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Experimental Investigation of the Savonius Turbine for Low-Speed Hydrokinetic Applications in Small Rivers

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ABSTRACT

The current study aims to investigate the power performance of 2-bladed and 3-bladed Savonius turbine rotors in a water channel to simulate a low river flow speed. The results were compared to those obtained in a wind tunnel under the same dynamic flow conditions. The comparison was made to determine the turbine characteristics in terms of their power performance when operating in different fluid mediums. The Reynolds number was set to 90200 in both cases, corresponding to an equivalent water flow speed of 0.59 m/s and a wind speed of 10 m/s, respectively. The low water flow speed tested in the water channel represents a narrower and shallower river, commonly found in rural areas of developing countries. The maximum C_P obtained in the water channel was 0.0070 for the 2-bladed rotor and 0.0053 for the 3-bladed rotor at λ = 0.16, respectively. The difference in maximum C_P obtained in the water channel compared with the wind tunnel was 5.7% for the 2-bladed rotor and 22% for the 3-bladed rotor, respectively. Despite being tested in different fluid mediums, the turbines in this study performed similarly, with the 2-bladed rotor outperforming the 3-bladed rotor. The results show that the turbine's performance is independent of fluid mediums, as both have demonstrated a similar trend. Therefore, the results for the turbine tested in wind or water medium should be applicable in both conditions and can be used in a practical application.

1. Introduction

The increase in atmospheric carbon dioxide emissions has posed a global threat to climate change, and with rising fossil fuel prices resulting from the recent COVID pandemic, the demand for other alternative energy resources is increasing significantly [1]. Renewable energy has the greatest potential to become a practical alternative solution among various energy resources because it reduces greenhouse gas emissions, is abundant around the world, cheap, and has the potential to reduce fuel prices [2]. For example, renewable energy-based hydropower technology is more sustainable due to its availability, efficiency, environmental friendliness, and independence from unpredictable weather conditions [3]. As hydropower is primarily based on the energy extracted from

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water, its implementation can help reduce the amount of energy used to burn fossil fuels, and thus, reduce the threat of climate change.

However, conventional hydropower plants are huge and require extensive land modification, causing additional environmental damage [4]. In comparison to hydropower, hydrokinetic technology is a more environmentally friendly solution because it does not require land clearing to build the hydropower plant. Hydrokinetic turbines work by manipulating the energy from the velocity of flowing water rather than the potential energy contained in a reservoir. Hydrokinetic turbines have a lower environmental impact, take up less space, and have a lower initial startup cost than hydropower [5].

Hydrokinetic turbines are classified into two types: horizontal axis (parallel flow) and vertical axis (perpendicular flow). Horizontal axis turbines operate at a higher rotor speed, and they perform best in ocean applications with strong currents. On the other hand, vertical axis turbines are preferable in areas with shallower and slower water currents, such as rivers or smaller channels [6]. The implementation of vertical axis hydrokinetic turbines (VAHT), particularly in rural and underdeveloped areas, is quite challenging due to a lack of research on their technical, economic, and environmental benefits [7]. Researchers have been investigating various design modifications to improve the turbine's performance. The complexity of the VAHT turbine is typically increased by the design, increasing the overall cost of turbine operation. This turbine is more difficult to manufacture and less practical for low-power output requirements. On the other hand, the Savonius hydrokinetic turbine (SHT) is a simple turbine comprised of two or three vertical blades (semi-circular shape, S-curve configuration) that operate on the drag force principle. It is powered by the difference in forces applied to each of the rotor blades. As it moves along the advancing blade and against the returning blade, the half-cylinder with the concave side facing the stream will experience more drag force. The difference in net drag forces causes the Savonius turbine to spin and rotate, which can then be converted to mechanical and electrical power [8]. The overall working principle of SHT is shown in Figure 1.

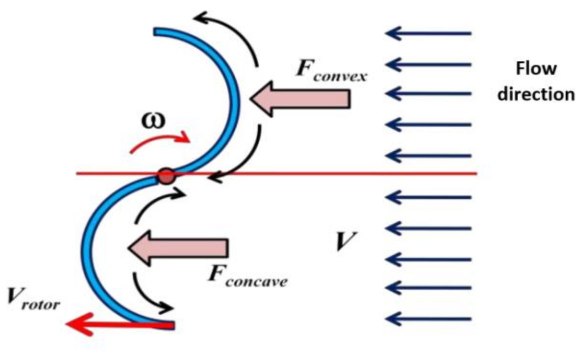


Fig. 1. Schematic diagram of the drag forces exerted on two blades Savonius rotor [8]

The Savonius power performance is generally lower than the rest of VAHT. This is because some of the torque generated on the advancing side of the turbine's blade was used to overcome the drag force on the returning side. As a result, the turbines extract much less current power than other similarly sized lift-types (i.e. Darrieus turbine). However, the SHT has the advantages of self-starting capability, simple design, and low maintenance [9]. Additionally, it is also independent of the wind direction and has a high starting torque at relatively low wind speeds [9]. The application of SHT is promising particularly in areas with low wind and water current velocity, such as Malaysia, Indonesia and South Africa [1,2].

Numerous studies on SHT rotors have been conducted to date, covering a wide range of aspects. For example, Alipour *et al.,* [10] investigated the effects of a newly proposed Savonius hydrokinetic turbine with a parabolic blade shape with a specific design configuration. The study was conducted numerically, and the results indicated that the power coefficient, C_P had increased by up to 12% increment in comparison to the conventional design. Mosbahi *et al.,* [11] conducted another study in which they utilized a helical Savonius turbine with a deflector system comprised of an airfoil and a converging wall. The deflector system managed to increase the C_P value to around 0.14, which was approximately 40% higher than the value obtained without the deflector system. Song *et al.,* [12] investigated the performance of a diffuser-augmented micro-hydro turbine using both numerical and experimental methods. The computational analysis was carried out using a Reynolds-Averaged Navier Stokes (RANS)-CFD model, while the experimental test was performed using open-air towing tank facilities. The experiment was conducted at a water stream velocity of 1.50 to 2.75 m/s, and the results verified the accuracy of the experimental and numerical simulation with an average deviation of 6%. In addition, Kothe *et al.,* [13] investigated the power performance of the Savonius turbine using numerical and experimental simulation. They used a wind tunnel facility to determine the performance of the turbine. According to their findings, the experimental and numerical simulations differed by 2.3% and 12.5% for torque and power coefficients, respectively.

Additionally, there are a variety of parameters that affect the performance of SHT rotors. These parameters include the blade aspect ratio, end plate, gap ratio, multi-staging, number of blades, and the effect of a counter-rotating rotor [14-16]. Regarding the impact of the number of blades, a few relevant studies have been conducted in the last few years. For example, Salleh *et al.,* [17] conducted an experimental evaluation to investigate the effect of a deflector on a conventional Savonius turbine with 2 and 3-bladed rotors. The coefficient of power was determined experimentally using a wind tunnel facility, and the results indicated that the 3-bladed configuration performed worse due to the cascading effect caused by the flow induced by the extra blade. Talukdar *et al.,* [18] examined the effects of a 2 and 3-bladed Savonius rotor consisting of various blade shapes and configurations. They conducted both a simulation and an experimental study using ANSYS-FLUENT software and a water flume channel. Their findings suggested that the 2-bladed semi-circular SHT, with an aspect ratio of 0.7 and overlap ratio of 0.15 produced the highest power coefficient, C_P. Saha *et al.,* [19] investigated the aerodynamic performance of Savonius turbine with one, two and three stages rotors. A total of 14 different types of wind rotors were investigated and the results indicate that the Savonius rotor with 2-stage and 2-blades produces the highest power coefficient. Another study by Halmy *et al.,* [9] corroborated Saha's findings, confirming that the 2-stage and 2-bladed rotor produced the highest C_P.

It is evident from these references that the study on the number of blades had already been addressed. However, these studies were typically conducted at high Reynolds number conditions (higher than Re = 100,000), which is not representative of the typical river stream conditions found in tropical countries such as Malaysia (with a river speed of approximately 0.5 - 0.6 m/s [1]). There are also other studies that compare various performance-extracting methods (i.e., numerical calculation, CFD simulation, wind tunnel data, and water flume data), where each method has its own distinct advantages. However, there is still a limited investigation into possible discrepancies between wind and water tunnel data. The discrepancies between the two experiments would limit the applicability of the data, particularly for any implementation in hydrokinetic applications that requires the use of two different mediums. As such, the main aim of this study is to evaluate the power performance of a basic, low aspect ratio (to fit the size of a small river commonly found in the rural areas), no endplate Savonius turbine in a low-velocity water channel. The results were then compared to wind tunnel data from Salleh *et al.,* [17], in which the Reynolds number was set to be

90200, corresponding to wind and water velocity of 10 and 0.59 m/s, respectively. The experimental results will be useful in predicting the performance and implementation of a Savonius turbine with a low aspect ratio, particularly at low speed and shallow river conditions.

2. Experimental Setup and Procedure

2.1 Water Channel

The experiment was conducted in a closed-loop mini water channel with a maximum height of 0.3 m and an overall perimeter of 4.5 m. A water propeller was used to control the speed of the water flow inside the water channel (12V-300W maximum power). The overall diagram of the water channel is shown in Figure 2. The experimental data from the water channel was then compared to the experimental data obtained from the wind tunnel conducted by Salleh *et al.,* [17]. A comparison of the geometric configurations of the water channel and wind tunnel is shown in Table 1.

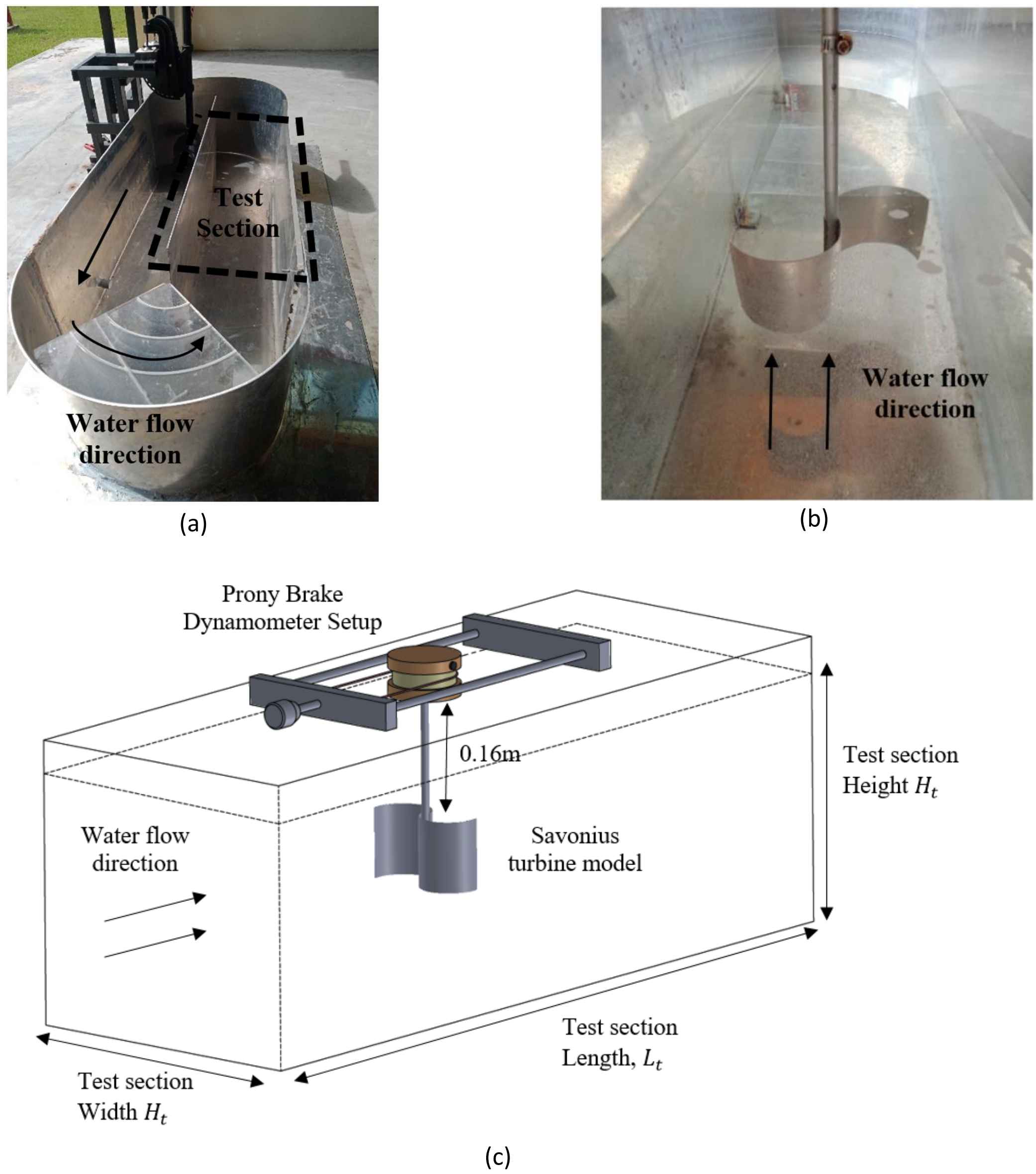


Fig. 2. Graphical illustration of the (a) water channel, (b) Savonius rotor in the water channel, and (c) experimental setup with the Prony brake located on top of the test section

Table 1
Geometric configurations of the water channel and wind tunnel

	Test section Length (m)	Test section Height $H_t(m)$	Test section Width, $W_t(m)$	Rotor aspect ratio	Blockage ratio
Water Channel	1.15	0.28	0.20	0.64	0.270
Wind Tunnel [17]	1.80	0.80	1.00	0.64	0.016

In the water channel system, a strong sidewall effect was expected to occur due to the small width-to-depth ratio of the test section area. Additionally, the incoming flow could be highly asymmetrical as a result of the sharp round-edge corner immediately after the test section area. The curvature may induce secondary flow, which disrupts the flow structure at the rear part of the turbine. Although the secondary flow is more pronounced in bends, Blanckaert [20] asserts that the magnitude of the secondary flow, energy losses, and turbulence do not increase proportionally to the curvature ratio, H/R. In other words, the curvature effect has a saturation point at which the magnitude of these parameters would no longer result in any significant increase. In terms of the influence on the turbine performance, a study by Guo *et al.,* [21] discussed the effect of a rear deflector, which resembles the round-edge wall in the current study. Their findings indicated that the presence of the rear deflector could have both positive and negative effects, with the latter occurring in the majority of cases. The maximum decrement in terms of power coefficient was estimated to be around 10% for various deflector configurations. The minimal decrement due to the rear deflector indicates that even if secondary flow occurred, it would have a minimal effect on the turbine C_P. For such reason, this effect would be considered insignificant and thus ignored during the experiment.

Note that the initial purpose of the water channel system was to provide a continuous stream of water current that replicated the conditions of an actual river stream. The design of the water channel was constrained by the cost and manufacturing capabilities, which hinders any major modification in the future. Regardless, the incoming flow was conditioned so that the experiment could only be conducted when there was no observable backflow. A blockage correction was also applied to minimize the blockage effect, and the variation in the incoming flow velocities was limited to less than 10% to ensure uniform flow.

2.2 Savonius Rotor Model

The experiment was conducted using a Savonius rotor with 2 and 3 blades. The rotor’s blade and shaft were made of Aluminum with a thickness of 1 mm, a height of 0.09 m, a diameter of 0.14 m, a central shaft diameter of 0.01 m, and an aspect ratio of 0.64. The Savonius configuration was fixed in comparison to the conventional Savonius rotor used by Salleh *et al.,* [17], who used an aluminum-based turbine with low cost and ease of fabrication. The low aspect ratio was chosen primarily for the current study’s intended application for electrification in rural and underdeveloped areas. According to a study published by Gasim *et al.,* [22], Sungai Pahang, the longest river in Malaysia, has an average depth to width ratio of 0.03. The low depth-to-width ratio indicates that a low aspect ratio turbine will be more practical and efficient at maximizing power output, as more turbines can be fitted into a given cross-sectional area. The aspect ratio of the turbine was fixed to AR=0.64, and the overall dimensions of the rotor are shown in Figure 3. No endplate was used for the rotor configuration, and the blade was mounted 0.16 m from the top of the test section area.

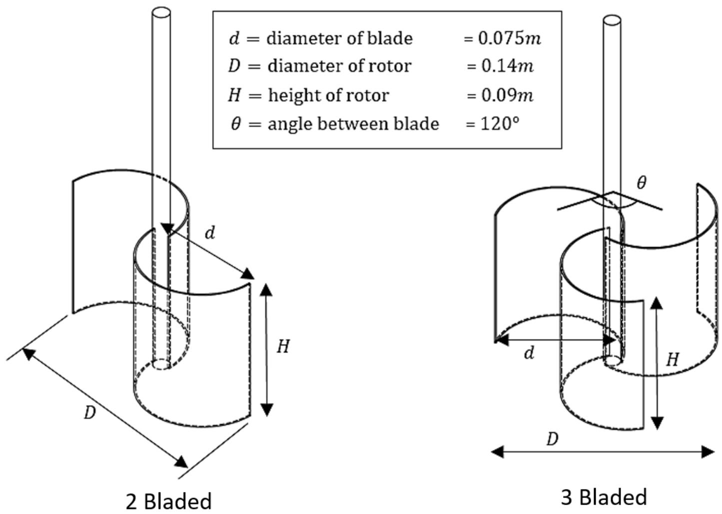


Fig. 3. Overall dimension of the Savonius rotor

2.3 Torque and Power Measurement

In general, the hydrokinetic turbine generates mechanical power by converting the kinetic energy of the water stream. Eq. (1) can then be used to calculate the mechanical power produced by the rotor by measuring the torque and angular velocity. The mean torque (T) was measured in this study using the Prony brake dynamometer setup, as illustrated in Figure 4. Two compression-tension load cells (±0.02% full-scale accuracy) were connected to a traction rope coiled around the radius of the pulley in the Prony brake dynamometer setup. The mean torque was calculated by comparing the readings from load cells 1 and 2. All measurement devices were calibrated before the experiment to ensure the reliability and accuracy of the data measured.

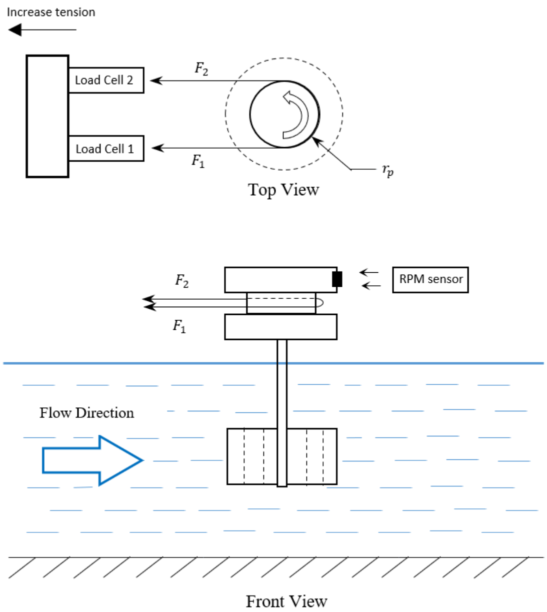


Fig. 4. The Prony brake dynamometer setup. F_1 and F_2 is the force due to the tightening of the traction rope, while r_p is the radius of the pulley

2.4 Water Flow Speed Measurement

The water flow speed in the channel was measured using an L300 A-type Current Flow Meter (±1.5% full-scale accuracy). The experiment was conducted at a Reynolds number of 90200, which corresponds to a water speed of 0.57 m/s and a wind speed of 10 m/s. The operating condition was chosen based on the typical range of river currents in rural areas of developing countries for hydrokinetic turbine applications, which is between 0.5 and 0.6 m/s [1,2].

2.5 Angular Velocity Measurement

The mean angular velocity of the pulley was measured by using an inductive proximity sensor (±0.05 full-scale accuracy). The sensor detected the presence of a magnet attached to the pulley and then measured the time it took for the pulley to complete a single rotation. The sensor and load cells were all connected to a central display unit, which measured and analyzed the instantaneous angular velocity and force. The overall experimental setup is shown in Figure 5.

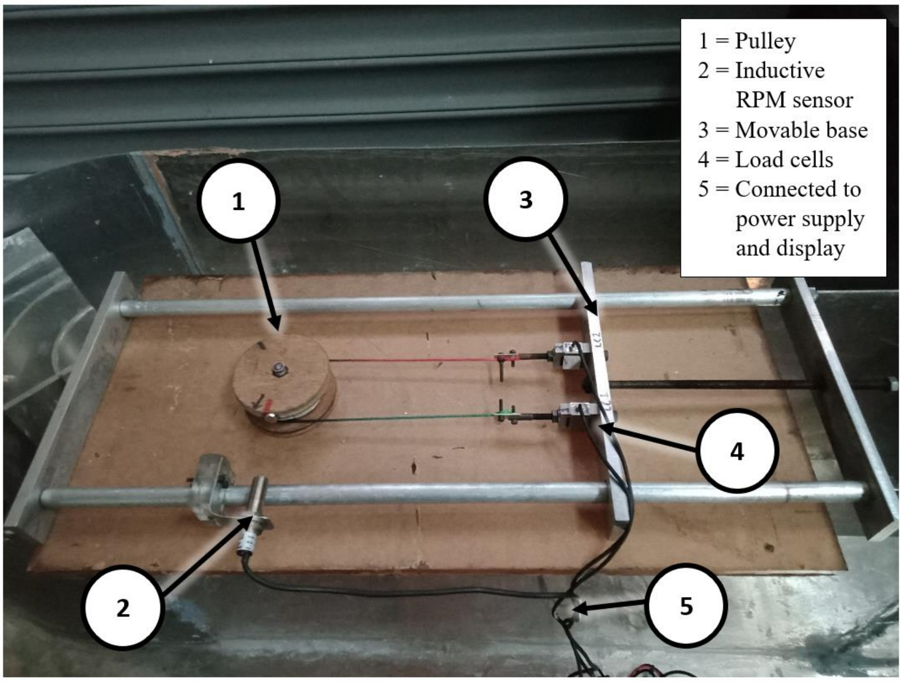


Fig. 5. The experimental setup of the Savonius rotor using the Prony brake dynamometer

The rotor was initially allowed to rotate during the experiment at its maximum rotational speed, also known as the ‘zero load condition’. The rotor load was gradually increased by adjusting the rope tension, decreasing the angular velocity. To ensure a fair comparison with the wind tunnel data from Salleh *et al.,* [17], the loads were increased until the angular velocity reached a similar range of tip speed ratio. The effect of varying the angular velocity on the torque reading was investigated, and the rotor performance was analyzed in terms of C_P and C_T.

3. Equations

The experiment was conducted in a closed-loop mini water channel with a maximum height of 0.3 m and an overall perimeter. The performance of the Savonius turbine model was evaluated in terms of power and torque. The power performance produced by the turbine rotor, P can be calculated using the following equation:

$$P = T \times \omega \tag{1}$$

where T is the torque of the rotor and ω is the angular velocity of the rotor. The T and ω can be determined by:

$$T = \Delta F \times r_p \tag{2}$$

and,

$$\omega = \frac{2\pi}{60} \times RPM \tag{3}$$

where ΔF is the force difference between F_1 and F_2, r_p is the radius of the pulley, and RPM is the revolution per minute of the rotor. The coefficient of power, C_P is the ratio of the mechanical power to the actual current power acquired in the same projected area:

$$C_P = \frac{2P}{\rho HDU^3} \tag{4}$$

where ρ is the density of the free stream medium (air or water), H is the height of the rotor, D is the diameter of the rotor, and U is the free stream velocity. The coefficient of torque, C_T is the ratio of torque generated by the rotor to the available torque from the current in the same projected area:

$$C_T = \frac{4T}{\rho HD^2U^2} \tag{5}$$

The thrust coefficient, C_H is defined as the total thrust force of the rotor per unit of frontal area per unit of incompressible dynamic pressure:

$$C_H = \frac{F}{0.5\rho HDU^2} \tag{6}$$

The tip speed ratio, λ, is the ratio between the tangential speed of the tip of a blade and the actual speed of the current:

$$\lambda = \frac{\omega D}{2U} \tag{7}$$

The Reynolds number is the ratio of the inertial force to viscous force occurring in a fluid flow and is given by the equation:

$$Re = \frac{\rho UD}{\mu} \tag{8}$$

The blockage ratio, BR is defined as the ratio of the turbine's projected area to the projected flow area in the stream channel, and is given by the equation:

$$BR = \frac{HD}{H_t W_t} \tag{9}$$

where H_t and W_t are the height and width of the channel, respectively. In the present study, the relative uncertainty of the Reynolds number, tip speed ratio, coefficient of torque and coefficient of power were 1.1%, 0.42%, 1.98% and 2.02%, respectively.

4. Results and Discussion

The power performance of the Savonius with 2 and 3 rotor blades in a water channel was investigated and compared to that of a wind tunnel under the same dynamic flow conditions. The comparison was made to identify the turbine characteristics in terms of power performance under various fluid mediums. The Reynolds number was set to 90200 in both cases, corresponding to a water flow speed of 0.59 m/s and a wind speed of 10 m/s, respectively.

4.1 Blockage Correction

The performance of the 2-bladed and 3-bladed Savonius turbines in a water channel was investigated and the experimental results were compared to those obtained in the wind tunnel by Salleh *et al.,* [17], using identical rotor geometric configurations and dynamic flow conditions. The torque coefficient (C_T) and power coefficient (C_P) of the rotor are shown in Figure 6 and 7, respectively. The overall results for the rotor tested in the water channel had a large discrepancy and were relatively higher than the wind tunnel experiment. These values have been classified as uncorrected due to the influence of the blockage ratio, which was not considered at the initial stage of the analysis.

The blockage ratio was calculated to be approximately 0.27, which was relatively higher than the blockage ratio for the experimental work conducted in the wind tunnel (0.016). According to Cengel [23], the blockage correction must be implemented if the blockage ratio is greater than 7.5% (0.075). This is because the water channel wall will have an adverse effect on the geometric and kinematic similarity of the tested model, thereby affecting the data and the measurements. A large blockage caused a local increase in velocity near the rotor section, and therefore, a velocity correction was applied to the water channel in the current study. The corrected velocity, V_c was calculated by applying Maskell's method [24]:

$$\frac{{V_c}^2}{U^2} = \frac{1}{1 - mBR} \tag{10}$$

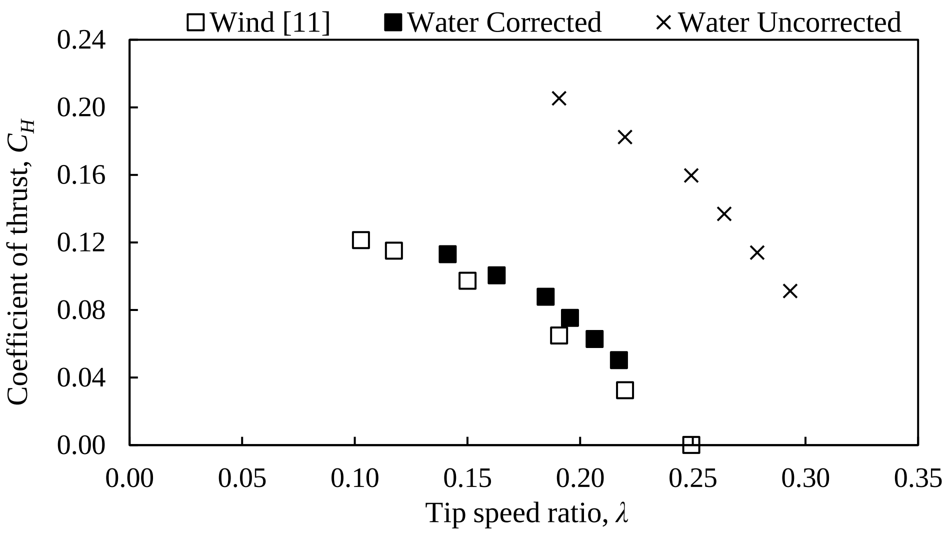
and;

$$m = 8.14BR^2 - 7.309BR + 3.23 \tag{11}$$

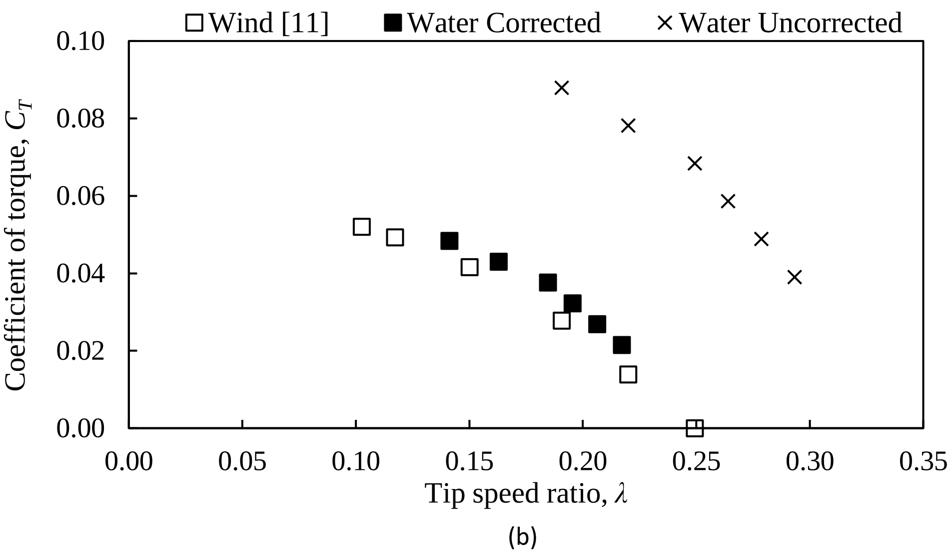
where *m* is the semi-empirical constant.

4.2 Effects of The Fluid Mediums on The Performance of the 2-Bladed Rotor

The comparison results between the water channel and the wind tunnel for the 2-bladed rotor with respect to the coefficient of thrust, C_H and coefficient of torque C_T are shown in Figure 6. The highest thrust and torque coefficients were observed at the lowest range of the tip-to-speed ratio. Some amount of thrust would be used to increase the rotational speed of the turbine, resulting in a lower thrust coefficient at higher λ. Given that torque is essentially a rotational equivalent of linear thrust force, the same pattern applies for both C_H and C_T . The decreasing trend for both C_H and C_T with increasing λ is consistent with previous studies [24,25], where the maximum C_T for the wind and water were recorded at ${C_T}_{max} = 0.467$ at $\lambda = 0.14$, and ${C_T}_{max} = 0.524$ at $\lambda = 0.10$, respectively.



(a)



(b)

Fig. 6. Comparison of the (a) coefficient of thrust, C_H and (b) coefficient of torque, C_T against the tip speed ratio, λ, for the 2-bladed Savonius rotor in the wind and water channel experiment

Overall, the water channel turbine data follows a similar trend to the wind tunnel data, with a slightly higher estimate of $0.14 \leq \lambda \leq 0.22$. While the wind tunnel experiment produced higher torque coefficient values, no data was recorded for the water channel experiment. This was due to the limitation of the turbine in performing efficiently in a water channel at a lower tip speed ratio ($\lambda \leq 0.14$) which will be discussed further in the following section.

The results for the coefficient of power (C_P) against the tip speed ratio λ is shown in Figure 7. For the wind and water, the maximum C_P was recorded at $C_{P_{max}} = 0.0066$ with $\lambda = 0.15$, and $C_{P_{max}} = 0.0070$ with $\lambda = 0.16$, respectively, and the C_P curves followed a similar trend to those reported by [19][18]. The C_P values were found to increase with increasing λ up to λ = 0.14 for wind, and λ = 0.16 for water. Following this point, the C_P began to fall with increasing λ.

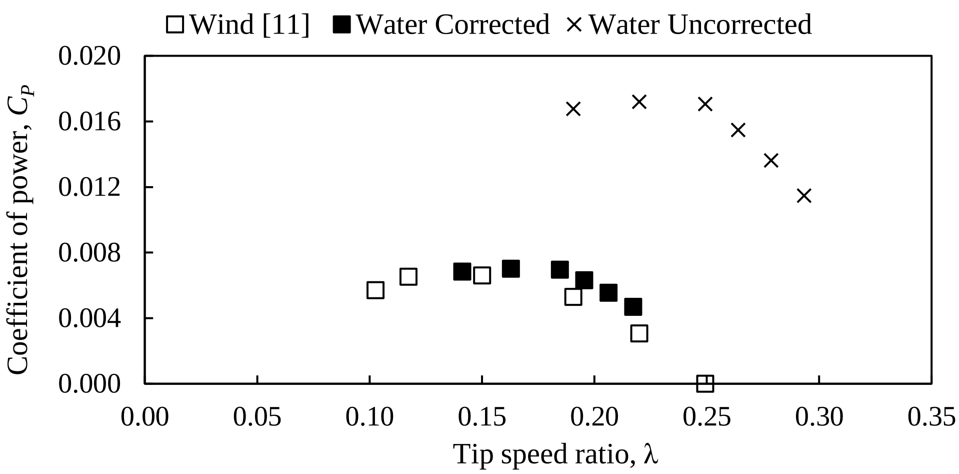


Fig. 7. Comparison of the coefficient of power, C_P against the tip speed ratio, λ, for the 2-bladed Savonius rotor in the wind and water channel experiment

The C_P plot revealed several observations. When compared to the wind, the water experiment was nearly identical at $\lambda \leq 0.15$. Following that, a significant difference in C_P values can be observed between the two cases. The prediction for the wind and water channel plots is comparable to the prediction of C_T discussed previously. The estimation for the water channel experiment was slightly higher than for the wind tunnel experiment. The largest percentage difference was observed between C_T and C_P at approximately 8.1% and 17.4%, respectively. Both experiments demonstrated a similar overall pattern and comparable values up to a certain percentage of differences. However, the slight difference between wind and water tunnel estimations can be attributed to several factors, including water buoyancy, wake generation, wake recovery and dynamic stall [15].

Theoretically, the behavior of the turbine will change as it moves from a higher to a lower density and from a lower to a higher velocity. To discuss the performance of the turbine, it is necessary first to level out the effects of different medium densities. For example, Sarma *et al.,* [15] are among the few researchers who compared the performance of Savonius-type turbines in wind and water channel experiments. Their work is similar to our current work, except for the absence of a 3-bladed turbine and a different normalizing method. They used the same power input to normalize the densities of both mediums, whereas the current study used the Reynolds number. In principle, both methods work by compensating for the difference in density caused by an increase or decrease in the current velocity. However, the increment value will be different because the two methods use different equations. Table 2 highlights the comparison between this work and several other similar works.

Table 2
Comparison of results with the previous studies on the Savonius turbine in wind and water channel experiment

Authors	Turbine type	Results	Remarks
Sarma *et al.,* [15]	Savonius 3 bladed AR = 0.7 Semi-circular No-endplate	The maximum power extracted by the Savonius hydrokinetic turbine (water) was increased by 61.32%. as compared to wind	Evaluation of power generated using water irrigation and wind tunnel testing. Use the same power input to find the equivalent velocity
Koko *et al.,* [26]	Micro-hydrokinetic horizontal turbine (mathematical modeling)	No comparison in terms of performance since the voltage output is fixed. The authors discussed the practicality of water turbines as compared to wind turbines	Use the same power output to find and the wind and water velocity. The dimension of the turbine is then varied based on the available water and wind speed in South Africa
Present study	Savonius 2 and 3 bladed AR = 0.64 Semi-circular No-endplate	The C_T and C_P for water experiment have a higher value of 8.1% and 17.4% respectively as compared to wind	Evaluation of C_T and C_P for 2 and 3 bladed Savonius. Use the same Reynolds number to find the equivalent velocity

The Reynolds number is a dimensionless parameter that quantifies the relationship between inertial and viscous forces [27]. The wind and water channel experiments were conducted at the same Reynolds number in this study. The effect of different medium densities is expected to level out as the medium velocities are varied (refer to Eq. (7)). As a result, the dynamic behavior of the two mediums will be similar. This principle is demonstrated to be valid in actual cases, as a similar pattern for C_T and C_P for wind and water channel experiments has been reported. Accordingly, it is necessary to state that the prediction of a turbine's performance for wind and water channel medium is possible (up to a specific percentage difference), provided that the Reynolds number remains constant.

4.3 Comparison Between The 2-Bladed and 3-Bladed Savonius Turbine

The torque and power coefficients for 2 and 3 bladed rotors are shown in Figures 8 and 9, respectively. The maximum C_T for 2 and 3-bladed rotors was found to be between 0.043 and 0.045. These values are nearly identical, indicating that both rotors have experienced the maximum torque before becoming unable to rotate. However, the 2-bladed was found to have a higher λ than the 3-bladed rotor. The increase in λ value indicated that the 2-bladed rotor had a higher rotational velocity than the 3-bladed rotor at the same load level. As a result, the C_P for a 2-bladed rotor will be greater than for a 3-bladed rotor because power is directly proportional to rotational velocity (refer to Figure 9).

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Volume 94, Issue 2 (2022) 29-46

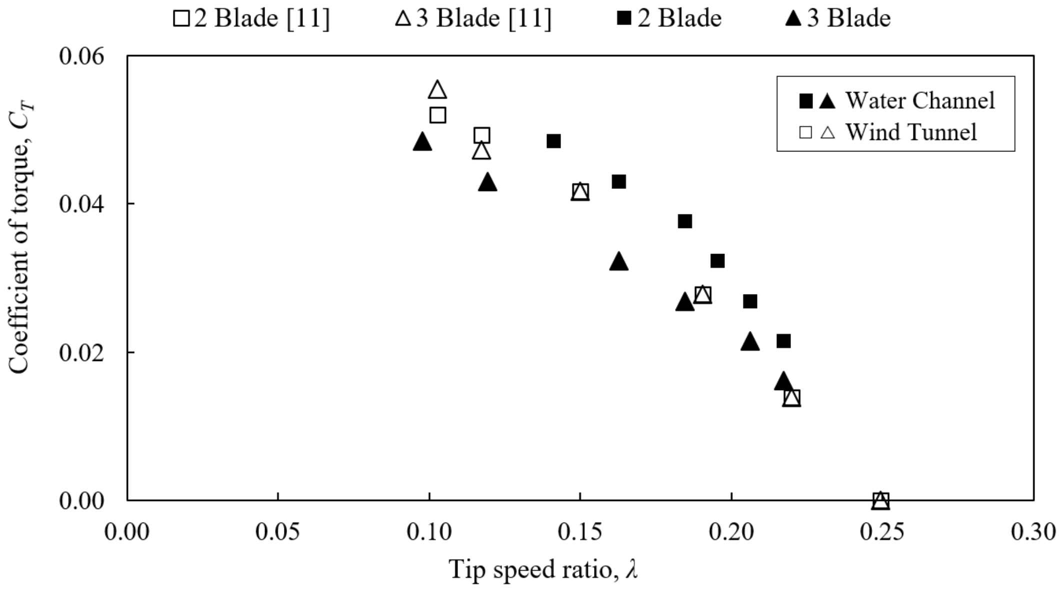

Fig. 8. Comparison of the coefficient of torque, C_T against tip speed ratio, ratio λ for 2 and 3 blade Savonius rotor in wind and water channel

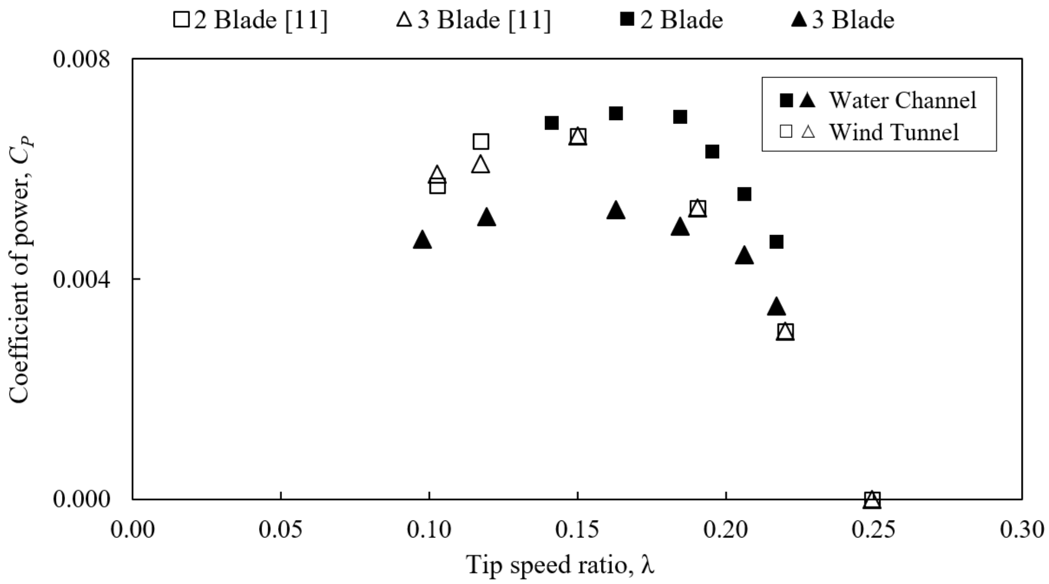

Fig. 9. Comparison of the coefficient of power, C_P against tip speed ratio, ratio λ for 2 and 3 blade Savonius rotor in the wind and water channel

In general, the presence of an extra blade results in one of the following effects; the air that strikes one of the blades (advancing blade) is reflected back on the following blade (returning blade), or the incoming flow that should be focused on the advancing blade is deflected by the succeeding blade, which is then deflected again by the next succeeding blade [17,19]. The reflected flow will oppose the direction of the turbine, whereas the deflected flow will cause a cascading effect in which the flow from each blade is affected by the flow from the previous blade. Both of these phenomena reduce the power output of the rotor, and the effect becomes more pronounced as the number of blades increases (due to the reduced distance between each of the blades).

The results for the current 2 and 3-bladed turbine indicate that the flow physics is similar to those of the conventional Savonius turbine with an endplate and a higher aspect ratio (AR>1) as discussed by Talukdar *et al.,* [18]. Talukdar discovered that the 3-bladed turbine causes an excessive deflection of the water stream, which in turn destabilizes the Coanda-type flow downstream of the advancing blade areas (refer to Figure 10). As a result, the pressure created by the flow increases the pressure in the downstream region, converting less energy into mechanical energy. This phenomenon was reflected in the reduced power and torque coefficients of the 3-bladed turbine, which is consistent with the previous literature.

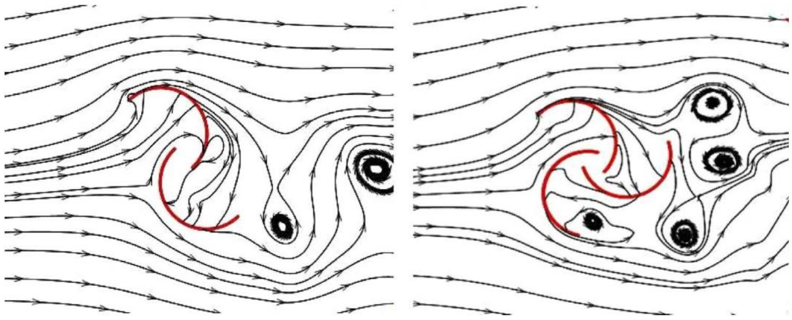

Fig. 10. Streamline pattern of (a) Two-bladed turbine and (b) Three-bladed turbine [18]

Nevertheless, the current experimental work demonstrates a similar pattern with the 3-bladed rotor having a lower C_P than the 2-bladed rotor. The $C_{P_{max}}$ of the 2-bladed rotor is approximately 24.2% higher than that of the 3-bladed rotor. The current study demonstrates that the improved performance of the 2-bladed turbine obtained in the previous study can also be applied to a Savonius turbine without an endplate, low AR, and low Reynolds number. The result is consistent with the result discussed by Salleh *et al.,* [17], who used the same configuration but tested it in a wind tunnel instead of a water channel. The maximum C_P obtained for the 2 and 3 bladed rotors, as well as some other parameters are listed in Table 3.

Table 3
List of $C_{P_{max}}$ values with corresponding λ and C_T values at $\lambda = 0.18$

Test condition	Wind 2-blade [11]	Wind 3-blade [11]	Water 2-blade	Water 3-blade	% Difference 2 Blade	% Difference 3 Blade
$C_{P_{max}}$	0.0066	0.0065	0.0070	0.0053	5.7	22.0
λ at $C_{P_{max}}$	0.15	0.15	0.16	0.16	6.3	6.3
C_T at $\lambda = 0.18$	0.034	0.033	0.037	0.027	8.1	22.2
C_P at $\lambda = 0.18$	0.0057	0.054	0.0069	0.0050	17.4	38.0

From Table 3, the $C_{P_{max}}$ was observed to be relatively low in comparison to the commonly reported values. According to the literature, Savonius turbines have $C_{P_{max}}$ values ranging from 0.020 to 0.40 [1,8,15,18,19,28]. A higher $C_{P_{max}}$ value could not be obtained during his experiment, due to several factors such as the low velocity in the water channel experiment and the absence of the rotor endplate. The use of an endplate will increase the momentum transfer from the current stream, due to the inability of the fluid to overflow from both ends of the Savonius bucket [29]. Note that no optimization of the rotor design was performed, as the primary intention of the current work is to compare the performance of the rotor with those reported previously by Salleh *et al.,* [17].

The rotor was also mounted only on one side, which increased the amount of energy lost due to increased bearing friction and wobbling action. The additional bearing friction was evident when the rotor abruptly stopped from a free rotating position after the flow was stopped, whereas the wobbling was observed during the early stage of the rotor's rotation. The wobbling action was suspected to be caused by an insufficient weight and a less sturdy rotor, as the Aluminium blade was only 1.5 mm thick and the rotor shaft was made using a hollow Aluminium tube. Note that the application of the rotor was intended for rural areas with limited access to electricity, which is why the cost constraint became a major factor. Nevertheless, the $C_{P_{max}}$ values are still comparable to those reported by Salleh *et al.,* [17], who investigated the performance of a Savonius without an end plate using the same exact design.

In addition, it is important to highlight that the turbine rotor was unable to complete a single full rotation in the low RPM cases, i.e., water channel at $\lambda \leq 0.14$. The rotor began to move at one rotor angle and then abruptly stopped as it passed through the other rotor angles. Although the initial starting torque was known to vary with rotor angle [30] [31], the friction force was found to be high in this experiment, as the rotor was observed to rotate freely at the same wind tunnel equivalent λ. Since this was not the case for the water channel experiment, the rotation in the water channel might have been too slow and brief, allowing a large portion of the water energy to pass freely or undisturbed [32]. At low RPM, the rotor will be unable to capture the kinetic energy of the free stream, resulting in a significant decrease in torque generation. The rotor will eventually come to a halt because this torque was insufficient to overcome the initial starting torque required at all rotor angles. This phenomenon explains why the C_T and C_P for a certain range of tip speed ratios could not be determined, as shown in $\lambda \leq 0.14$ for the water channel experiment.

The current λ range for the water channel, however, was sufficient to compare the rotor's performance as the maximum C_P the peak can be seen in the tip speed ratio of $0.14 \leq \lambda \leq 0.17$. Overall, the C_P and C_T plots for this experiment follow a conventional Savonius pattern. The 2-bladed Savonius rotor performed significantly better than the 3-bladed rotor due to the reflected flow impinging on the returning blade and the cascading effect on the flow induced by the extra blade.

5. Conclusions

The performance of a conventional 2 and 3-bladed Savonius hydrokinetic turbine was evaluated in this study using a water channel experiment. The experimental data were compared to wind tunnel data from (Salleh *et al.,* 2020) at a constant Reynolds number of 90200, corresponding to wind and water channel velocity of 10 m/s and 0.59 m/s, respectively. The experimental results indicate that C_T decreases with increasing λ, whereas $C_P$increases with increasing λ up to λ = 0.16 for water. At the same λ range (i.e. $\lambda = 0.18$), the C_T and C_P of the wind and water experiments differ by 8.1% and 17.4%, respectively. The maximum C_P of the 2-bladed rotor was recorded at $C_{P_{max}}$ = 0.0070 which corresponds to λ = 0.16 , while the maximum C_P of the 3-bladed rotor was recorded at $C_{P_{max}}$ = 0.0053 which corresponds to λ = 0.16. The results indicate that the 2-bladed rotor performs better (up to 24%) than the 3-bladed rotor due to the returned flow impinging on the returning blade and the cascading effect of the flow induced by the extra blade.

The current work established that the 2-bladed performed better in terms of C_P and C_T, which applied even when the aspect ratio was low, there was no endplate, and the Reynolds number was low. However, the overall C_P and C_T performance of the current turbine remains lower than the reported values, which can be attributed to the unoptimized turbine and water channel designs that are constrained by cost and manufacturing capabilities. For this reason, the authors would like to highlight several recommendations for future work, including the following:

i. To improve the connection between the turbine shaft and secure it to the top of the test section. Due to the small size of the turbine and its lightweight, it is more likely that the turbine will wobble rather than spin steadily around its axis of rotation. This wobbling can be reduced by anchoring the turbine to the top and bottom parts of the test section or by using a larger turbine with a greater moment of inertia.
ii. To use an endplate for the turbine and replace the turbine shaft with a more solid material. For now, both components were made of aluminum sheet and Aluminum hollow pipe, which were easily bendable as the turbine was subjected to the water stream.

Credit Authorship Contribution Statement

M.Syukri M. Shamsuddin: Investigation, Methodology, Formal analysis, Writing - original draft. Nujjiya A. Mu'in: Investigation, Methodology, Formal analysis. Noorfazreena M. Kamaruddin: Conceptualization, Methodology, Formal analysis, Writing – review & editing, Supervision, Project administration.

Declaration of 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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References

[1] Salleh, Mohd Badrul, Noorfazreena M. Kamaruddin, and Zulfaa Mohamed-Kassim. "Savonius hydrokinetic turbines for a sustainable river-based energy extraction: A review of the technology and potential applications in Malaysia." *Sustainable Energy Technologies and Assessments* 36 (2019): 100554. https://doi.org/10.1016/j.seta.2019.100554

[2] Behrouzi, F., M. Nakisa, A. Maimun, and Y. M. Ahmed. "Renewable energy potential in Malaysia: hydrokinetic river/marine technology." *Renew Sstain Energy Rev* 62 (2016): 1270-1281. https://doi.org/10.1016/j.rser.2016.05.020

[3] Paish, Oliver. "Small hydro power: technology and current status." *Renewable and sustainable energy reviews* 6, no. 6 (2002): 537-556. https://doi.org/10.1016/S1364-0321(02)00006-0

[4] Yah, Nor F., Ahmed N. Oumer, and Mat S. Idris. "Small scale hydro-power as a source of renewable energy in Malaysia: A review." *Renewable and Sustainable Energy Reviews* 72 (2017): 228-239. https://doi.org/10.1016/j.rser.2017.01.068

[5] Güney, Mukrimin Sevket, and Kamil Kaygusuz. "Hydrokinetic energy conversion systems: A technology status review." *Renewable and Sustainable Energy Reviews* 14, no. 9 (2010): 2996-3004. https://doi.org/10.1016/j.rser.2010.06.016

[6] Khan, M. Jahangir, M. Tariq Iqbal, and John E. Quaicoe. "A technology review and simulation based performance analysis of river current turbine systems." In *2006 Canadian Conference on Electrical and Computer Engineering*, pp. 2288-2293. Ieee, 2006. https://doi.org/10.1109/CCECE.2006.277821

[7] Vermaak, Herman Jacobus, Kanzumba Kusakana, and Sandile Philip Koko. "Status of micro-hydrokinetic river technology in rural applications: A review of literature." *Renewable and Sustainable Energy Reviews* 29 (2014): 625-633. https://doi.org/10.1016/j.rser.2013.08.066

[8] Ali, Mohammed Hadi. "Experimental comparison study for Savonius wind turbine of two & three blades at low wind speed." *International Journal of Modern Engineering Research (IJMER)* 3, no. 5 (2013): 2978-2986.

[9] Halmy, Muhammad Syahmy Mohd, Djamal Hissein Didane, Lukmon Owolabi Afolabi, and Sami Al-Alimi. "Computational Fluid Dynamics (CFD) Study on the Effect of the Number of Blades on the Performance of Double-Stage Savonius Rotor." *CFD Letters* 13, no. 4 (2021): 1-10. https://doi.org/10.37934/cfdl.13.4.110

[10] Alipour, Ramin, Roozbeh Alipour, Farhad Fardian, Seyed Saeid Rahimian Koloor, and Michal Petrů. "Performance improvement of a new proposed Savonius hydrokinetic turbine: a numerical investigation." *Energy Reports* 6 (2020): 3051-3066. https://doi.org/10.1016/j.egyr.2020.10.072

[11] Mosbahi, Mabrouk, Ahmed Ayadi, Youssef Chouaibi, Zied Driss, and Tullio Tucciarelli. "Performance study of a Helical Savonius hydrokinetic turbine with a new deflector system design." *Energy Conversion and Management* 194 (2019): 55-74. https://doi.org/10.1016/j.enconman.2019.04.080

[12] Song, Ke, Wen-Quan Wang, and Yan Yan. "Numerical and experimental analysis of a diffuser-augmented micro-hydro turbine." *Ocean Engineering* 171 (2019): 590-602. https://doi.org/10.1016/j.oceaneng.2018.12.028

[13] Kothe, Leonardo Brito, Sérgio Viçosa Möller, and Adriane Prisco Petry. "Numerical and experimental study of a helical Savonius wind turbine and a comparison with a two-stage Savonius turbine." *Renewable Energy* 148 (2020): 627-638. https://doi.org/10.1016/j.renene.2019.10.151

[14] Didane, Djamal Hissein, Muhammad Amir Zafran Saipul Anuar, Mohd Faizal Mohideen Batcha, Kamil Abdullah, Mas Fawzi Mohd Ali, and Akmal Nizam Mohammed. "Simulation study on the performance of a counter-rotating savonius vertical axis wind turbine." *CFD Letters* 12, no. 4 (2020): 1-11. https://doi.org/10.37934/cfdl.12.4.111

[15] Sarma, Neelam K., Agnimitra Biswas, and Rahul D. Misra. "Experimental and computational evaluation of Savonius hydrokinetic turbine for low velocity condition with comparison to Savonius wind turbine at the same input power." *Energy conversion and management* 83 (2014): 88-98. https://doi.org/10.1016/j.enconman.2014.03.070

[16] Guney, Mukrimin Sevket. "Evaluation and measures to increase performance coefficient of hydrokinetic turbines." *Renewable and Sustainable Energy Reviews* 15, no. 8 (2011): 3669-3675. https://doi.org/10.1016/j.rser.2011.07.009

[17] Salleh, Mohd Badrul, Noorfazreena M. Kamaruddin, Zulfaa Mohamed-Kassim, and Elmi Abu Bakar. "An experimental study on the improvement of a 2-Bladed and 3-Bladed conventional savonius rotors with a deflector for hydrokinetic application." *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences* 67, no. 1 (2020): 93-104.

[18] Talukdar, Parag K., Arif Sardar, Vinayak Kulkarni, and Ujjwal K. Saha. "Parametric analysis of model Savonius hydrokinetic turbines through experimental and computational investigations". *Energy Conversion and Management* 158, (2018): 36–49. https://doi.org/10.1016/j.enconman.2017.12.011

[19] Saha, U. K., S. Thotla, and D. Maity. "Optimum design configuration of Savonius rotor through wind tunnel experiments." *Journal of Wind Engineering and Industrial Aerodynamics* 96, no. 8-9 (2008): 1359-1375. https://doi.org/10.1016/j.jweia.2008.03.005

[20] Blanckaert, K. "Saturation of curvature-induced secondary flow, energy losses, and turbulence in sharp open-channel bends: Laboratory experiments, analysis, and modeling." *Journal of Geophysical Research: Earth Surface* 114, no. F3 (2009). https://doi.org/10.1029/2008JF001137

[21] Guo, Fen, Baowei Song, Zhaoyong Mao, and Wenlong Tian. "Experimental and numerical validation of the influence on Savonius turbine caused by rear deflector." *Energy* 196 (2020): 117132. https://doi.org/10.1016/j.energy.2020.117132

[22] Muhammad Barzani, Gasim. "River flow conditions and dynamic state analysis of Pahang River." *American Journal of Applied Sciences* 10, no. 1 (2013): 42-57. https://doi.org/10.3844/ajassp.2013.42.57

[23] Y.A., Cengel. *Fluid Mechanics: Fundamentals And Applications.* Tata McGraw Hill Education Private Limited, 2010.

[24] Patel, Vimal, Ganapathi Bhat, T. I. Eldho, and S. V. Prabhu. "Influence of overlap ratio and aspect ratio on the performance of Savonius hydrokinetic turbine." *International Journal of Energy Research* 41, no. 6 (2017): 829-844. https://doi.org/10.1002/er.3670

[25] Salleh, Mohd Badrul, Noorfazreena M. Kamaruddin, and Zulfaa Mohamed-Kassim. "The effects of deflector longitudinal position and height on the power performance of a conventional Savonius turbine." *Energy Conversion and Management* 226 (2020): 113584. https://doi.org/10.1016/j.enconman.2020.113584

[26] Koko, Sandile Phillip, Kanzumba Kusakana, and Herman Jacobus Vermaak. "Micro-hydrokinetic river system modelling and analysis as compared to wind system for remote rural electrification." *Electric Power Systems Research* 126 (2015): 38-44. https://doi.org/10.1016/j.epsr.2015.04.018

[27] Bachant, Peter, and Martin Wosnik. "Effects of Reynolds Number on the energy conversion and near-wake dynamics of a high solidity vertical-axis cross-flow turbine". *Energies* 9, no. 2 (2016): 1–18. https://doi.org/10.3390/en9020073

[28] Kumar, Anuj, and Rajeshwer Prasad Saini. "Performance parameters of Savonius type hydrokinetic turbine–A Review." *Renewable and Sustainable Energy Reviews* 64 (2016): 289-310. https://doi.org/10.1016/j.rser.2016.06.005

[29] Jeon, Keum Soo, Jun Ik Jeong, Jae-Kyung Pan, and Ki-Wahn Ryu. "Effects of end plates with various shapes and sizes on helical Savonius wind turbines." *Renewable energy* 79 (2015): 167-176. https://doi.org/10.1016/j.renene.2014.11.035

[30] Salleh, Mohd Badrul, Noorfazreena Mohamed Kamaruddin, Zulfaa Mohamed Kassim, and Elmi Abu Bakar. "Influence of a Deflector on a Self-Starting Speed and Power Performance of a Two-Bladed Savonius Hydrokinetic Turbine". *18th International Conference on Sustainable Energy Technologies*, (2019): 1–10.
[31] Kamoji, M. A., S. B. Kedare, and S. V. Prabhu. "Performance tests on helical Savonius rotors." *Renewable Energy* 34, no. 3 (2009): 521-529. https://doi.org/10.1016/j.renene.2008.06.002
[32] Ragheb, Magdi, and Adam M. Ragheb. "Wind turbines theory-the betz equation and optimal rotor tip speed ratio." *Fundamental and advanced topics in wind power* 1, no. 1 (2011): 19-38. https://doi.org/10.5772/731