 4.37 l/s and a maximum waterfall height (head) of 4 meters, to meet the need for electrical energy during activities in nature. The research that has been carried out has produced a turbine that can rotate, but performance testing has not been possible because the runner was damaged (broken) when loaded because it uses a 3D printing process [26]. This prototype was further developed by increasing the thickness of the blades and turbine housing. In this study, the efficiency of the turbine is still unknown, because the turbine shaft is directly connected to the generator so the torque value cannot be measured [27]. The PHPP prototype in previous studies also still has several obstacles, such as the material used for the turbine housing is not strong enough because it is made by a 3D printing process so there is leakage in the nozzle and bearing housing. In addition, the turbine shaft is directly connected to the generator so that the turbine efficiency and generator efficiency cannot be investigated [28].

In this study, the design of the portable PLTPH will be further developed by replacing the turbine housing and bearing housing using PVC material and processed by a lathe process (machining) so that it is more precise and stronger. In the performance testing equipment setup, a transmission between the turbine and generator is also added; equipped with a special mechanism for torque measurement so that the efficiency of the turbine and generator can be investigated. In addition, this study also conducted a fluid simulation to investigate the flow patterns that occur in the turbine so that opportunities for improving turbine performance can be identified.

2 Research Method

To achieve the research objective of producing a more reliable portable PHPP prototype that can produce electrical power according to the target power achievement of 20 watts, this research was carried out in 3 stages of activity: (1) Design development (2) Prototype performance testing (3) Flow pattern simulation.

2.1 Design Development

The development of this Portable PHPP prototype refers to the results of previous prototype studies. The resulting portable PHPP design model can be seen in Fig. 1 with the specifications shown in Table 1.

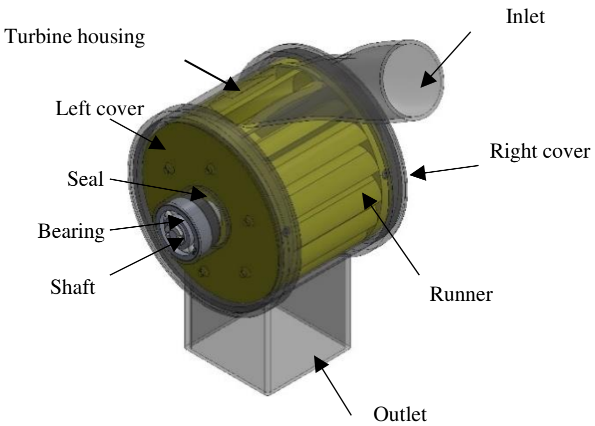


Fig. 1. Portable PHPP design model

Table 1. Portable cross-flow PHPP Specifications

Parameters	Value/Specification	Unit
Runner diameter	100	mm
Runner length	80	mm
Number of blades	18	blades
Design speed	500	rpm
Design head	2 - 4	m
Runner material	PLA (3D Printed)	-
Casing material	PVC	-
Dimension	200 x 175 x 150	mm

2.2 PHPP Prototype Performance Testing

The performance testing of the PHPP prototype was carried out to obtain the values of hydraulic power, mechanical power, and electrical power so that turbine efficiency, generator efficiency, and overall efficiency could be investigated. The test installation setup equipment is shown in Fig. 2. Performance testing rig components are: (1) Water tank; (2) Pump to circulate water (head and flow generator); (3) Bypass valve: valve for bypass circulation to the tank; (4) Main valve: regulates the rate of water flow into the turbine; (5) Flow meter: measuring water flow rate; (6) Pressure gauge: measures the pressure or head of water entering the turbine; (7) Turbine: converts fluid energy (head and flow) into mechanical energy in the form of shaft rotation and torque; (8) Torque measuring instrument: mechanism and instrument to measure the torque; (9) Generator: produces electrical output power from the mechanical energy of the turbine;

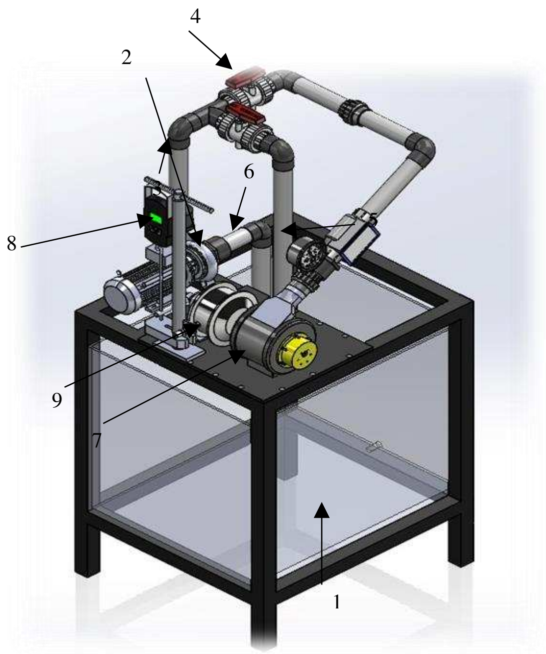


Fig. 2. Installation of performance testing rig

To obtain the hydraulic power value, a pressure gauge is used to measure the head, and a flow meter to measure the flow rate. The mechanical power measurement uses an rpm meter to measure the rotational speed and is equipped with a mechanism so that the torque value can be measured using an arm mechanism and scales (force meter). To determine the output electrical power, lamps are used as load variations, and the voltage and electric current values produced are measured. The test was conducted at a head of 2.3 meters and a flow of 220 l/m according to the maximum head and discharge that can be achieved by the pump installed in the test installation setup. The test variation is in the form of load variations from the lights. The electrical output power and efficiency of the PHPP prototype can be calculated based on the test data using Eq.s 1-8:

Hydraulic Power Calculation:

$$P_h = \rho . g . H . Q \tag{1}$$

Where, ρ is the density of water (kg/m^3), g is the acceleration due to gravity (m/s^2), H is the head (m), and Q is the discharge (m^3/s),

Torque Calculation:

$$T = F \; . \; L \tag{2}$$

F is the measured force (N) and L is the length of the measuring arm which is 10 cm or 0.1 m.

Angular Velocity Calculation:

$$\omega = \frac{2\pi n}{60} \quad (3)$$

ω is the angular velocity (rad/s), n is the rotational speed (rpm)

Mechanical Power Calculation:

$$P_m = \omega \times T \quad (4)$$

P_m is the mechanical power (watt), T is the torque (N.m).

Electrical Output Power Calculation:

$$P_e = V \times I \quad (5)$$

P_e is electrical output power (watt), V is voltage (volt), I is electric current (ampere).

Turbine Efficiency Calculation:

$$\eta_t = \frac{P_m}{P_h} \quad (6)$$

Generator Efficiency Calculation:

$$\eta_{generator} = \frac{P_e}{P_m} \quad (7)$$

Overall Efficiency Calculation:

$$\eta_{overall} = \frac{P_e}{P_h} \quad (8)$$

2.3 Flow Simulation Set-up

Flow simulation is conducted to investigate the flow patterns inside the turbine so that opportunities for improving turbine performance can be identified using SolidWorks Flow Simulation software. The meshing and boundaries for flow simulation can be seen in Fig. 3. The runner is set as a rotating region with a rotation speed of 500 rpm based on the turbine design.

The turbine model with 18 blades has a meshing of 4997 fluid cells. The inlet is set as static pressure at 1.23 bar(a) or equivalent with 2.3 m of water head and the outlet is set as environmental pressure at 1.023 bar(a). The observed result parameters are pressure distribution, velocity distribution, volume fraction of water, flow pattern, and torque generated. The flow simulations are observed in transient conditions and the iterations are performed until the resulting torque curves show a similar pattern.

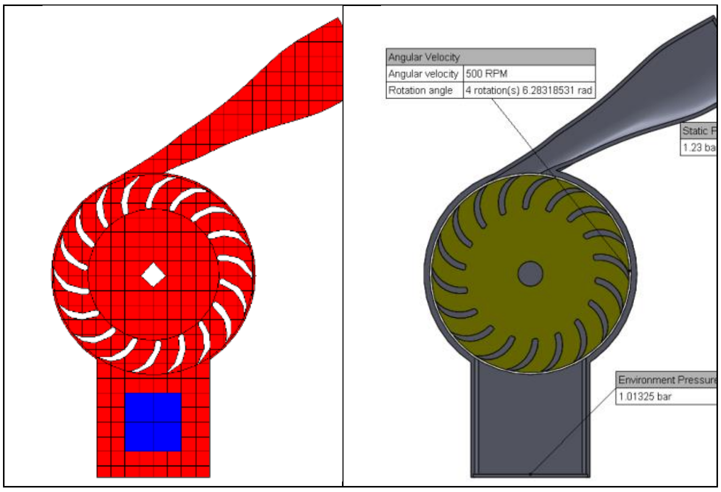


Fig. 3. Meshing dan boundaries

3 Results and Discussion

3.1 Prototype Performance Test Results

To obtain the performance of the portable PLTPH prototype, testing was carried out on the developed prototype with a test setup as shown in Fig. 4. This testing stage was carried out by activating the pump unit which can regulate the pressure (head) and flow using the two valves which are adjusted to the required water head and flow [29].

Next, the testing was carried out with variations in lighting loads, and then changes in the values of rotation speed (rpm), torque (N.mm), voltage (volts), and current (amperes) were monitored and recorded.

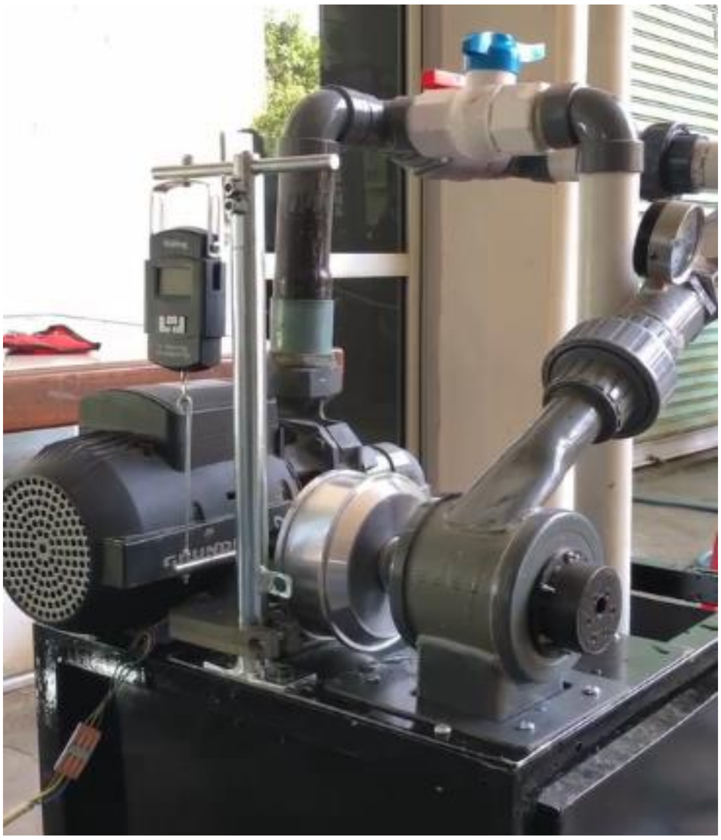


Fig. 4. Experimental installation set-up

The experimental data are shown in Table 1. Running experiment no. 1 is an operating condition without electrical loading so that the output electrical power and overall efficiency of PHPP are 0.

The test result data is then processed using Eq.s (1) to (5). The results of the data processing are displayed in the form of hydraulic input power values, mechanical output (shaft) power, and electrical output power. Based on these three data, turbine efficiency, generator efficiency, and overall efficiency can then be calculated using Eq.s (6) to (8) with the results as shown in Table 2.

Table 1. Experimentally measured data

No	H (m)	Flow (LPM)	n (rpm)	F (kgf)	V (volt)	I (A)
1	2.3	220	787	0.27	43.8	0.00
2	2.3	220	560	0.56	28.6	0.60
3	2.3	220	495	0.65	25.4	0.78
4	2.3	220	458	0.69	23.3	0.88
5	2.3	220	428	0.72	21.4	0.96
6	2.3	220	411	0.72	20.4	0.98

Table 2. Experimental calculation results

No	P_H (W)	P_M (W)	P_E (W)	η_m (%)	η_e (%)	η_o (%)
1	82.7	21.6	0.0	26.1	0.0	0.0
2	82.7	32.2	17.0	38.9	52.8	20.6
3	82.7	**32.8**	19.8	**39.6**	60.3	23.9
4	82.7	32.2	**20.5**	38.9	63.7	**24.8**
5	82.7	31.8	**20.5**	38.4	64.7	**24.8**
6	82.7	30.3	19.9	36.7	65.7	24.1

The gradual loading was carried out to investigate the highest output value and the optimal value that can be produced by the generator and turbine. The highest electrical output power obtained at a water head height of 2.3 m was 20.5 watts at a rotational speed (n) of 428 rpm and 458 rpm with an overall efficiency of 24.8% as shown in Table 2 and Fig. 5.

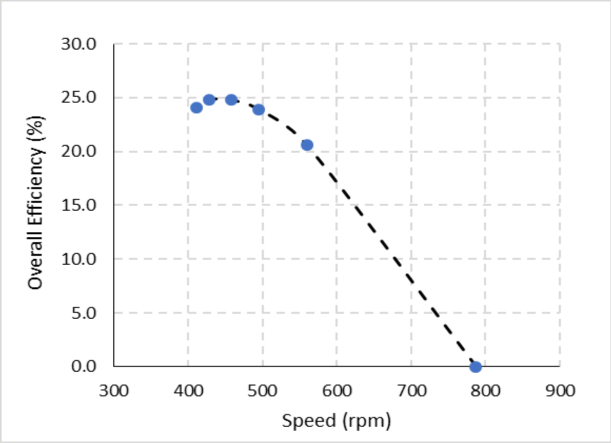


Fig. 5. The electric output power vs rotor rotational speed

The highest mechanical (shaft) power produced was 32.8 watts at a rotational speed (n) of 495 rpm with a turbine efficiency of 39.6% as shown in Table 2, Fig. 6, and Fig. 7.

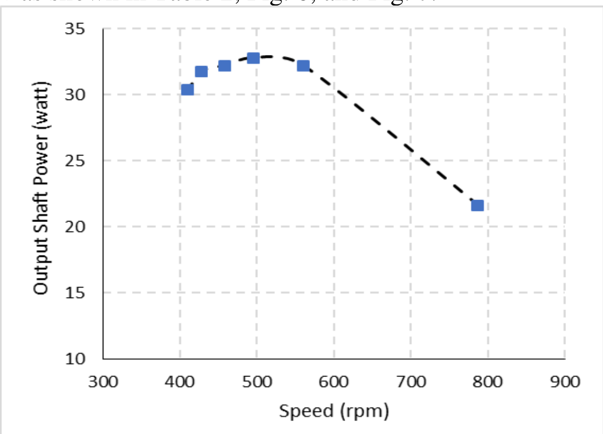


Fig. 6. The mechanical (shaft) power vs rotational rotor speed

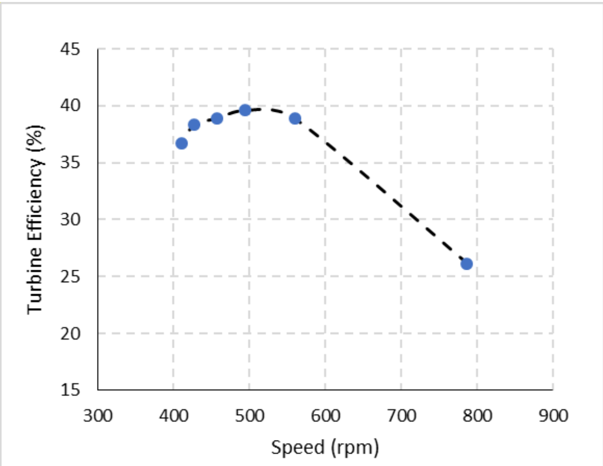


Fig. 7. The turbine efficiency vs rotational rotor speed

Based on the prototype performance tests, it shows that the highest turbine efficiency is obtained at 495 rpm; similar to the design speed of 500 rpm. This indicates that the performance of the turbine design and prototype can operate according to its design.The turbine efficiency of 39.6% is quite good for a small turbine, but still has the potential to be improved, one of which is by optimizing the flow pattern.

3.2 Flow Simulation Results and Flow Pattern Analysis

Through a flow simulation, the flow patterns that occur in the turbine can be investigated to identify opportunities that can be done to improve turbine performance. Fig. 8 shows the water flow pattern in transient conditions when water begins to enter the turbine. Water exits the nozzle and begins to hit the runner blades at t = 0.020 seconds. At t = 0.040 seconds, water has begun to enter several runner blades and begins to produce torque. At t = 0.060 seconds, water has passed through the working path of the cross-flow turbine runner, and some of it begins to exit towards the outlet channel. At t = 0.100 seconds, the water flow has completely passed through the runner and exited through the outlet channel. At t = 0.300 seconds, it appears that some water is still carried upwards, indicating that the process has begun to reach the steady state. When it has reached the steady state, the next step is to investigate the pressure distribution, velocity distribution, volume fraction of water, flow patterns, and torque produced.

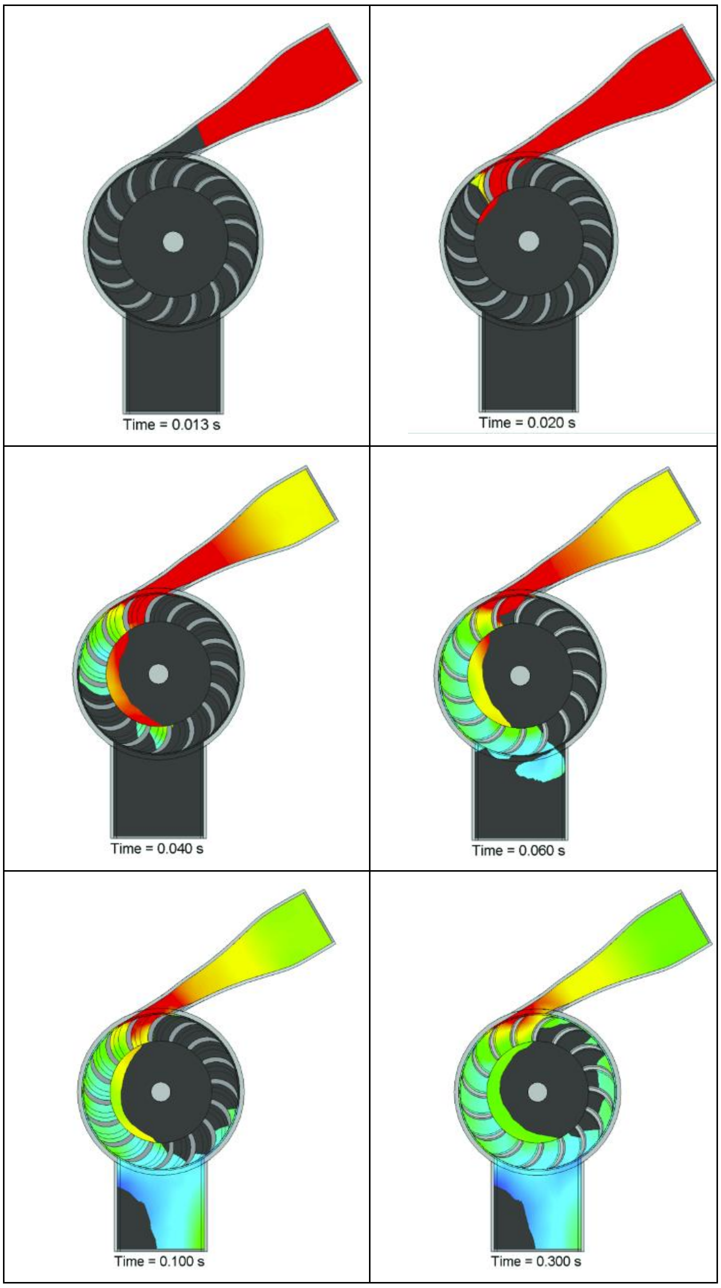


Fig. 8. Transient conditions of water entering the turbine

Fig. 9 shows the pressure distribution and velocity distribution at steady state. Both images show the energy conversion process in the nozzle; the change in pressure energy (head) into velocity head is indicated by the pressure drop from 1.23 bar(a) to about 1.16 bar(a) and the increase in velocity at the nozzle tip from 3,095 m/s to 5,181 m/s.

Fig. 10 and Fig. 11 show the volume fraction of the water pattern and water velocity vector inside the turbine when passing through the runner blade. It can be seen that the water passes through the runner blade with two turns before finally exiting through the outlet channel. This shows that the flow pattern is by the flow pattern of the cross-flow turbine where the energy conversion process occurs impulsively when entering the runner blade and when exiting the runner blade so that the process of converting kinetic energy into shaft power can be more optimal.

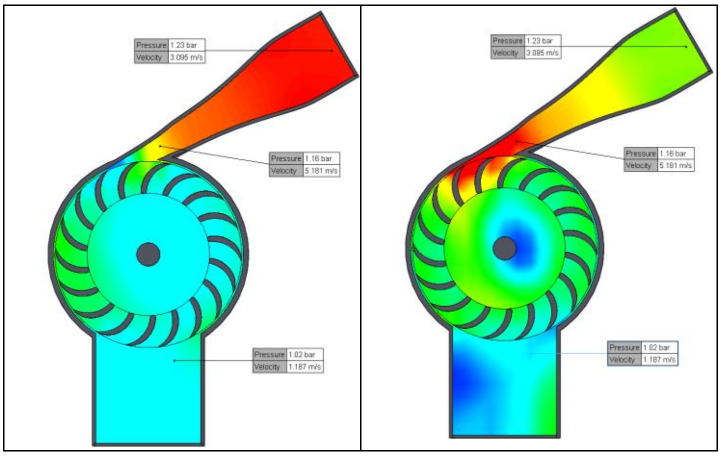


Fig. 9. Pressure and velocity distribution

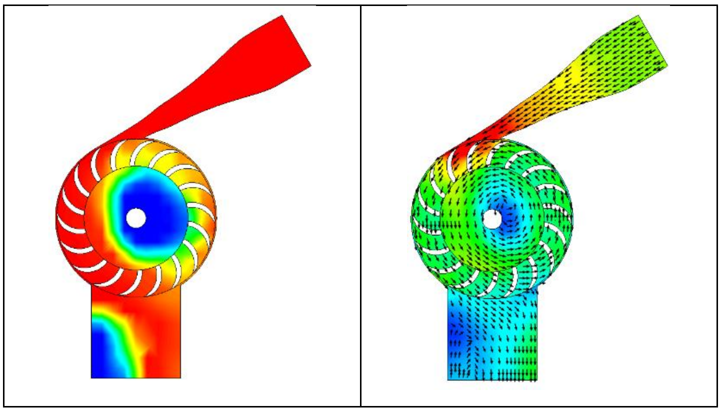


Fig. 10. Volume fraction of water and velocity vector

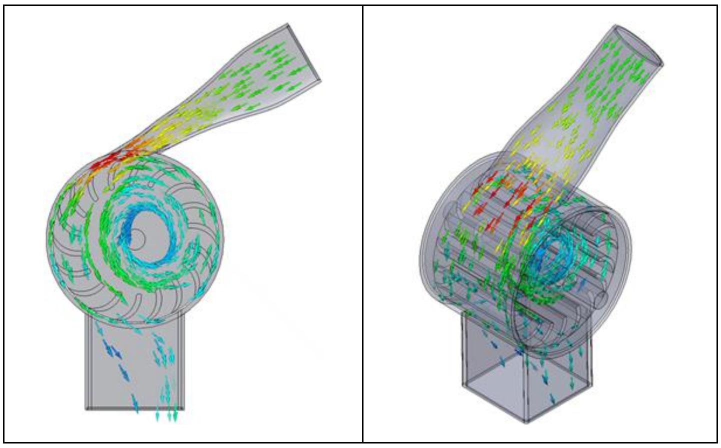
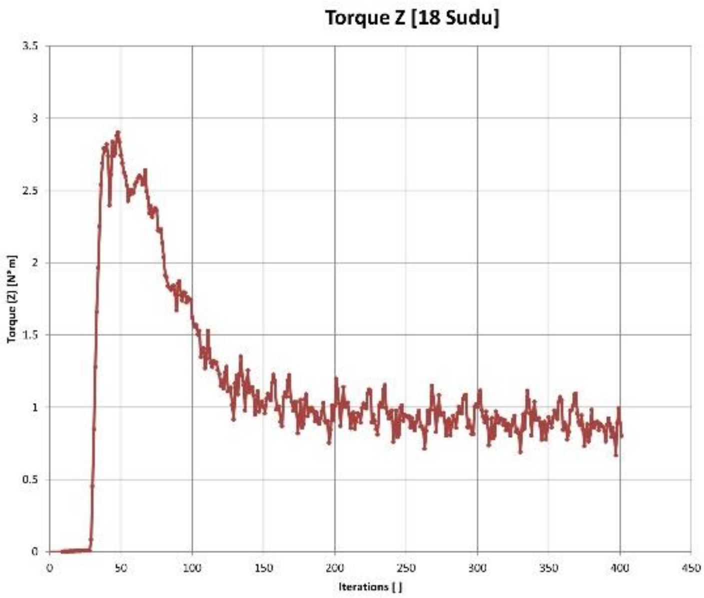


Fig. 11. Water flow pattern inside the turbine

At the head of 2.3 meters, the inlet water velocity is 3,095 m/s or equivalent to a flow rate of around 190 LPM; then the hydraulic input power can be calculated using Eq. 1 to be 71.45 watts. Fig. 12 shows the iteration and calculation of the energy absorbed by the runner blade in the form of torque with an average value of 0.88910 N.mm. The torque value is generated at 500 rpm or 52.3 rad/s; based on these data, the potential power (shaft) of the turbine can be calculated using Eq. 4 to be 45.6 watts. By using Eq. 6, the turbine efficiency based on the simulation flow data is 63.9%.



Goal Name	Unit	Value	Averaged Value	Minimum Value	Maximum Value	Progress [%]	Use In Convergence
SG Torque (Z) 2	[N*m]	0.80084	0.88910	0.66701	1.09387	100	Yes

Fig. 12. Iteration process for the calculation of the resulting torque

The flow simulation results show higher turbine efficiency when compared to the efficiency of the test results; this is reasonable because the simulation has not taken into account mechanical losses such as friction on seals and bearings on the turbine and generator and other losses. The efficiency in the simulation which is still significantly higher than the efficiency of the experimental results also indicates that there is still potential to increase the efficiency of the turbine prototype.

3.3 Discussion

The utilization of very low heads application not only can use cross-flow turbines but vertical vortex turbines can also be used with an efficiency of around 28% by using runners with dimensions of 350 mm in diameter and 240 mm in height [30]. However, vortex turbines are generally large and require civil construction preparation so they cannot be applied as portable power generators.

The peak efficiency of cross-flow turbines is often lower than that of Kaplan and Francis turbines, but the simplicity of their manufacture and stable efficiency under various conditions are often the reasons for their selection. The simple mechanical system means that the manufacturing and maintenance processes can be carried out by local labor. The production and maintenance costs of cross-flow turbos are also generally lower than those of Kaplan or Francis turbines [31].

Compared to the performance of the previous PHPP prototype [28], the performance of the PHPP prototype developed in this study has shown a significant increase in performance as indicated by an increase in the highest turbine efficiency from 26% to 39.6%. In addition, based on laboratory testing experience, it shows that the ease of installation and reliability are much better. However, this prototype must be further tested in real conditions in field environments to further investigate the reliability and other field operation constraints. This PHPP is designed to be operated at a very low head of less than 3 meters, so for field applications, a 1.5-inch flexible hose that can be folded can be used; as commonly used in firefighting applications or even thinner flexible plastic hoses can also be used.

The flow simulation results show that the turbine efficiency can reach 63.9% which is higher than the efficiency of the test results of 39.6%; this is reasonable because the simulation has not considered mechanical losses such as friction on the seals and bearings on the turbine and generator and other losses.

Improvements that can be done to increase the efficiency of the prototype are: (1) using seals that have smaller friction losses, (2) modifying the shape and dimensions of the nozzle so that any losses in this component can be minimized, and (3) conducting a study of the runner dimensions, especially to obtain the optimum ratio of the length to diameter.

4 Conclusion

The experimental results showed that the portable PHPP prototype was able to produce electricity meeting the target of 20.5 watts at a head of 2.3 m and a flow rate of 220 liters/minute with a maximum turbine efficiency of 39.6% at a rotational speed of 495 rpm. The resulting PLTPH prototype has overall dimensions of around 200 x 175 x 150 mm with a mass of no more than 3 kg which is easy to carry for nature survey or adventure activities in remote areas. However, the developed portable PHPP prototype needs to be further tested in an actual environment to investigate the reliability and other field operation constraints.

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