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Pico hydro propeller turbine prototype experimental study for very low head applications

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Abstract

There is a lot of untapped potential for low-head and very low-head (VLH) hydroelectric power in Indonesia. The challenge in developing VLH is that the locations are very difficult to access by vehicle. One example is in the interior of South Kalimantan Province, where it takes more than 12 hours to reach the location on foot. This paper discusses an experimental study of a pico hydro propeller turbine prototype for VLH applications which is suitable for use in remote areas of Indonesia. Its design is simple and lightweight, and it is made from PVC. The turbine's specifications include a power output of 250 W with a net head of 1.53 m. The turbine was designed with four different runner models, including variations in the number of blades and their geometric shapes. The runner models are type 1 and 2 with five and four blades, respectively, and type 3 (in a shallow configuration) and type 4 (in a steep configuration) with 3 blades. The generator used was a DC, 36 V, with a maximum power of 500 W, 2,500 rpm, and 1 phase. An AC lamp was used as the generator load, so an inverter from DC to AC was used in this test. The propeller turbine was tested in the laboratory. The experiments were conducted at various flow rates by adjusting the rotational speed of the supply pump and the electrical load using incandescent lamps. The test results are presented as graphs showing the relationship between flow rate and rotational speed, hydraulic and electrical power, and efficiency. The experimental results indicate that the turbine with a type 3 runner model featuring three blades in a gentle slope configuration has the highest efficiency, approximately 72.5 %.

Keywords: renewable energy; hydro power; propeller turbine design; flat flow stream; water turbine runner.

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I. Introduction

Based on a study conducted by Tefera and Kasiviswanathan [1] it is known that the global potential of hydropower capacity ranges from 2.9 terawatts (TW) during the dry season to approximately 21.01 TW during the rainy season. The annual energy available can reach 25.48 to 184.17 petawatt hours per year (PWh/year). However, due to various constraints such as the efficiency of power plant components, topographical conditions, and power plant capacity factors, not all available theoretical potential is technically feasible. This study reveals that, considering these constraints, the annual energy that can be produced from technically feasible locations ranges from 7.06 to 49.05 PWh/year [1]. Global annual electricity production from hydropower is estimated to reach 4,370 TWh. Compared to other renewable energy sources, hydropower accounts for approximately 63 % and nearly 16 % of total energy production [2].

In Indonesia, most hydroelectric power plants are built by utilizing waterfalls. Generally, waterfalls are located far from residential areas and are difficult to reach by land transportation, so they must be reached on foot. Waterfalls can also be obtained by damming river flows, but the civil engineering costs are quite high. On the other hand, many flat rivers flow near residential areas, both in rural and urban areas. However, these flat river flows have not been widely utilized as power plants. The technology to convert flat river flows into electrical energy is typically referred to as a very low head turbine (VLHT). VLHT can be applied to heads or waterfall heights of less than 3.4 meters with flow rates up to 30 m^3/s [3][4]. This type of turbine has several advantages, including low system and civil engineering installation costs, a simple design, ease of operation, and fish-friendly characteristics [3].

In recent years, VLHT development has seen significant progress in terms of design, efficiency, and environmental sustainability. Quaranta et al. [5] reported that the application of VLHT in irrigation channels and navigation dams can reduce installation costs to <5000 €/kW with efficiency supported by fish-friendly systems and adaptive control. Quaranta *et al.* [4] conducted research focused on the design, ecological behavior, costs, and performance of VLHT. To support good ecology, it is essential to ensure that VLHT designs do not harm fish or significantly alter river habitats, one way being to provide fish migration pathways and meet local environmental standards. Utilizing dams in existing irrigation channels and water distribution networks is a good option for reducing environmental impacts [6][7].

Various types of VLHT have been developed by many researchers. Gallego *et al.* [8] developed and produced a low-cost Turgo turbine for low-head applications to assess the effects of various geometric design elements such as nozzle diameter, number of nozzles, and the impact of jets on turbine efficiency. Other studies investigated Turgo turbines in VLH applications include [9][10][11]. Another type of turbine that can be applied to VLH is the siphon turbine, where using computational fluid dynamics (CFD), Zhou *et al.* [12] developed an ultra-low head siphon turbine with various distributors, runner blade shapes, and distributor geometric parameters. Distributors with a bell shape and four guide vanes produced the highest power at the lowest head. VLHT was also developed by Mejiartono *et al.* [13] in the form of a mixed-flow pump as a turbine (PAT), achieving an efficiency of 35–40 % based on CFD simulations and experimental tests, making it an effective and economical solution for areas with flat flow characteristics (low head).

Recent studies have shown that VLHT development is becoming increasingly complex and efficient through design optimization and analysis approaches. Some researchers have conducted VLHT optimization such as Soesanto *et al.* [14] who used a genetic algorithm to optimize the stagger angle of the turbine runner. This optimization resulted in a 4.29 % improvement in hydraulic performance. Haghighi *et al.* [15] designed and simulated an axial VLH turbine with movable rotor blades on the runner section. The results at a constant rotational speed of 40 rpm showed that increasing the runner opening angle enhances optimal efficiency. Another optimization aimed at creating design innovations to reduce VLHT production costs was conducted by Hoghooghi *et al.* [16]. The research by Novendra *et al.* [17] showed that using the Grey Wolf optimizer (GWO) algorithm to regulate system frequency load frequency control (LFC) can maintain the stability of low-head power generation systems with frequency more effectively. This is evident from smaller overshoot values and stabilization times compared to conventional control methods, both in isolated systems and grid-connected systems.

Meanwhile, Djalal *et al.* [18] investigated methods to maintain frequency stability in turbines using a combination of magnetic energy storage (SMES) and capacitors (CES). With the assistance of the Cuckoo Search algorithm, they successfully reduced frequency spikes by 33 % and made the low-head turbine system stabilize more quickly. Another VLHT study involved designing a micro turbine swirler validated using CFD, which could reduce production costs by up to 70 % [19].

Sudsuansee *et al.* [19] developed a propeller turbine with variable blade angles capable of maintaining high efficiency exceeding 70 % within a low head and flow rate range.

In terms of turbine materials, Sritram *et al.* [20] revealed that lightweight water turbine blades can increase torque and efficiency, but the maximum rotation speed remains the same. Heavy turbines take longer to reach maximum speed than lightweight turbines, so they also take longer to generate electricity. Sritram *et al.* [20] studied the effect of turbine materials made from steel and aluminum on the efficiency of gravity-driven hydroelectric power plants. The torque of aluminum turbines is approximately 8.4 % higher than that of steel turbines.

A literature review shows that several studies on design optimization have only been conducted through research and simulation, without direct experimental testing in the field or the laboratory. The implementation of VLH turbines in the real world is very different from theory, especially in terms of parameter configuration. Additionally, the current VLHT designs are complex, require numerous components, and are quite heavy due to their metallic materials. This makes them less suitable for use in Indonesia especially in remote areas that are difficult to access by vehicles. Furthermore, each VLH location has distinct flow characteristics and river morphology. The challenge lies in adapting the system design to operate optimally in locations with seasonal flow fluctuations, high sediment levels, or limited space without requiring extensive additional construction. Therefore, further studies on VLHT are crucial, not only to bridge the gap between design and real-world application but also to provide sustainable energy solutions.

Based on this background, a Propeller-type water turbine prototype has been designed and tested that can operate at VLH, making it suitable for application in remote areas of Indonesia that are difficult to reach by vehicle. The turbine is designed to be simple and easy to manufacture. Most of the turbine components are made of PVC plastic, making it lightweight, corrosion-resistant, and relatively inexpensive to manufacture. To obtain an optimal propeller turbine runner design, this study used a triangular velocity analysis approach on a 2D airfoil profile to design the dimensions and basic shape of the turbine runner. The turbine's power capacity was designed to be relatively small, around 250 W, considering the needs and ease of mobilization to remote communities. With this relatively small power capacity, the required water flow rate and head are also relatively small and low, making it easier to apply in many locations. The development of this VLHT is expected to contribute to self-sufficient electricity supply, particularly in remote areas.

II. Materials and Methods

A. Very low head hydro power plant

In general, hydropower can be divided into two groups: hydropower that works at a high and low head or is called VLH. VLH type of hydropower plant uses a water turbine called a VLHT and is applied to a head or height of falling water of around 1.5 - 3.4 m [3]. However, along with advances in technology there have been several innovations so that VLHT can also be applied to heads lower than 1.5 m, namely heads of 1 meter, as stated by Rohmer *et al.* [21]. Some of the turbines that can be applied to flat river flows or VLH are Propeller turbines [22][23][24], axial flow siphon turbines [25], Archimedes screw turbines [21][26], Waterwheels [27], and Vortex turbines [28][29][30].

The amount of generated power (P) that a water turbine can generate is calculated using equation (1). Measurement of water volume flow rate (Q) is carried out by measuring the water velocity (v) and the cross-sectional area of the water (A) shown in equation (2).

$$P = \rho \cdot g \cdot Q \cdot H_{net} \cdot \eta \quad (1)$$

$$Q = v \cdot A \quad (2)$$

where P is generated power (W), ρ is water mass flow rate (kg/m^3), g is gravity velocity (= 9.81 m/s^2), Q is water volume flowrate (m^3/s), H_{net} is net height or clean height (m), η is system efficiency (%), v is water velocity (m/s), and A is cross-sectional area of the water (m^2).

The generator used in this study is a generator that is available on the market and modified to suit the design of the turbine construction. The generator is a 36 V DC type with a maximum power of 500 W, 2500 rpm, and 1 phase. The DC generator is chosen to consider the variation in output, which can adjust the difference in the rotation due to the availability of existing heads. In addition, length and diameter dimensions are selected based on the capability of the power that can be generated and the design of the system's overall size.

B. Research procedure

This study was conducted in stages as shown in Figure 1. This activity begins with a literature review on the current development of VLHT. To design a water turbine, the initial data required is the amount of water energy potential that can be generated with the planned head and discharge parameters.

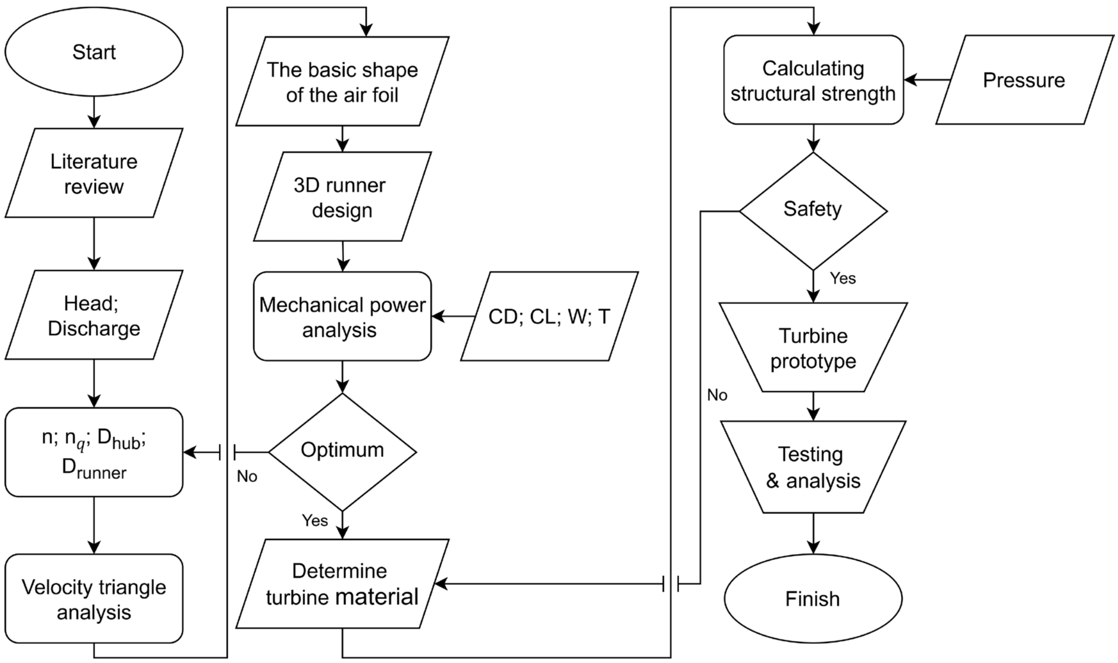

Figure 1. Research flowchart.

Next, the main dimensions of the water turbine such as the hub diameter, runner diameter, and other dimensions will be calculated with reference to the turbine rotation to match the type of turbine to be used. To obtain a VLHT design with optimal efficiency, velocity triangle analysis is conducted, and the basic shape of the airfoil is determined to meet aerodynamic conditions. With the assistance of turbine runner design software coded in the Python programming language, a 3D runner design is obtained.

To ensure the water turbine runner design is appropriate mechanical power analysis and structural strength calculations are performed. Subsequently, the prototype manufacturing process and laboratory testing are conducted to determine the actual performance of the VLHT produced.

C. Turbine specification

The propeller turbine designed in this study is an axial flow reaction turbine which usually has three to five blades. Propeller turbines are widely used at low heads with small to large volumes of water. Propeller turbines operate at low heads and with water capacities ranging from 0.5 to 1000 m^3/s [31].

Propeller turbine design calculations are carried out analytically. The calculation results will provide a profile picture of the runner. In this study four runner models were designed with variations in the number of blades and geometric shapes, namely the five blades model (type 1), the 4 blades model (type 2), the three blades in a sloping shape (type 3), and the three blades in steep shape (type 4). Turbine-specific speed n_q in (rpm) units are calculated using equation (3). Furthermore, the tangential velocity of water entering the blade U_1, blade outer and inner diameter are shown in equations (4) to (6). Furthermore, the amount of efficiency shows the performance of the Propeller turbine prototype at its nominal condition. Equations (7) to (9) are used to obtain turbine efficiency.

$$n_q = n \cdot \frac{\sqrt{Q}}{H^{\frac{3}{4}}} \tag{3}$$

$$U_1 = U_1^* \cdot \sqrt{2 \cdot g \cdot H} \tag{4}$$

$$D_1 = \frac{60 \cdot U_1}{\pi \cdot n} \tag{5}$$

$$D_N = 0.5 \cdot D_1 \tag{6}$$

$$P_e = V \cdot I \tag{7}$$

$$P_h = \rho \cdot g \cdot Q \cdot H \tag{8}$$

$$\eta = \frac{P_e}{P_h} \cdot 100\% \tag{9}$$

where n is the amount of rotation per minute (rpm), U_1 is tangential velocity of water entering the blade (m/s), U_1^* is the constant of tangential velocity (m/s) which its value is derived from the specific velocity graph, D_1 is blade outer diameter (m), D_N is blade inner diameter (m), P_e is real electrical power (W), V is voltage (V), I is current (A), P_h is hydraulic power (W), and η is system efficiency (%).

D. Turbine performance testing

Propeller turbine testing was carried out at the Hycom laboratory owned by the Indonesian Ministry of Education, Culture, Research, and Technology. In this experiment the volume flow rate is varied by adjusting the rotational speed of the supply pump. The

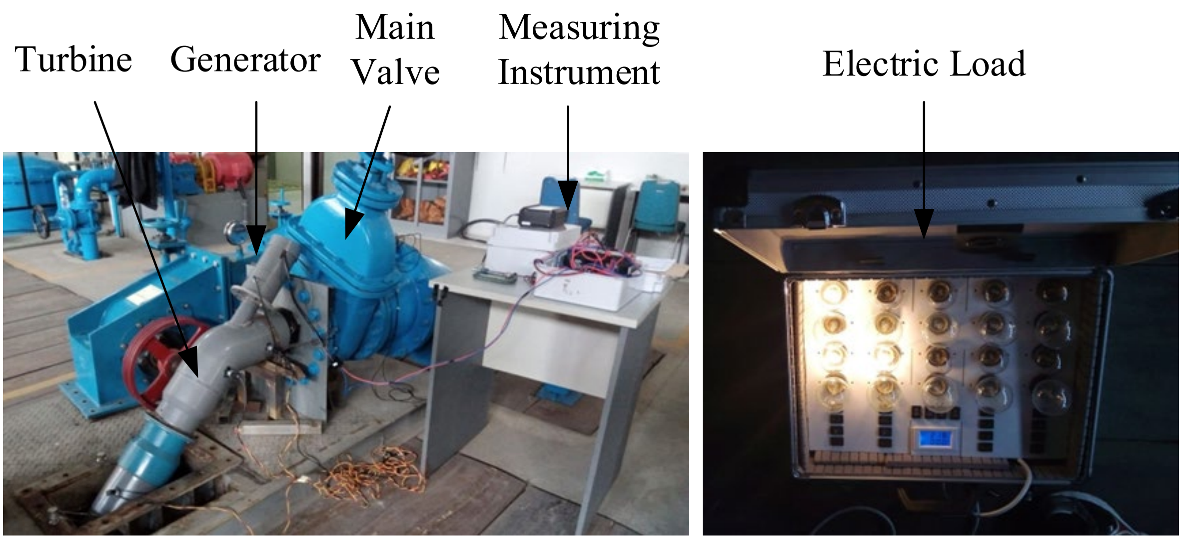

Figure 2. System experiment in laboratory.

head is kept constant using a control tub and an incandescent lamp is used as the electrical load. Several pieces of equipment are needed in the data collection process including flow meters, electric loads, tachometers, multi-testers, roll meters, and data loggers.

The parameters measured were voltage, current, turbine rotation, water discharge, and head. Voltage and current were measured using a multi-tester, water volume flow rate was measured using a flow meter whose data was stored in a data logger, turbine rotation was measured using a tachometer, and the head was measured using a rollmeter. Propeller turbine testing is shown in Figure 2, while the VLHT testing procedure is as follows:

Prepare the equipment and install the measuring instruments in the designated positions.

1. Prepare the equipment and install the measuring instruments in the designated positions.
2. Turn on the supply pump.
3. Once stable, record the volume flow rate of the flowing water.
4. Gradually increases the electrical load until the maximum power from the generator is achieved.
5. Record the turbine speed.
6. Gradually increase the water flow rate by increasing the frequency of the supply pump motor.
7. Record the water flow rate, electrical power, and turbine rotation.
8. Turn off the supply pump.
9. Replace the blade with another type to be tested.
10. Repeat steps (2) to (9) for all types of blades being tested.

Prototype testing of the VLHT was conducted to obtain data on the efficiency of the water turbine with variables such as water flow rate, water level, turbine shaft rotation, and generator output power. From the inlet-side data, the potential hydraulic power was calculated using equation (8). The voltage and current from the generator will be measured as outlet power and using equation (7) the real electrical power will be obtained. By comparing the input power and output power, the efficiency of the water turbine can be calculated using equation (9).

III. Results and Discussions

Initial data used in the design of the propeller turbine, analytical calculation results, and turbine blades specifications are shown in Table 1. It shows the design specifications for propeller turbine blades with a flow rate of 0.025 m^3/s, a net head of 1.53 m, and a rotation of 1500 rpm. Using equation (3) to (6), the specific rotation of the turbine is 172.4 rpm, the outer diameter of the runner is 0.13 m, and the hub diameter is 0.065 m. From the design data, several variations of the blade design were made with a different number of blades, namely 5, 4, 3 blades (type 1 to 3). For runners with 3 blades, two models were made: the sloping blade model (type 3) with stagger angle 55.4° and the steep blade model (type 4) stagger angle 53°. The reason for creating two runner models with 3 blades is to find out the performance of the blade design with different specific rotation selections. Type 4 blades are designed to work at 1300 rpm with a specific rotation of 149.4 rpm.

The experiment results and power calculations are displayed in flow rate to rotation, hydraulic power, and electric power graphs, as shown in Figure 3. In general, with an increase in the flow rate of water entering the turbine, the turbine rotation, hydraulic power, and electric power also increase, following the theoretical

Table 1.
Blades turbine specifications.

Parameter	Unit	Type			
		1	2	3	4
Flow rate	m³/s			0.025	
Net Head	m			1.53	
Rotation	rpm	1500	1500	1500	1300
Specific rotation	rpm	172.4	172.4	172.4	149.4
Blades number				3 (sloping shape) stagger angle 55.4°	3 (step shape) stagger angle 53°
Outlet diameter	m			0.13	
Hub diameter	m			0.065	
Material				PVC plastic	

rules as contained in equation (7) and equation (8), where the flow rate is directly proportional to the turbine rotation, turbine voltage, hydraulic power and electrical power.

From Figure 3(a) shows that in turbine type 1, rotation and hydraulic power tend to increase more steeply than the other three runner types. In contrast to turbine type 1, turbine type 2 has the steepest increase in rotation compared to turbines 1, 3, and 4 (Figure 3(b)). Whereas turbine type 3 (Figure 3(c)) and type 4 turbine (Figure 3(d)) where these two types of turbines use runners with the same number of blades, namely 3, the increase in rotation is identical, increasing moderately. The increase in hydraulic power of turbine type 3 is the most gentle compared to other turbines. Of the four types of turbines tested, the increase in electric power has a trend that tends to be almost the same. The flow rate increase graph is in line with the results of research conducted by Sritram and Suntivarakorn [32], Titus and Bakthavatsalam [33], and Ghaniy *et al.* [23].

Generally, the relationship between turbine power and turbine rotation is that power will increase with increasing rotation and decrease again after the propeller rotation reaches a specific rotation. When the propeller rotation reaches a stall propeller condition, the power will start to drop slowly. At the design flow

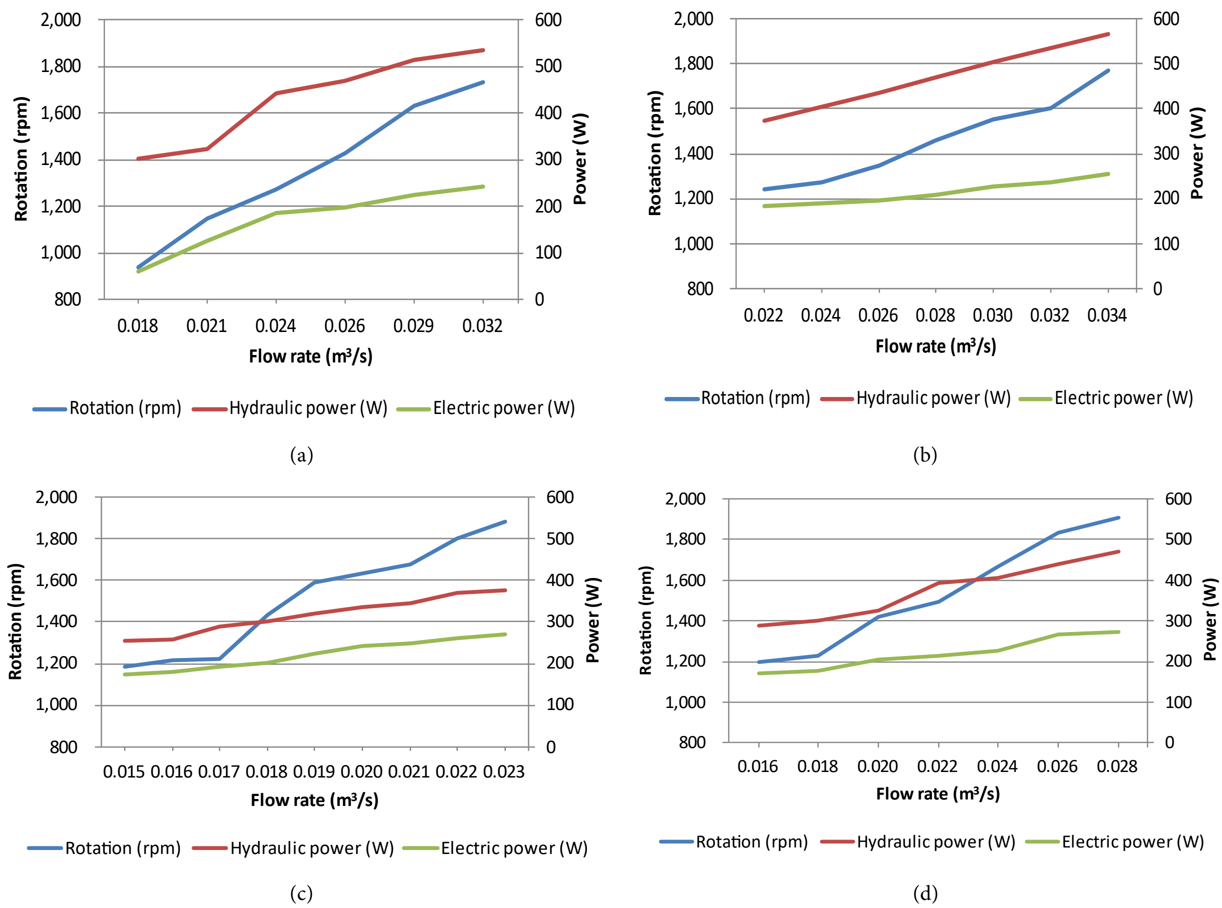

Figure 3. Graph of test results for the flow rate to rotation and power: (a) runner type 1; (b) runner type 2; (c) runner type 3; (d) runner type 4.

rate, which is around 0.025 m^3/s, rotation, hydraulic power, and electrical power generated for type 1 are 1,350 rpm, 416 W and 190 W; type 2 are 1,311 rpm, 421W and 193 W; type 3 are 1,881 rpm, 375 W and 270 W, and type 4 are 1,749 rpm, 422 W and 246 W. These results show that for type 1 and 2 runners, the design flow rate produces lower turbine rotation compared to the design, while for types 3 and 4 resulting in higher turbine rotation than design. Type 3 (3 blades, sloping shape) produces the highest electrical power compared to type 1 (5 blades) and type 2 (4 blades) because it is an ideal number of blades. The more blades, the shorter the path length of the water passing through the blades so that the blades do not completely absorb the potential energy of the water. In addition, losses and friction are greater in the cross-sectional area of the blade with a greater number of blades. At the same number of blades (3 blades), type 4 (steep shape) has lower electrical power compared to type 3 (sloping shape) because type 3 produces a higher axial force compared to type 4. Axial force plays a significant role in the torque generated by water turbines, especially very low-head turbines. This is in line with what Saleem *et al.* [34].

Furthermore, the relationship between the flow rate to electrical power of the four types of blades is shown in Figure 4 and the relationship between flow rate to efficiency is shown in Figure 5. Figure 4 shows that the electric power generated by runner types 3 and 4 is greater than that of types 1 and 2. The electric power of type 3 turbines is the largest, followed by type 4 and type 2 turbines. While type 1 turbine is the turbine with the smallest electric power. In general, the four types of runners that have been tested have almost the same polynomial graph trend, where with increasing water discharge, the electric power generated by the turbine also increases. The characteristics of the propeller turbine are strongly influenced by the amount of water discharge. The characteristics of water turbines like this are in line with the results of research conducted by Bai *et al.* [35]. The turbine is always made in such a way that the highest power is achieved at a predetermined velocity.

Figure 5 describes the relationship between the water discharge into the turbine and the electrical efficiency. From the graph it can be seen that turbines type 1 and 2 have almost the same efficiency trend where the maximum efficiency of both types of turbines is around 45 %. Turbine type 3 has the highest maximum efficiency which is around 70 %. While the type 4 turbine has a smaller maximum efficiency than type 3, which is around 60 %. In general, at the same dimensions, the greater the number of blades the lower the efficiency. In type 1 turbines, the turbine efficiency does not increase significantly with an increase in flow discharge. At the design discharge condition of 0.025 m^3/s, the turbine has an efficiency of about 41 % and this is the lowest efficiency compared to other types of turbines. With the number of blades totaling 5, the chord of the blade becomes shorter so that the blades cannot fully convert the existing potential energy into motion energy. In line with turbine type 1, turbine type 2 also produces turbine efficiency that does not experience a significant increase along with the increase in flow discharge. In this type 2 turbine, the efficiency generated at a design discharge of 0.025 m^3/s is around 43 %.

In contrast to runner types 1 and 2, runner type 3 increases efficiency significantly with increasing flow rate. At conditions close to the design discharge of 0.025 m^3/s, the turbine efficiency increases to more than 72 %. This type 3 runner with 3 blades is the most ideal compared to the other types because at volume flow rates below the design flow rate of 0.025 m^3/s, a turbine rotation of 1500 rpm is already achieved so that with an increase in flow rate, the power generated will also increase. In line with runner type 3, runner type 4 has similar characteristics, where the turbine efficiency increases with increasing flow rate, where at a design flow rate of 0.025 m^3/s, the turbine efficiency is around 59 %, so type 3 has a greater efficiency than type 4.

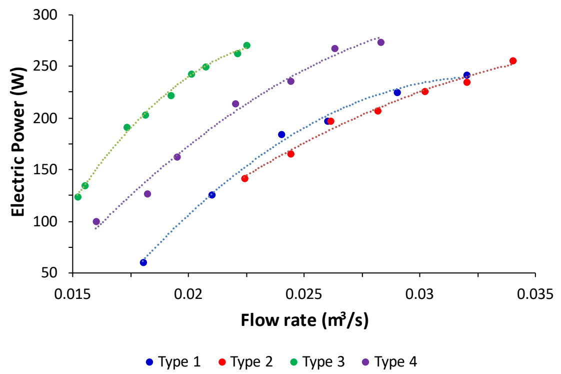

Figure 4. Graph of flow rate to electrical power test results.

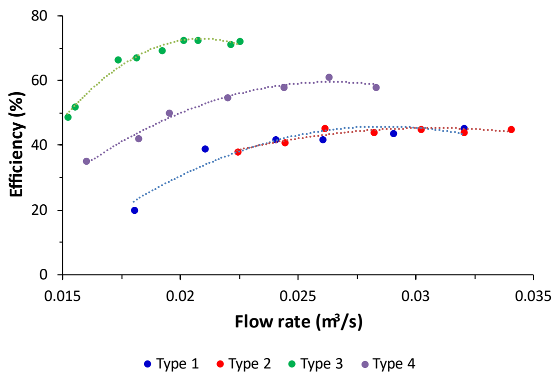

Figure 5. Graph of flow rate to efficiency test results.

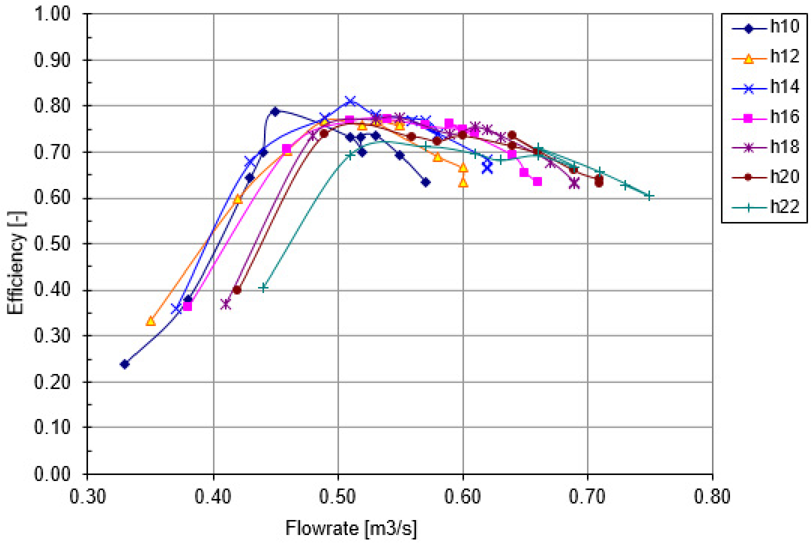

Figure 6. Graph of overall efficiency vs flow rate [36].

The flow rate versus efficiency graph shown in Figure 5 is identical to the results of research conducted by Phitaksurachai *et al.* [36] using an axial propeller turbine for low head small hydro power applications. Their research shows that efficiency increases in line with increasing flow rate up to a certain point (design point) and efficiency decreases if the flow rate continues to increase (Figure 6). The decrease in efficiency after the flow rate exceeds the design point is caused by losses in the fluid flow system due to turbulence resulting from increased water flow velocity. As is known, the Reynolds number is greatly influenced by water velocity and pipe diameter. At the same pipe diameter, if the flow rate increases, the water velocity increases, thereby increasing the Reynolds number. Ultimately, the water flow becomes more turbulent, resulting in greater losses.

From the analysis of experimental data, it can be seen that VLHT designs with 5 and 4 blades tend to produce greater resistance due to accumulation or flow disturbance, thereby reducing turbine efficiency. Conversely, VLHT configurations with 3 blades (types 3 and 4) provide an optimal balance between resistance and flow continuity, allowing fluid to flow more smoothly between the blades. VLHT with 3 blades and a shallower stagger angle (type 3) has proven to be more effective in aligning the fluid flow direction with the blade surface (inflow alignment), thereby reducing energy loss due to turbulence. Meanwhile, the steeper stagger angle (type 4), despite the small difference, causes the blades to operate at a less optimal angle of attack, reducing the lift-to-drag ratio and negatively impacting efficiency. The VLHT developed in this research is expected to be applied in remote areas of Indonesia, thereby increasing the electrification ratio and further driving the development of renewable energy.

IV. Conclusion

Experimental studies on a prototype propeller turbine for VLH applications have been conducted using a 250 W pico hydro turbine with 1.53 m net head. The turbine was analyzed with four runner models with varying number of blades and geometry shapes. Runner type 1 uses 5 blades, type 2 uses 4 blades, type 3 uses 3 blades with a sloping shape, and type 4 uses 3 blades with a steep shape. The experimental results show that at a flow rate of about 0.025 m^3/s, the type 3 turbine with 3 blades in the shape of ramps (stagger angle 55.4°) has the highest efficiency of about 72 %, followed by the type 4 runner with a steep slope angle (stagger angle 53°) which has an efficiency of 59 %. Runner types 1 and 2 produced the least efficiency with only 41 % and 43 %, respectively. These results show that the greater the number of blades in the same dimension, the lower the efficiency. Furthermore, speed triangle calculations on the water foil profile, and the design of a water turbine runner coded in the Python programming language, a prototype with performance of over 70 % was produced. For future research, the focus will be on optimizing the runner design and testing it in the field under varying environmental conditions to assess performance, reliability, and various challenges in real-world conditions. This will result in a VLHT design that has been proven in the field and is ready for application.

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Declarations

Author contribution

All authors contributed equally as the main contributor of this paper. All authors read and approved the final paper.

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Competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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