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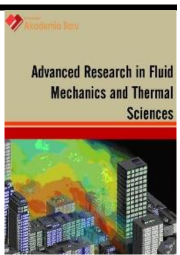

An Experimental Study on the Improvement of a 2-Bladed and 3-Bladed Conventional Savonius Rotors with a Deflector for Hydrokinetic Application

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ABSTRACT

An experimental investigation has been performed to investigate the effect of a deflector on the power performance of a 2-bladed and 3-bladed conventional Savonius rotors which has not been covered in the previous studies. The rotors were tested inside a closed-circuit wind tunnel at 10 m/s of air flow velocity (equivalent to 0.57 m/s of water flow velocity) at a Reynolds number of 90200. Two cases were considered in the investigation: a 2-bladed and 3-bladed rotor, each tested without and with a deflector at an angle (δ) of 60°. The performance of the rotors was analyzed in terms of coefficient of power (C_P) and coefficient of torque (C_T) with respect to the tip speed ratio (λ). Results showed that the presence of the deflector significantly improved the performance of both rotors. Without any deflector, C_P for the 3-bladed rotor was slightly lower than that of the 2-bladed rotor. This reduction is caused by a cascading effect on the flows induced by the extra blade. When augmented, C_P for the 2-bladed and 3-bladed rotors increased by 128.36% and 604.62%, respectively. Such significant improvements, especially on the 3-bladed rotor were attained as the cascading effect on the returning blades reduced. The deflector functioned by shielding the returning blade of the rotor from impinged by the incoming flow. Without any augmentation device, the unobstructed flow would have dragged the blades in the opposing direction and thus reducing the positive torques generated by the rotors. This study highlighted the practicality of using a simple flat deflector as an augmentation device to enhance the power performance of a Savonius rotor for hydrokinetic application.

1. Introduction

Fossil-fuel holds the prime share of global energy production for ages. However, considering the negative impacts of fossil-fuel on the environment and the scarcity of its reserves, many countries around the world are looking for alternative energy resources that are clean, renewable and sustainable [1,2]. Hydro is one of the renewable energy resources besides solar, wind, thermal and biomass that has high potential to be tapped for energy production to solve global fossil-fuel crisis.

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The hydro resource can come in many forms such as ocean, tidal and river. For countries with tropical climate that receive an ample amount of rainfall every year such as Malaysia, there is a large capacity to directly harness clean energy from flowing rivers using hydrokinetic turbines (HKT).

Unlike conventional large hydropower plants, hydrokinetic systems are considered as more sustainable since they do not require the constructions of dams or water reservoirs, which can be damaging to the surrounding ecology and society. Generally, a hydrokinetic turbine shares similar principles to those of a wind turbine, with the exception of the flowing medium. Since water is about 800 times denser than air, a hydrokinetic turbine can produce more power if compared to a similar wind turbine provided there is flowing water [3]. Hydrokinetic turbines have the highest potential to be employed in remote areas for communities living in close proximity to rivers but without access to main electrical grids.

Hydrokinetic turbines can be primarily classified into two depending on their rotational axis: horizontal- or vertical-axis. Horizontal-axis turbines achieve optimal performance at higher rotor speeds, suitable for ocean and tidal applications where the currents are normally high. Vertical-axis turbines, on the other hand, are more suitable for operations under shallow channels or rivers with limited water flow rates [4].

Of the vertical-axis turbines, Savonius rotors can be potentially employed in rivers with low flow rate due to their better self-starting capabilities [5]. Moreover, the rotors have much simpler design than their lift-based counterparts such as the Darrieus turbines that use intricate airfoil profile blade, as shown in Figure 1. Therefore, they offer lower construction and maintenance costs.

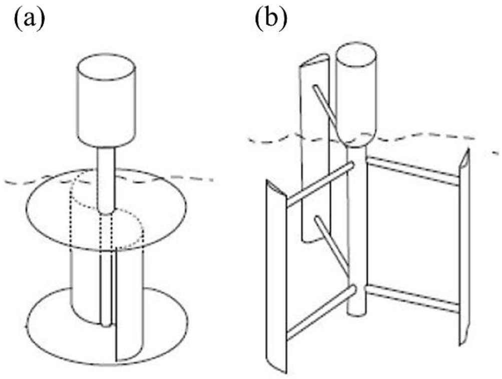

Fig. 1. Vertical-axis turbines (a) Savonius rotors (b) Darrieus turbines [6]

However, the Savonius rotors suffer from poor performance with low coefficient of power, normally less than 0.3 [7]. Due to this fact, various attempts have been made to improve the performance of the Savonius rotors either by altering the geometric configurations of the rotors or employing augmentation techniques. The rotation of a Savonius rotor is primarily driven by drag force produced by the flow that impinges on the rotor blades. A conventional Savonius rotor has semicircular advancing and returning blades where each blade has a concave and convex side as shown in Figure 2.

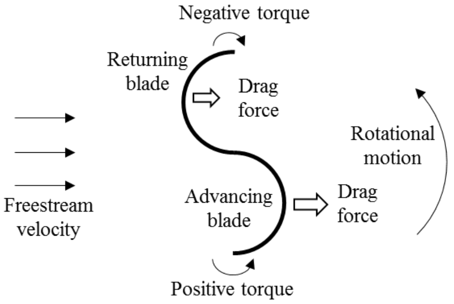

Fig. 2. Drag forces acting on a conventional Savonius rotor blade (top view)

The drag force on the advancing blade concave side generates positive torque that rotates the rotor whereas the drag force on the returning blade convex side generates negative torque that opposes the rotor rotation. The rotor will be able to rotate if there is positive net torque between its blades. Therefore, the performance of the Savonius rotor can be improved if the drag force on the returning blade is reduced. Due to this fact, there are various techniques that have been proposed and investigated to reduce the negative torque on the rotor which consequently improves the performance of the rotor, as depicted in Figure 3.

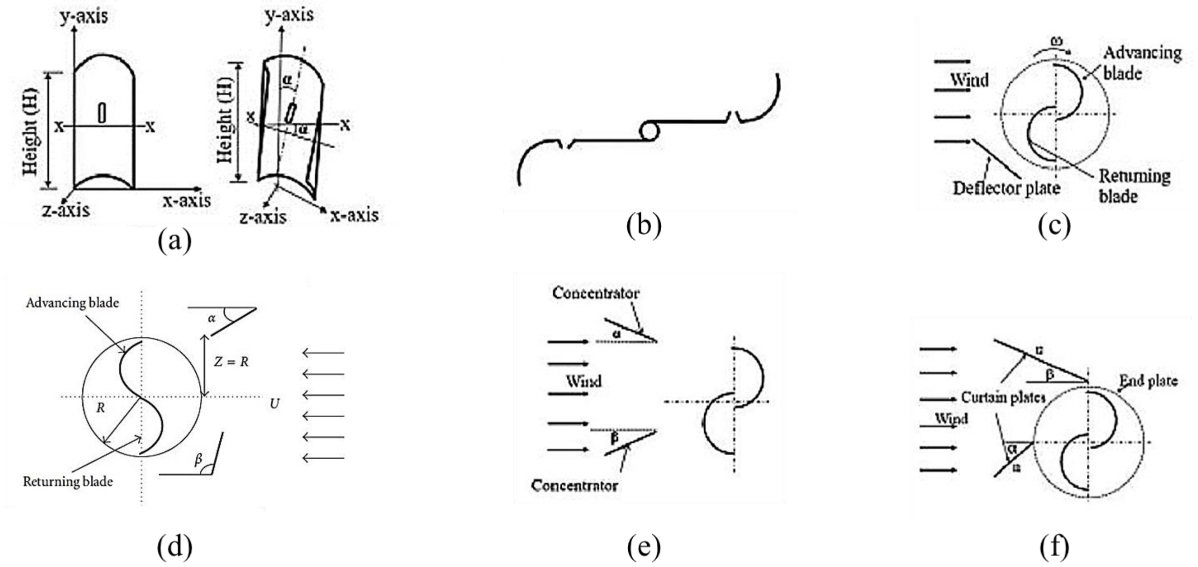

Fig. 3. Various techniques to improve rotor performance (a) valves (b) venting slots (c) deflector plate (d) advancing and returning blade deflectors (e) concentrator (f) curtain plates (modified from [8])

Rajkumar and Saha [9] have incorporated valves, see Figure 3(a), in a twisted blade Savonius rotor simply named as valve-aided twisted Savonius (VATS) where the rotor has been tested in a low speed wind tunnel. In the mechanism of VATS rotor, a small deflecting plate that acts as the valve is hinged on the concave side of the rotor blades in front of a hole. As the convex side of the returning blade advancing towards the incoming free stream, the valve on the concave side of that blade is opened. This action allows the free stream to pass through the blade thus reducing the drag force on that blade. At the same time, the valve on the concave side of the advancing blade is closed as the blade advances in the free stream direction hence increasing the static torque of the rotor. Saha *et al.,* [10] have adopted the same technique where the valve has been incorporated in semicircular and twisted blade Savonius rotors. In their study, two and three semicircular and twisted blades with single, double and triple stages have been tested without and with valve respectively. The two-stages with three twisted blades Savonius rotor with a valve are found to have higher coefficient of power than the rotor without the valve of about 0.3.

Alom and Saha [11] have used venting slots on a 2-bladed semicircular Savonius rotor, a technique similar to Abraham *et al.,* [12] and Plourde *et al.,* [13]. The vent is placed as an opening on the advancing and returning blades of the rotor, see Figure 3(b). It allows freestream to pass thorough the blades in order to reduce the drag force on the returning blade. In their study, three different vent configurations have been considered and numerically tested. It is found that the rotor with vent position located the most further from the rotor center exhibited the highest maximum coefficient of power of 0.292 where it has improved by 7.53% in comparison to the coefficient of power of the conventional semicircular Savonius rotor. The improvement of coefficient of power is fairly low due to the fact that some of the incoming freestream can also pass through the advancing blade hence reduces pressure drag that contributes for the positive torque on the rotor.

A significant improvement on the Savonius rotor performance can be observed with the implementation of augmentation techniques such as deflector and concentrators [8]. Ogawa and Yoshida [14] have performed a wind tunnel experiment to investigate the effect of deflector on the performance of 2-bladed Savonius rotor, see Figure 3(c). In their study, the rotor performance was evaluated at various deflector angles in the range of 30° to 90°, relative to the incoming flow direction. They found that the highest improvement in coefficient of power by 12% can be achieved for 60° deflector angle in comparison to without deflector case. The deflector acts as a wall that shielding the returning blade from being hit by the incoming free stream hence reducing the drag force on that blade. Meanwhile, a study conducted by Huda *et al.,* [15] by using a deflector plate has showed around 20% improvement of coefficient of power relative to the conventional rotor without any deflector plate. Golecha *et al.,* [16] have also performed experimental study on a modified 2-bladed Savonius hydrokinetic rotor with a deflector in an open water channel at Reynolds number of 132000. In their study, 8 configurations of deflector plate have been placed upstream of the returning blade. The found that the deflector angle of 101° produced the best rotor performance in which the maximum coefficient of power of 0.21 can be achieved with relative increment of 50% from the rotor without any deflector plate.

Based on the optimized returning blade deflector configuration, Golecha *et al.,* [17] added another deflector plate upstream of the advancing blade of modified Savonius rotor, see Figure 3(d). In their study, the distance of deflector from rotor center is varied from 1 to 1.8 rotor radius whereas the deflector angle is varied from 15° to 60°. They found the advancing blade deflector located at 1.8 rotor radius and deflector angle of 50° has contributed the highest improvement in coefficient of power by 150% whereas the maximum coefficient of power has increased to 0.35. Roy *et al.,* [18] studied and investigated the performance and starting characteristics of 2-bladed semicircular Savonius rotor by employing two deflectors upstream of the rotor. These deflectors are arranged such that they form a concentrator, see Figure 3(e), that capable to direct or channel the free stream towards the advancing blade, hence, increasing the drag force on that blade. The technique is similar to those of nozzle and curtain plates studied by Shikha *et al.,* [19] and Altan and Atilgan [20], see Figure 3(f). At optimal concentrator configuration, the maximum coefficient of power of 0.32 can be achieved by the rotor where the rotor performance has improved by 47.5% as compared to Savonius rotor without any concentrator.

Previous studies have demonstrated the practicality of deflector as one of the augmentation techniques that contributes to significant improvement in the turbine performance. However, the studies only considered 2-bladed conventional Savonius rotors and for more than two blades case, it has yet to be investigated through experimental study. For instance, previous studies that investigated the effect of deflector on 2-bladed and 3-bladed Svonius rotors as conducted by Mohamed *et al.,* [21] was limited to numerical study with the objective was to obtain optimal deflector configuration for each rotor. Whilst, Wahyudi and Adiwidodo [22] considered a non-conventional four-bladed configuration in their numerical and experimental studies to investigate the effect of moving deflectors.

Therefore, the present study aims to investigate the effect of deflector on the power performance of conventional Savonius rotors with different number of blades with respect to the same deflector configuration. Two conventional Savonius rotors i.e., 2-bladed and 3-bladed rotors have been tested in a closed circuit wind tunnel to investigate the effect of deflector on their power performance for hydrokinetic application. Experimental results in terms of coefficient of power and coefficient of torque are analyzed and compared.

2. Savonius Rotor Models

In this study, a two conventional Savonius rotor models had been tested in a closed-loop wind tunnel, i.e., the 2-bladed and 3-bladed rotors. The rotors had identical dimensions with height (*H)* of 0.09 m and diameter (*D)* of 0.14 thus the rotors had an aspect ratio *(AR)* of 0.64. The aspect ratio of the rotors considered in this study was similar to the 3-bladed conventional Savonius HKT studied by Sarma *et al.,* [23]. The blades of the rotor had a semicircular profile with a diameter (*d)* of 0.075 m and it was made of 1 mm thick aluminium. The blades were fixed on a central shaft of 0.01 m in diameter and it was made of aluminium. For the 2-bladed rotor, the blades were arranged at 180° phase orientation whereas for the 3-bladed rotor, the blades were arranged at 120° apart from each other. The rotors had no endplates (that covered the top and bottom of the blades). Figure 4 shows the Savonius rotors tested in the present study. From the direction of the incoming free stream, the blade with a concave shape is called the advancing blade while the convex shape blade is called the returning blade.

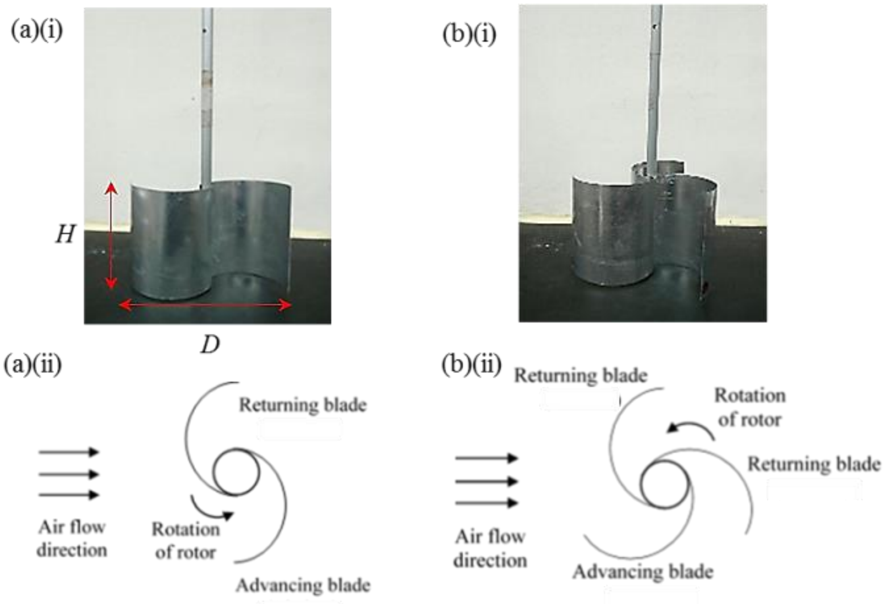

Fig. 4. Savonius rotor models. (a)(i) 2-bladed rotor (side view) and (a)(ii) schematic diagram of 2-bladed rotor (top view), (b)(i) 3-bladed rotor (side view) and (b)(ii) schematic diagram of 3-bladed rotor (top view). *H* is the height of rotor and *D* is the diameter of rotor

3. Experimental Setup

The experiment was conducted in a closed-circuit wind tunnel with a rectangular test section of 1.8 m length × 1.0 m width × 0.8 m height and a contraction ratio of 10:1. The tested model is placed at the centre of the test section where the shaft of the rotor is held by two ball bearings for stability and another end part is attached to a pulley located at the top of the test section as shown in Figure 5. The pulley is attached to a Prony brake dynamometer setup used to acquire dynamic torque.

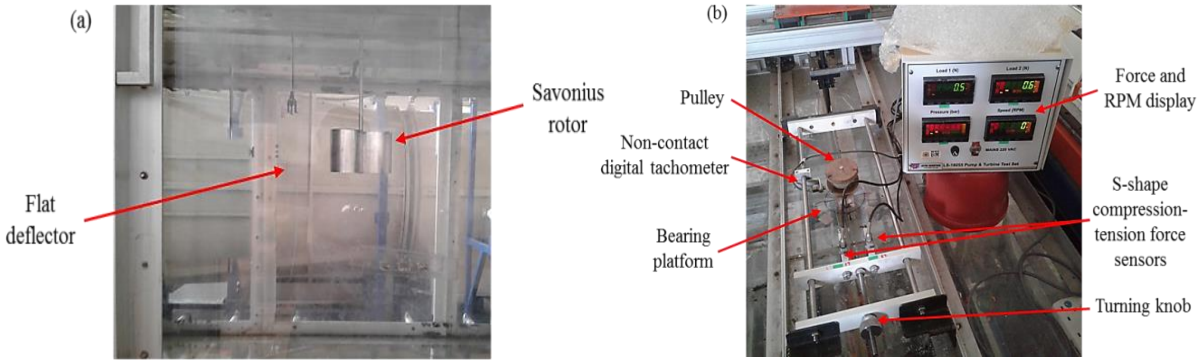

Fig. 5. Experimental setup to study the performance of Savonius rotors (a) Savonius rotor and a flat deflector inside the wind tunnel test section and (b) Prony brake dynamometer setup on top of the test section for torque measurement

3.1 Savonius Rotors with Deflector

A flat deflector made of clear acrylic plate (0.255 m height × 0.15 m width × 0.008 m thick) is placed upstream of the returning blade to investigate the effect of a deflector and its influence on the performance of Savonius rotor. It is longitudinally positioned 0.145 m from the central shaft such that it covered the whole returning blade swept area as shown in Figure 6. The flat deflector is configured such that the angle between the air flow direction and the flat deflector which is defined as deflector angle, δ = 60°. According to Ogawa and Yoshida [14], for a flat deflector laterally positioned close to the centre of the rotor, this deflector angle resulted in the optimal performance of the rotor. Note that for the current study, only one deflector angle was considered since optimization of deflector angle on the rotor performance is beyond the scope of the present work.

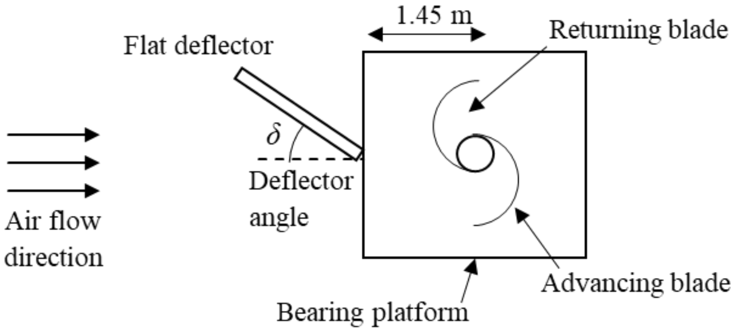

Fig. 6. Flat deflector position upstream of the Savonius rotor (top view)

3.2 Torque Measurement Method

In this study, the performance of the rotor is investigated by acquiring the dynamic torque generated by the rotors using the Prony brake setup located at the top of the test section (see Figure 2). The setup consists of a two S-type tension-compression force sensors (±0.02% full scale accuracy) mounted horizontally on a support rig. The force sensors are attached to a traction belt which is coiled around the pulley. Force measurements acquired by these sensors can be read through a digital display. A non-contact digital tachometer (±0.05% full scale accuracy) is used to measure the rotor rotational speed in revolution per minute (RPM). The RPM reading of the rotor is obtained by shining a laser beam from the tachometer on a reflective tape that is attached to the pulley.

The experiment is conducted at air flow speed, $U = 10$ m/s, with a Reynolds number, *Re* = 90200. These operating condition parameters corresponded to 0.57 m/s of water flow speed which is within the range of water flow speed for river current HKT application [24,25]. First, the rotor is allowed to rotate at its maximum rotational speed known as zero load condition for several seconds until it has reached a steady rotational motion. Then, the rotor is gradually loaded by tightening the traction belt to reduce the rotation of the rotor by 20 RPM interval. As the rotation of the rotor reduced, the force measurement acquired by the force sensors as well as the RPM of the rotor are recorded. Then, the dynamic torque with respect to the rotor rotation is calculated by obtaining the force difference between the force sensors which will be discussed in the next subsection.

3.3 Data Reduction

The torque, T generated by the rotors can be obtained as follows:

$$T = \Delta F \times r_p \tag{1}$$

where ΔF is the force difference between the force sensors and r_p is the radius of the pulley (r_p =0.03 m). The angular speed of the rotor, ω is given by:

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

where RPM is the rotor rotation measured from the non-contact digital tachometer. Then, the coefficient of torque, C_T can be obtained from:

$$C_T = \frac{4T}{\rho H D^2 U^2} \tag{3}$$

where ρ is the density of free stream (air as working medium in this case), H is the high of the rotor, D is the diameter of the rotor and U is the air flow speed. Meanwhile, the coefficient of power, C_P is given by:

$$C_P = \frac{2T\omega}{\rho H D U^3} \tag{4}$$

Based on Eq. (4), the C_P can be improved if T and ω are increased. C_T and C_P are two non-dimensional values commonly use to evaluate the performance of the rotor. These values usually plotted against tip speed ratio, λ where:

$$\lambda = \frac{\omega D}{2U} \tag{5}$$

Other important parameters are the Reynolds number, Re given by:

$$Re = \frac{\rho U D}{\mu} \tag{6}$$

Where μ is the dynamic viscosity of the air and the blockage ratio, *BR* given by:

$$BR = \frac{HD}{H_{WT} W_{WT}} \tag{7}$$

Where H_{WT} and W_{WT} is the height and width of the wind tunnel test section respectively. The blockage ratio was calculated as $BR = 0.016$. Since the blockage ratio was small, it has no significant effect on the coefficient of power of the rotors [24]. Therefore, the blockage correction is not considered in this study.

4. Results and Discussion

In this study, the performance of the 2-bladed and 3-bladed rotors was analyzed for two cases i.e., without and with a deflector (δ = 60°). Figure 7 shows the comparison of the coefficient of power, C_P with respect to the tip speed ratio, λ for the 2-bladed and 3-bladed rotors without and with a deflector, respectively. For all cases, the C_P curves for both rotors show a similar trendline. It is found that the variation of C_P with respect to the λ at first increases up to a maximum value at certain λ and then decreases as the λ increases. The maximum coefficient of power, $C_{P_{max}}$ for the 2-bladed rotor without deflector is 0.0067 at $\lambda = 0.16$. For the 2-bladed rotor with a deflector, $C_{P_{max}}$ increases up to 0.0153 at $\lambda = 0.22$. The presence of a deflector upstream of the rotor significantly improves the C_P of the 2-bladed rotor by 128.36% relative to the case without deflector. Whilst, the C_P curve of the 3-bladed rotor without deflector is marginally lower than that of the 2-bladed rotor of the same case where its $C_{P_{max}}$ is about 0.0065 at $\lambda = 0.12$. With the presence of deflector, the $C_{P_{max}}$ of the 3-bladed rotor is increasing up to 0.0458 at $\lambda = 0.37$ with a significant improvement by 604.62% relative to the case without deflector. The deflector acts as a shielding plate that blocks the incoming air flow from impinging on the returning blade. This reduces the drag force on the returning blade and therefore reduces the power loss due to negative torque that opposes the rotational motion of the rotor which consequently leads to a more efficient power extraction.

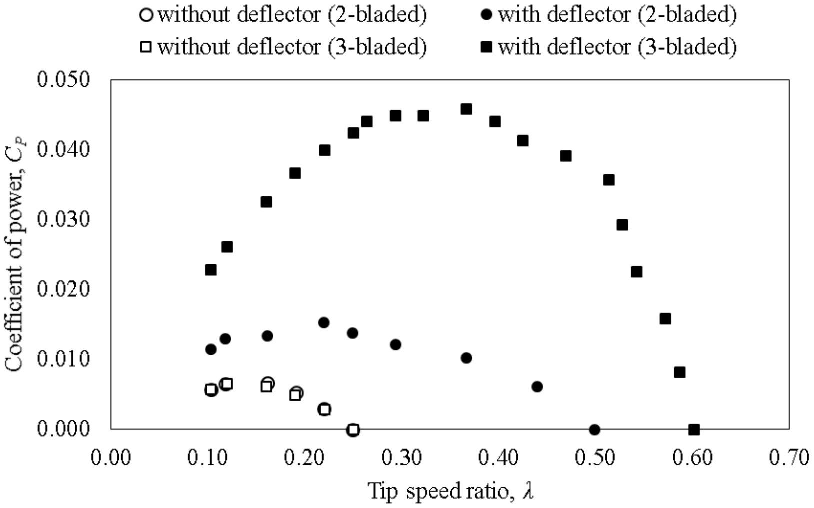

Fig. 7. Comparison of the coefficient of power, C_P against tip speed ratio, λ for 2-bladed and 3-bladed rotors without and with a deflector (δ = 60°)

By comparing the coefficient of torque, C_T against the tip speed ratio curves in Figure 8, it is found that the curves exhibit a similar trend where the C_T decreases with the increment of λ. The C_T curve for the 2-bladed rotor without deflector is slightly higher than that of the 3-bladed rotor of the same case. However, the C_T curves of both rotors with a deflector are significantly higher than the curves without any deflector case at all range of λ. The C_T that corresponds to the $C_{P_{max}}$ of the 2-bladed rotor with a deflector is 1.67 larger than the C_T corresponds to the $C_{P_{max}}$ of 2-bladed rotor without deflector. Whilst, the C_T that corresponds to the $C_{P_{max}}$ of the 3-bladed rotor with a deflector is 2.25 larger than the C_T that corresponds to the $C_{P_{max}}$ of the 3-bladed rotor without deflector. The low value of C_T for the without deflector case is probably because the rotors need to overcome negative torque that opposes the rotation of the rotors due to the drag force on the returning blade. In contrast, the incoming air flow is blocked by the deflector from impinging on the returning blade thus the drag force and the negative torque are reduced. Therefore, more positive net torque can be generated by the rotor which contributes to useful mechanical power.

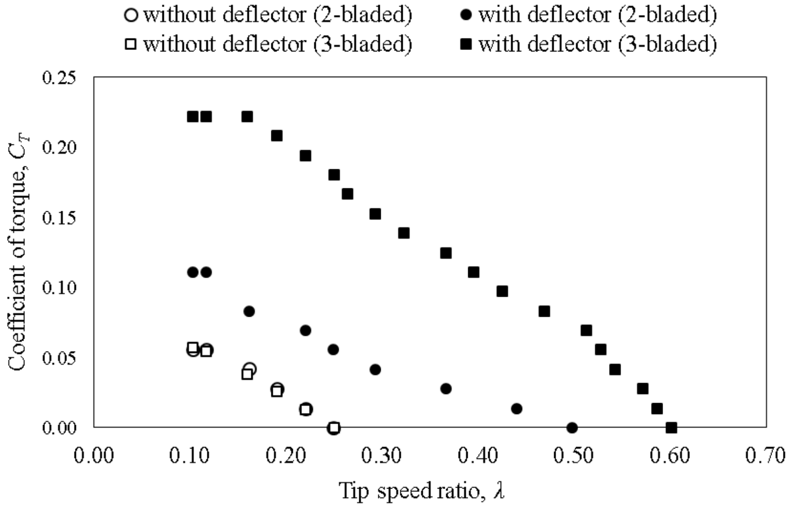

Fig. 8. Comparison of the coefficient of torque, C_T against tip speed ratio, λ for 2-bladed and 3-bladed rotors without and with a deflector (δ = 60°)

Table 1 lists the maximum coefficient of power, $C_{P_{max}}$, coefficient of torque, C_T and tip speed ratio, λ that correspond to the $C_{P_{max}}$ and maximum tip speed ratio, λ_{max} of the 2-bladed and 3-bladed Savonius rotors without and with a deflector.

Table 1
List of $C_{P_{max}}$, corresponding C_T and λ and λ_{max} of the 2-bladed and 3-bladed Savonius rotors without and with a deflector at 10 m/s air flow speed (0.57 m/s water flow speed and $Re = 90200$)

Rotor	Case	$C_{P_{max}}$	C_T at $C_{P_{max}}$	λ at $C_{P_{max}}$	λ_{max}
2-bladed	without deflector	0.0067	0.0419	0.16	0.25
	with a deflector (δ = 60°)	0.0153	0.0694	0.22	0.50
3-bladed	without deflector	0.0650	0.0542	0.12	0.23
	with a deflector (δ = 60°)	0.0458	0.1249	0.37	0.60

Based on Table 1, the $C_{P_{max}}$ of the 3-bladed rotor without deflector is slightly lower than that of the 2-bladed rotor of the same case. It is probably due to the extra number of blade arranged at an orientation of 120° apart from each other which is smaller than the blade arrangement of the 2-bladed rotor i.e. 180°. This causes the incoming air flow, where it would focus on the preceding blade (advancing blade), to be frequently deflected by the following blade (returning blade) which then also deflected by the next following blade. According to Kumar and Saini [6], this situation induces a cascading effect where each blade affects the fluid flow of the following blade. With the presence of a deflector, however, $C_{P_{max}}$ of the 3-bladed rotor significantly increases, three times higher than the $C_{P_{max}}$ of the 2-bladed rotor of the same case. As the deflector blocks the air flow from impinging on the returning blades, it minimizes the cascading effect on the 3-bladed rotor since only the advancing blade is mostly exposed to the incoming air flow. Therefore, the negative torque that opposes the rotational motion of the rotor decreases. Besides, due to the smaller blade orientation of the 3-bladed rotor, the frequency of the advancing blade of the rotor impinged by the incoming flow is high which causes the rotor to rotate at high angular speed. High angular speed indicates that there is less energy loss from the rotor hence allowing more power to be extracted. This explains the experimental results where λ_{max} of the 3-bladed rotor with a deflector is found to be higher than that of the 2-bladed rotor with the deflector. The experimental results demonstrate the effectiveness of a deflector in improving the performance of the rotors where it acts as a shielding plat that consequently reduces the drag force on the returning blade and negative torque on the rotor. However, the implementation of the deflector at δ = 60° upstream of the returning blade is more effective for the 3-bladed rotor than the 2-bladed rotor.

5. Conclusion

In this study, the performance of a 2-bladed and 3-bladed conventional Savonius rotors without and with a deflector for the hydrokinetic application has been investigated. Wind tunnel experiments were performed at 10 m/s, equivalent to 0.57 m/s water flow speed at $Re = 90200$ to evaluate the performance of the rotors in terms of their coefficients of power, C_P, coefficients of torque, C_T and tip speed ratios, λ with respect to both cases. The experimental results showed that the performance of each rotor in terms of its C_P, C_T and λ increased with the presence of the deflector positioned at δ = 60° upstream of the returning blade of the rotor. Initially, the C_P of the unaugmented 3-bladed rotor was lower than that of the 2-bladed rotor. When augmented with a deflector, the maximum coefficients of power, $C_{P_{max}}$ for the 2-bladed and the 3-bladed rotors have improved by 128.36% and 604.62%, respectively. Such significant improvements were due to the obstruction of the incoming flows, by the deflector, from impinging on the returning blades. In the unaugmented cases without any deflector, the flow was unobstructed that impinging on the returning blade, dragging it to the opposing direction and reducing the generation of positive torques. The results demonstrate the effectiveness of a deflector in improving the performance of both rotors, particularly the 3-blade rotor.

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