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Design and performance test of series underwater Savonius rotors with horizontal axis

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ABSTRACT

The energy of river water flow or irrigation canals can be utilized by using a horizontal axis Savonius turbine, which converts low-speed river flow into electrical power with good design. The design of this turbine needs to pay attention to several parameters, namely, the deflector angle, the number of blades, the diameter and thickness of the blades, and the diameter and thickness of the end plates. However, the problem usually encountered is imperfect turbine construction due to the large drag force that occurs so that the power generated is low. Based on this background, it is proposed to manufacture and test the performance of a series Savonius underwater rotors with a horizontal axis. The research results found that the generator voltage without load was 25.6 V when the turbine only rotated at 47.2 rpm, whereas when under load, the average power produced was 8.5 watts with an average turbine speed of 31 rpm. The highest efficiency value on the rotor is 86.73%, with a torque value of 3.36 at a turbine speed of 29.9 rpm. This indicates that the tool can generate large torque at low speeds.

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1. INTRODUCTION

The rapid development of technology in this digital era has made electrical energy one of the primary needs in society. During the increasing consumption of electrical power, fossil energy which is the primary energy source is decreasing and harms the environment, thus demanding a shift from conventional energy to renewable energy [1], [2]. Indonesia is a country that has abundant natural resources that can be utilized as a source of renewable energy, one of which is water energy. Water energy is one of Indonesia's most widely used renewable energies because of its enormous availability. However, the utilization of water energy potential only reaches 7.2% of Indonesia's total water energy potential, reaching 75,091 MW [3].

Water flow with a high flow rate and the head has been widely used with several types of turbines, such as the Pelton, Francis, and Kaplan turbines [4], [5]. In contrast, the water flow in Indonesia is generally a low-velocity flow of 1 m/s. It tends to have a low head, so that is still underutilized because it requires a damming process first, which will affect costs and cause damage to the environment around the dam [6]. To take advantage of these water flows, innovative technologies are needed that can be used to convert low-velocity water flows into electrical energy [7]. One is the horizontal axis Savonius turbine, which can be used underwater with low-speed water flow. Savonius type turbine has several advantages, such as simple construction and large torque [8]. The energy of river water flow or irrigation canals can be utilized by using a horizontal axis Savonius turbine, which converts low-speed river flow into electrical power with good design. The design of this turbine needs to pay attention to several parameters, namely, the deflector angle (direction plate), the number of blades, the diameter and thickness of the blades, and the diameter and thickness of the end plates [9], [10].

Several modifications are needed to optimize the utilization of hydropower plants so that the generator performance can be maximized [11]. Cho *et al*. [12] and Gunawan *et al*. [13] discussed the increase in the output power of the Savonius hydraulic turbine by modifying the blade profile. The study by [14], [15] researched underwater rotor turbines carried out with a different number of blades, namely three blades, six blades, and nine blades. The results showed that adding a guide plate could improve turbine performance due to an increase in the difference in torque between the convex and concave sides of the blade. This study also stated that the turbine with three blades produces the most significant power coefficient (Cp) and moment coefficient (Cm) values among the other two blades. Another study by [16] can conclude that the aspect ratio is directly proportional to the power coefficient. In addition, adding end plates at each end of the rotor can increase the turbine power coefficient by up to 36% [17], [18]. Based on previous studies, the problem usually encountered is imperfect turbine construction due to the large drag force that occurs so that the power generated is low. Therefore, this research proposes to manufacture and test the performance of a series of Savonius underwater rotors with a horizontal axis.

Part one of this article discusses the introduction and research background. Part two discusses the research methodology. This research begins with a literature study before starting research. A literature study is an activity or process of collecting information from various literacy sources about previous research that is relevant to the research to be carried out. Then proceed with a discussion of system design. The third section discusses the results and discussion.

2. METHOD

2.1. Planning stage

In this study, the planning stage is the process of designing or drawing the design pattern of the Savonius turbine to be made. This design drawing provides an overview of the tool to be made by considering several aspects, such as the efficiency of the device to suit the elements at the test site. Figure 1 shows the dimensions of the multilevel Savonius turbine frame and the dimensions of the end-plate. Figure 2 shows the blade and reflector dimensions. Figure 3 shows the complete underwater Savonius rotor design.

2.2. Testing and data retrieval stage

The testing and data collection steps are as follows: i) Make sure all turbine components are correctly installed; ii) Put the appliance on the water line; iii) Make sure the turbine works correctly before the picking process data starts; iv) Measure flow velocity and discharge in waterways; v) Record and measure the load and rotation of the turbine; vi) Measuring the rotational speed of the turbine with a Tachometer; vii) Measure the voltage and current generated by the generator using a multimeter; viii) Record the measurement results in the table; ix) Repeat steps 6-8 with a different load; and x) Testing is complete.

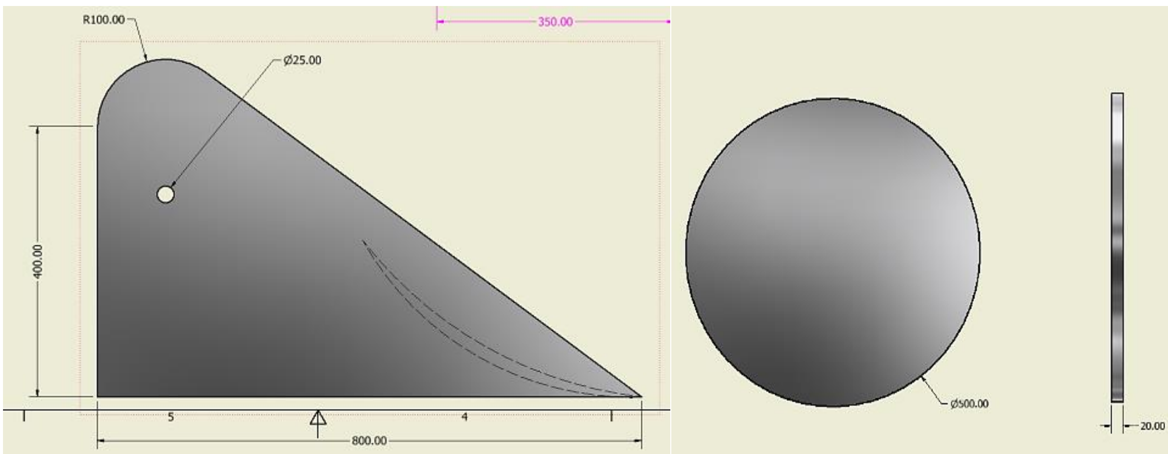

Figure 1. Dimensions of Savonius turbine frame and the end-plate

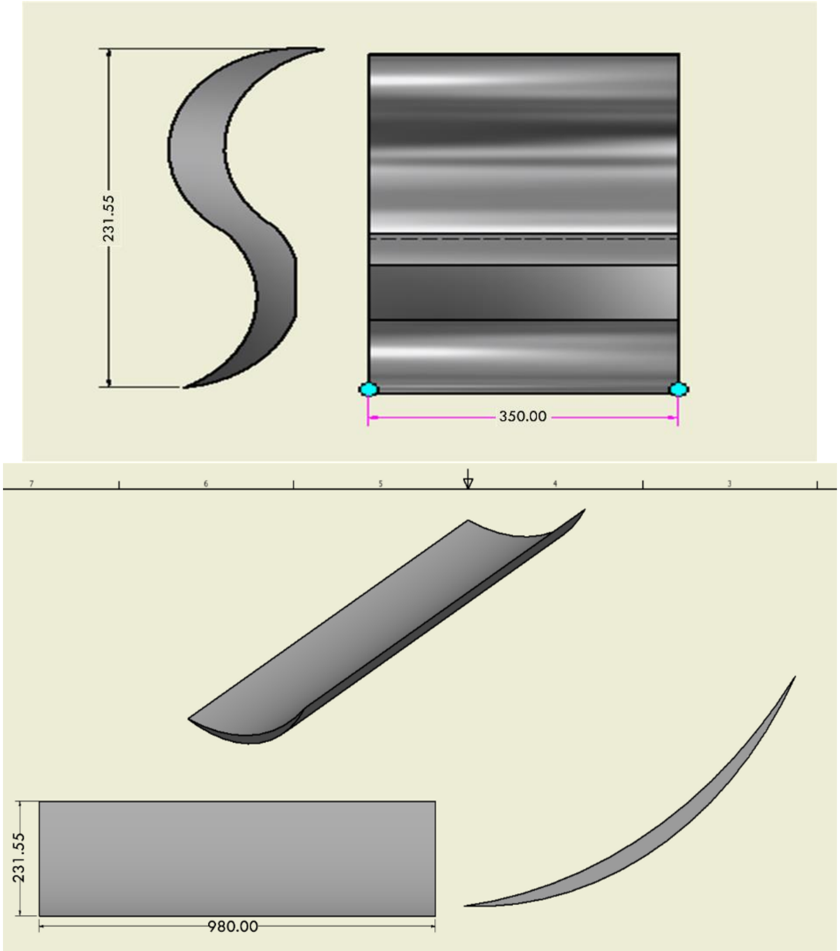

Figure 2. Blade and reflector dimensions

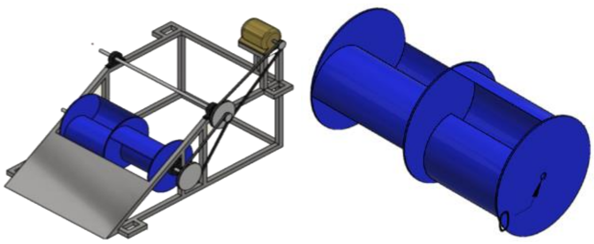

Figure 3. Design of the underwater Savonius rotor

2.3. Data processing and analysis stage

After the test data has been collected, the next step is data processing and analysis. The data processing is carried out as follows: i) calculate water power (P_a), ii) calculate generator power (P_{gen}), iii) calculate the turbine power (P_t), iv) Calculate the tip speed ratio (TSR) value, v) calculating turbine efficiency (η_t), vi) calculating the moment coefficient (C_m), and vii) calculating system efficiency (η_s).

2.4. Savonius turbine formula

The performance of an underwater Savonius rotor can be affected by several parameters. The following are some parameters calculated in the underwater Savonius rotor test.

2.4.1. Discharge (Q)

Water discharge is a quantity that states the amount of water flowing per unit of time that passes through a specific cross-section. This water discharge test is carried out to determine how much flow in volume per unit of time. To find out how much water flow capacity can be found, use the (1) and (2) [19]. Q is water discharge in m^3/s, V is velocity of water flow in m/s, A is cross-sectional area in m^2, h_0 is depth of water in meters, and l is width of the canal in meters.

$$Q = V \times A \tag{1}$$

$$A = h_0 \times l \tag{2}$$

2.4.2. Frontal cross-sectional area

The frontal cross-sectional area is the projection coefficient of the rotor directly facing the water flow. This coefficient can be calculated using (3) [20], [21]. H is rotor height in meters and D is rotor diameter in meters.

$$A = H \times D \tag{3}$$

2.4.3. Water power (watt)

Water power is the power contained in water that can rotate the water wheel. The equation can find water power [22]. P_{water} is water power in watt, ρ is density of water in kg/m^2, A is rotor cross-sectional area in m^2, and v is water speed in m/s.

$$P_{water} = \frac{1}{2}\ x\ \rho\ x\ A\ x\ v^3 \tag{4}$$

2.4.4. Power generators (P_{gen})

Generator power is the amount of electrical power generated by the generator. Generator power can be calculated using (5) [23]. V is voltage in volt and I is current in ampere.

$$P_{gen} = V * I \tag{5}$$

2.4.5 Angular speed

The angular speed can be calculated based on the speed of the Savonius rotor shaft using (6) [24]. ω is the angular velocity in rad/s, and n is turbine rotation in rpm.

$$\omega = \frac{2\pi n}{60} \tag{6}$$

2.4.6. Torque (τ)

Torque is the rotating force generated by the turbine shaft or the turbine's ability to do work. Torque is usually given the symbol τ [25]. The unit for torque is pounds-feet or kilogram force-meter (kgf m). In British units, it is ft.lb while in SI it is Nm. T is torque in Nm, m is mass in kg, g is gravity in m/s^2, and r is shaft spokes in meters.

$$T = m\ x\ g\ x\ r \tag{7}$$

In addition to (7), the torque value can also be calculated using (8).

$$T = \frac{P_{gen}}{\omega} \tag{8}$$

2.4.7. Turbine power (P_t)

Turbine power is the power that a turbine can generate to drive a generator. The (9) can calculate turbine power [26]:

$$P_t = \frac{2\ \pi n\ t}{60} \tag{9}$$

2.4.8. Tip speed ratio (TSR)

Tip speed ratio (TSR) is the ratio of the tip speed of the rotor to the rate of the water flow. The TSR value can be calculated using (10) [27]. D is rotor diameter in meters, V is water flow rate in m/s, and ω is the angular velocity in rad/s.

$$TSR = \lambda = \frac{\omega \times D}{2v} \tag{10}$$

2.4.9 Moment coefficient (C_m)

The moment coefficient is the rasio between the torque generated by the rotor and the torque value that occurs when water hits the rotor [28]. T is torque in Nm, ρ is density of water in kg/m^2, A is channel cross-sectional area in m^2, D is rotor diameter in meters, and V is water speed in m/s.

$$C_m = \frac{T}{\frac{1}{4}\rho\ A\ D\ v^2} \quad (11)$$

2.4.10. Power coefficient (C_p)

The power coefficient is the rasio value between the power produced by the generator and the power possessed by the water passing through the rotor [29]. P_{gen} is generator power in watt and P_{water} is water power in watt.

$$C_p = \frac{P_{gen}}{P_{water}} \quad (12)$$

2.5. Design

2.5.1. Rotor design Savonius underwater series with a horizontal axis

The design process begins with conducting a location survey in the Bulutana irrigation canal, Gowa, to find out how much discharge and water flow velocity is so that it can determine the design power of the underwater Savonius rotor series with the horizontal axis. Figure 4 shows the dimensions of the irrigation canal. A simple float method is used to measure the speed of irrigation canals, namely by flowing an object floating on the water with a path distance of 1 meter. Then calculate the time it takes for the thing to get from the starting point to the ending point. This experiment was carried out three times, shown in Table 1. From the measurement data using the simple float method, the average time required can be show in Table 2.

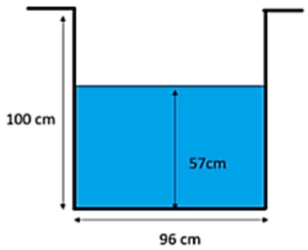

Figure 4. Dimensions of irrigation canals

Table 1. Measurement of water flow velocity using the float method

Test	1	2	3
Time (s)	2.15	1.49	1.87
Distance (m)		1	

Table 2. Result average time and flow velocity

Average Time	Flow Velocity
t = $\frac{t_1+t_2+t_3}{amount\ of\ data}$	v = $\frac{s}{t}$
t = $\frac{2.15 + 1.49 + 1.87}{amount\ of\ data}$	v = $\frac{1m}{1.84s}$
t = 1.84s	t = 0.54 m/s

The underwater Savonius rotor series design with a horizontal axis is carried out by theoretical analysis of the calculation of discharge, water power, turbine diameter, and the resulting turbine power. Based on literature studies and design assumptions, the following are the variables for designing the underwater Savonius rotor. Water flow rate (v): 0.54 m/s and water depth (a): 0.57 m. Based on the parameter calculation results, the results of the series underwater Savonius rotor design with a horizontal axis for power generation can be seen in Table 3.

Table 3. Design results of the underwater Savonius rotor series with the horizontal axis

No.	Design Data	Information
1	Frontal cross-sectional area	0.375 m^2
2	Hydraulic Power	29.52 watts
3	Turbine Diameter	0.5 m
4	Generator Capacity	300 watts
5	Rotor Material	Galvanized
6	Turbine Efficiency	75%
7	Planned Power	22.14 watts

2.5.2. Test line diagrams

Figure 5 shows a diagram of the testing process carried out. The generator is coupled with two pulleys with a transmission ratio of 7:2. There are two measuring instruments on the shaft: digital scales to measure load and a tachometer to measure rotation.

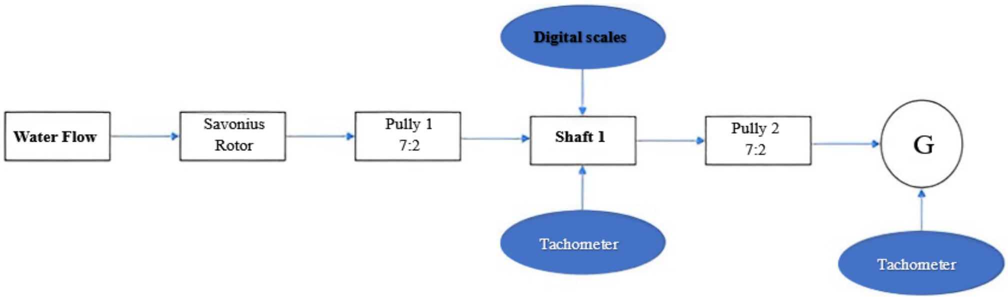

Figure 5. Line diagram of the underwater Savonius rotor in series with the horizontal axis

3. RESULTS AND DISCUSSION

The Savonius rotor with a horizontal axis is a device that converts the kinetic energy of water into rotational motion energy on the turbine shaft. The impulse reaction produces a torsional moment on the blade shaft, which causes the runner to rotate and continue to rotate as long as the water is flowing. The constructions for the underwater Savonius rotor series with a horizontal axis are hollow iron size 3 cm x 3 cm, pulley size 7" and 2", belt sizes A 51 and A 52, and type permanent magnet generator. The physical form of the series underwater Savonius rotor with the horizontal axis that has been made is presented in Figure 6. Tables 4-6 shows the data obtained from the tests carried out.

Figure 6. Construction result for series underwater Savonius rotor with horizontal axis

Table 4. The Savonius rotor torque test

Load (kg)	Transmission Round 1	Turbine Rotation (rpm)
1	210.7	58.5
2	195.9	54.4
3	179.5	49.9
4	161.3	44.8
5	154.7	43.0
6	142.4	39.6
7	133.5	37.1
8	119.2	33.1
9	107.8	29.9
10	92.9	25.8
11	81.2	22.6
12	73.4	20.4
13	66.8	18.6
14	60.1	16.7
15	53.5	14.9
16	29.1	8.1
17	0.0	0.0

Table 5. The Savonius rotor test without load

Generator		T_{Speed} (Rpm)
Speed (Rpm)	V (V)	
580	22.5	44.75
595	24.2	46
612	25.6	47.2

Table 6. The Savonius rotor test with load

Load (watt)	T_{Speed} (rpm)	Generator Speed (rpm)	V (V)	I (A)
10	33.7	437	13.86	0.5
20	32.48	421	12.2	0.75
30	31.17	404	11.6	0.77
40	30.7	398	11.4	0.77
50	30.32	393	11.3	0.77
60	30	390	11.1	0.79
65	30	390	11.1	0.79
70	29.78	386	10.2	0.79

Based on the test results in Tables 4-6, data processing can be carried out based on (3) to (12). The following section discusses the results of data analysis. Based on Figure 7, it is known that the amount of torque affects the number of rotations of the rotor. The maximum torque occurs at a loading of 17 kg, where the rotor stops rotating with a torque of 6.35 Nm. The minimum rotor efficiency of 18.84% occurs at a load of 1 kg with a rotor rotation of 58.5 rpm and a torque value of 0.37 Nm. At the same time, the efficiency of the rotor reaches a maximum point of 86.73% at a loading of 9 kg with a rotation of 29.9 rpm and a torque value of 3.36 Nm. After loading 9 kg, the efficiency of the rotor decreased due to the increased loading with constant water power.

Based on Figure 8, it is known that the amount of loading affects the rotational speed of the rotor. When loading with a light load, the turbine rotation decreases as the load increases. The maximum rotation of the rotor is 33.7 rpm at a load of 10 watts and reaches a minimum rotation of 29.78 rpm at a load of 70 watts. Based on previous research, at a load of 10 watts, the rotor rotation produces 32.59 rpm. Meanwhile, based on our research with the same load, the resulting rotor rotation was 33.7 rpm. This means that there is an increase in rounds of 3.28%. Based on Figure 9, it is known that loading affects the energy produced by the generator. From a load of 10 watts to 20 watts, power is significantly increased by 24.26%. Meanwhile, at a load of 20 watts to 65 watts, the generator power tends to be constant and decreases by 8.1%. The increasing load causes this with continuous water power.

Based on Figure 10, it is known that the tip speed ratio affects the value of the torque coefficient. The value of the torque coefficient increases as the TSR value decreases. The TSR value decreases with increasing load and vice versa. The value of the torque coefficient increases with increasing load. However, at a load of 70 watts, the value of the torque coefficient has decreased due to the reduced power generated by the generator. The highest TSR value of 1.33 occurs at the lowest torque coefficient value of 0.214. Based on Figure 10, the system's efficiency tends to increase to the maximum point and will decrease as the TSR value increases. System efficiency reaches its highest point, 75.3%, at a 20-watt load, with a TSR value of 1.285. Then the system efficiency decreased to 66.3% at a load of 70 watts with a TSR value of 1.178. The system efficiency decreases because the load continues to increase with constant water power.

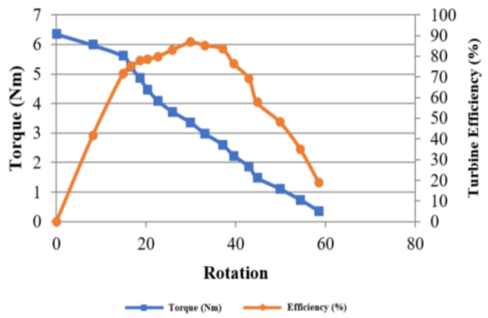

Figure 7. The relationship between rotation, torque, and turbine efficiency

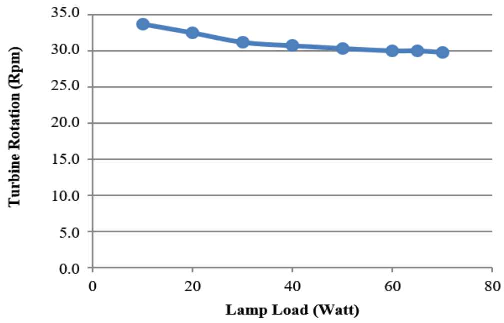

Figure 8. The relationship between lamp load and rotor rotation

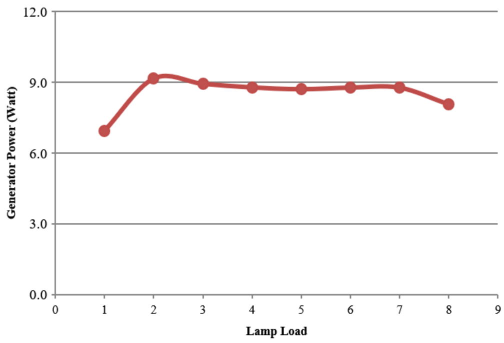

Figure 9. The relationship between lamp load and generator power

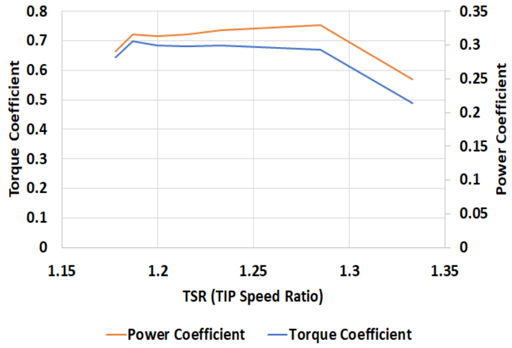

Figure 10. The relationship between the tip speed ratio with the torque and power coefficient

4. CONCLUSION

The series underwater Savonius rotor design results with a horizontal axis have been built and tested. The design results consist of several parts, namely the frame, shaft, rotor blades and deflectors, with a rotor blade diameter of 35 cm and a turbine length of 70 cm. Based on the research results on the Savonius underwater series rotor with a horizontal axis, the highest efficiency value for the rotor was obtained at 86.73% with a torque value of 3.36 at a turbine speed of 29.9 rpm. This indicates that the tool can generate large torque at low rates. Based on the study's results, it was found that the no-load generator voltage generated by the series underwater Savonius rotor after being transmitted is 25.6 V when the turbine only rotates at 47.2 rpm. In contrast, when the condition is loaded, the average power that can be generated is 8.5 watts with a moderate -average turbine speed of 31 rpm.

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