An Effect of Twist Angle on Performance of the Vertical Axis Wind Turbine Blades

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Abstract: ***The Vertical Axis Wind Turbine (VAWT) represents a unique form of power generation technology. Recent studies have shown that vertical axis wind turbine is more suitable in low wind speed areas. In order to increase the efficiency of the power generated, it is necessary to design turbine blades in accordance with the specifications of vertical wind turbines that operate at low rotation speed. The present work uses a variable twist angle of the Savonius blades with a variation in twist angles of 0°, 30°, 60°, 90°, 120°, 150°, and 180°. The blade is tested at wind speed used of 3 and 4 m/s in wind tunnel. The performance of the blade evaluated is in terms of tip speed ratio (TSR), torque, and coefficient of power (Cp). The results showed that maximum TSR and torque are obtained with twist angle of 90º. The TSRs are 0.381 and 0.445 at a wind speed of 3 m/s and 4 m/s, respectively. The torque is 0.33 Nm at wind speed of 3 m/s as well as at wind speed of 4 m/s. Meanwhile, the maximum Cp is occurred at wind speed of 3 m/s. The values are 0.468, 0.449 and 0.401 at twist angle of 0°, 90°, and 180°, respectively. Increasing wind speed decreases the Cp. The greater the wind speed, the greater the energy converted. However, the actual power also depends on the profile of the turbine blades. The highest actual power is obtained by blades with a twist angle of 90°.***

Keywords: Turbine; vertical; Savonius; coefficient of power

1. Introduction

Energy is one of the most important needs for human life. Until now, the most widely used energy is conventional petroleum based energy, so it is very important to develop a technology that can take advantage of the existing renewable energy potential. Due to the excessive use of fossil fuels, the world faces serious problems related to energy depletion and environmental pollution [1, 2]. To solve the problem, many alternative energy sources for replacement of fossil fuels have been proposed. Renewable energy has attracted a lot of attention due to the significant investment in research and development by the government and various policies made by the government to expand it into the private sector [2-4]. Another major reason why a different energy source has to be discovered is the potential risk of running out of fossil fuels over the coming decades. Therefore, to minimize and avoid the detrimental consequences of dependence on fossil fuels, a large amount of research is being carried out to improve the efficiency and reliability of renewable energy resources, such as wind energy [5].

According to Indonesia Energy Projection, Indonesia has various and huge potential of renewable energy sources as presented in Table 1 [3] Indonesia has renewable energy potential almost 445 MW which are in form of about 208 MW solar energy, 95 MW of hydro power, 61 MW of wind energy, 33 MW of bioenergy, and the rest are in form of geothermal and tidal energies. Since Indonesia has long coastal line, it is very potential to develop wind turbine in Indonesia.

Table 1: Indonesia renewable energy potential [3]

Renewable energy form	Potential (MW)
Solar	32.654
Hydro	75.091
Wind	**60.647**
Bioenergy	32.654
Geothermal	29.544
Mini & Micro Hydro	19.385
Tidal	17.989
Total	443.208

Wind energy can be managed in various ways, one of which is by using a savonius type wind turbine, which is the Vertical Axis Wind Turbine (VAWT) type [6-10]. Savonius wind turbines can rotate easily at low wind speeds [11]. Different types of savonius wind turbines have been developed with their respective advantages and disadvantages. VAWT is based on aerodynamic drag, except for the Darrieus type. Research efforts on these turbines are focused on increasing aerodynamic efficiency by reducing the effects of drag and increasing lift [12]. It is thought to be an efficient solution for built up areas where the wind is unstable. VAWT design can be categorized into two groups, viz. Savonius and Darrieus [13, 14].

VAWT has many potential advantages, especially for operation in urban environments and offshore floating platforms and has many advantages over Horizontal Axis Wind Turbine (HAWT) [4, 5]. However, in general the VAWT experiences lower efficiency compared to the HAWT. Therefore, intensive research on the aerodynamic improvement of VAWT has been observed in recent years . The Savonius wind turbine is a simple, semi-cylindrical vertical axis device mounted on the opposite side of the vertical shaft [15-17]. The Savonius wind turbine is for a two-blade arrangement and operates with a drag force, so it cannot rotate faster than the wind speed. This means that the tip speed ratio is equal to 1 or less [18]. Horizontal shaft type windmills generally consist of 2 or more propellers. The size of the rotor diameter affects the wind energy conversion. The larger the rotor diameter, the greater the energy produced. As reported by Han, D. [19], another benefit of helical blades is that the blade produces low noise and low output fluctuation. The following is the relationship in mathematical form between wind speed and wind energy The moving objects such as the wind has kinetic energy (Ek) which is equal to [20]

$$Ek = \tfrac{1}{2} mV^2 \quad (1)$$

The amount of energy captured from the wind is exponentially proportional to the wind speed. Assuming no losses, the power produced by the wind turbine is roughly the same as Eq. (2) [20]

$$P = \tfrac{1}{2} \rho \times A \times (V_{wind})^3 \quad (2)$$

Due to the fact that the blade of the windmill cannot be closed completely (open system), and other effects, the blade can only has 50-70% of real efficiency. The η is the result of ηmax and the ratio of the actual to the total power.

$$P = \eta P_{tot} = \eta \frac{1}{2g_c} A v^3 \quad (3)$$

Where the η value is between 30% and 40% for real windmills.

$$P_{\max} = \frac{1}{2g_c} \rho A v_t \left(v_i^2 - v_e^2 \right) \quad (4)$$

$$P_{\max} = \frac{8}{27g_c} \rho A v_i^3 \quad (5)$$

Thus, the maximum efficiency becomes

$$\eta_{\max} = \frac{P_{\max}}{P_{tot}} = \frac{8}{27g_c} x \; 2g_c = 0{,}529 \quad (6)$$

From the results of the above calculations of Eq. (6), it can be said that windmills are able to convert no more than 60% of the total wind power into useful power. The Savonius turbine in principle looks very promising for conditions in single-storey buildings with flat roofs, but can also be useful for example for offshore platforms as well as for automated marine stations that collect climate data [21]. There has been some literature regarding the Savonius helical wind turbine by numerical computation [22-26] . However, they have focused on their specific case. For example studying a Savonius-Darrieus turbine model combined with a k-turbulence model, and they validated their numerical model through comparisons with available results by trying to obtain performance data for the Savonius helical turbine, and interestingly, they found a marginal increase in power coefficient. Several researchers conducted numerical and experimental studies on various Savonius helical turbines, but the software platform and test models used were not reliable enough to support power performance. By paying attention to existing studies, it is evident that many previous researchers focused on studying various forms of Savonius wind turbines [27-30].

In order to support previous studies, a Savonius Helix blade vertical axis windmill was fabricated and test its performance at different twist angle of the blade in the present work. It is hoped that this research can find the optimal helical twist angle to improve the performance of wind turbines. Helix shape, has a performance similar to adding multiple stages to the rotor. The moment oscillation when operating using the helix rotor is significantly reduced. In general, based on research, helical performance is not much different from that of semi-circular profiles. The present work aims to investigate an effect of twist angle of performance of Savonius blade, i.e. tip speed ratio (TSR), torque, and coefficient of power (Cp) is calculate as Eq. 7 [4].

$$C_P = \frac{T\omega}{0.5\rho A V_\infty^3} \quad (7)$$

2. Materials and Methods

Figure 1 shows flow diagram of the present work. The work is started by manufacturing of the prototype of the blade. For convience and low cost, the fabrication of the blade is performed using 3D printer. After the model is obtained, the experimental work is performed in laboratory of Mechanical Engineering Institut Sains dan Teknologi AKPRIND. Once the data collection is obtained, the performance of the blade is analysed. The experiment use a wind tunnel to get the otpimum design of the savonius wing turbine blade.

In the present work, the blade model used in this study is the S-type Savonius wind turbine with a modified helix-shaped rotor which has a variation of the twist angle. The prototype of the Savonius with different twist angle is manufactured using 3D printing. The blades are made from poly lactic acid (PLA). The prototype of the Savonius blades are made with a rotor height of 100 mm, a rotor diameter of 100 mm, a blade thickness of 2 mm, a shaft height of 120 mm, and a shaft diameter of 6 mm. Figure 2 shows the prototype of Savonius blade at different twist angle, i.e. 0°, 30°, 60°, 90°, 120°, 150°, and 180°.

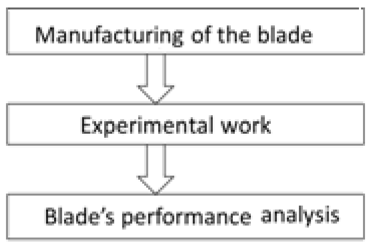

Figure 1: Flow diagram of the present work

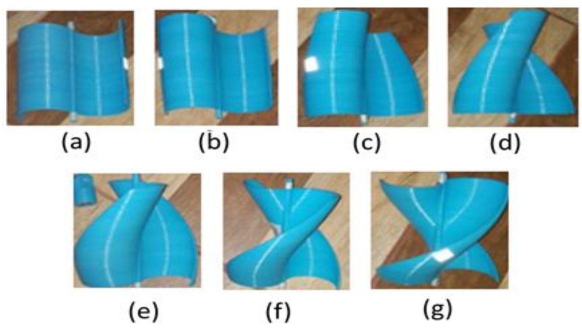

Figure 2: The prototype of Savonius Helix Wind Turbine

Paper ID: SR211208094211 DOI: 10.21275/SR211208094211

Figure 3 present the schematic diagram of the experimental setup of the present work in wind tunnel. The setup consist of the wind speed, the prototype of the rotor, and the measured devices. The test is conducted using a wind tunnel fan as a source of wind energy as shown in Figure 3. For each twist angle variation, the test is performed at wind velocity of 3 m/s and 4 m/s. The speed in the wind tunnel is controlled to obtain wind velocity of 3 m/s and 4 m/s. An Anemometer is used to measured wind speed in the wind tunnel. In order to measure the torque, prony brake is used. Meanwhile, the rotational speed of the rotor is measured using tachometer. The performance of the blade is evaluated in terms of tip speed ratio of the blade (TSR), torque generated by the rotor, and coefficient of power of the rotor. The torque generated by the rotor is calculated using weight of the load applied (F) and radius the rotor as shown in Eq (7).

$$T = F \, x \, r \quad (7)$$

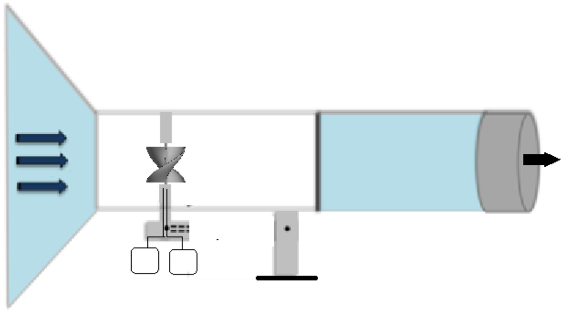

Figure 3: A schematic diagram of the experimental setup by using wind tunnel

3. Results and Discussion

Figure 4 displays the effect of twist angle of rotation speed of the rotor. Wind turbine rotation is very dependent on wind speed, the rotational speed increases as increasing wind speed. However, different turbine blades will also provide a difference to the wind turbine rotation for the same wind speed. From Figure 4, we can see that the trend of the rotational speed of the blade at different twist angle at wind speed of 3 m/s and at wind speed of 4 m/s are similar. The turbine rotational speed fluctuates when twist angle is changed and reach maximum at twist angle of 90°. The graph in Figure 4 also indicates that rotational speed of the rotor increases as increasing wind velocity. The highest rotational speed of the 90° twist angle rotor are 250 rpm and 350 rpm at wind speed of 3 m/s and 4 m/s, respectively.

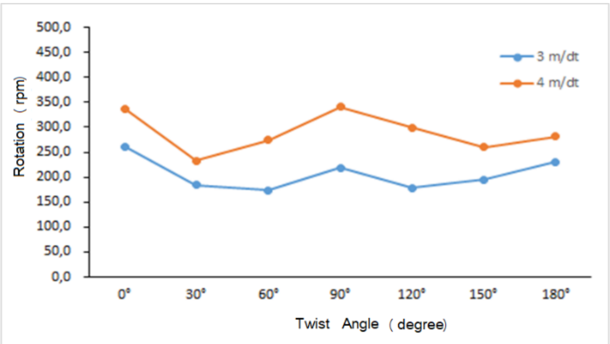

Figure 4: The effect of twist angle on rotational speed at different wind speeds

The effect of the twist angle on the tip speed ratio (TSR) at wind speed of 3 m/s and 4 m/s are given in Figure 5. Typically, the trend of the TSR are similar for both wind velocities. The TSR fluctuates when twist angle changes. The TSR reach the highest values at twist angle of 90° for both wind velocities. From Figure 5, it can be observed that the TSR at wind speed of 4 m/s is higher than that at wind speed of 3 m/s. The values are 0.381 and 0.445 at a wind speed of 3 m/s and 4 m/s, respectively. This indicates that the TSR is affected by twist angle and obviously by wind speed.

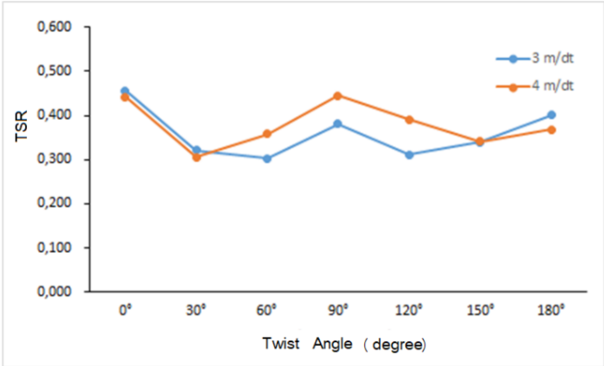

Figure 5: The effect of twist angle on the TSR at different wind speeds

Meanwhile, the torque (T) is the multiplication between the force (F) and the distance measured to the centre of the axis (r). The results of the effect of the twist angle on torque with variations in wind speed are shown in Figure 6. The graph in Figure 6 shows that the increasing wind speed does not affect a significant increase in torque. Maximum torque is obtained at a twist angle of 90°. The same maximum torque of 0.33 Nm occurs at both wind speed. The torque yield is also influenced by the turbine weight while the materials used and the dimensions of the turbine are light and small. Therefore, the torque results are almost the same.

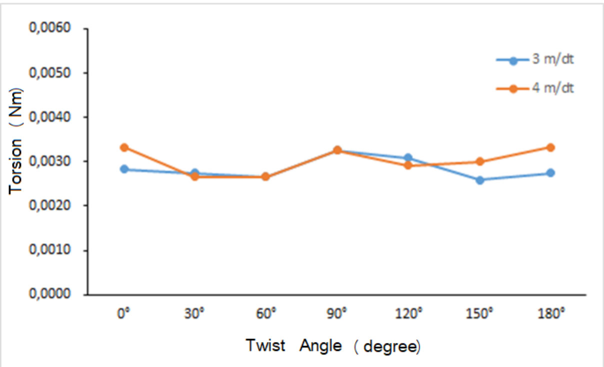

Figure 6: The effect of twist angle on torque at different wind speeds

Figure 7 displays an effect of twist angle on actual power generated by the blade at different wind speeds. The actual power of the wind turbine depends on the wind speed. The greater the wind speed, the greater the energy converted. However, the actual power also depends on the profile of the turbine blades. The similar trend of actual power are shown in Figure 7 for wind speed of 3 m/s and 4 m/s. The highest actual power is obtained at blades with a twist angle of 90°. Meanwhile, the effect of the twist angle on the coefficient of power (Cp) of the blade at different wind speeds is given in Figure 8. The graph shows that the Cp with the highest values are observed at 0°, 90°, and 180º at wind speed of 3 m/s. The values are 0.468, 0.449 and 0.401, respectively. An increase in wind speed decreases the Cp. It can be seen in Figure8, the 3 m/s wind speed generates a greater Cp than the 4 m/s wind speed for each twist angles.

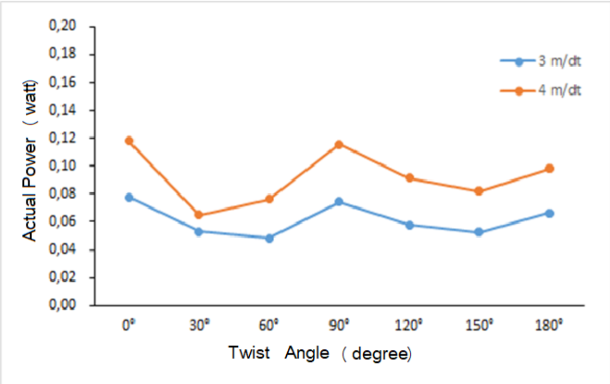

Figure 7: The effect of twist angle on power at different wind speeds

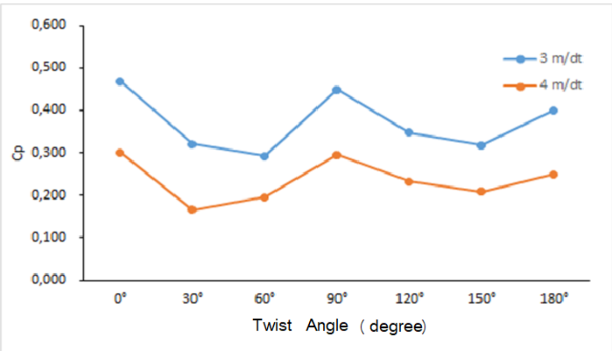

Figure 8: The effect of twist angle on coefficient of power at different wind speeds

According to Betz's law, there is a limitation of maximum energy that can be produced by wind turbines. No turbine can capture more than 59.3% of the kinetic energy of the wind. The turbine power coefficient can only reach as high as a factor of 0.593 which is also known as the Betz coefficient [31]. Based on this theory, the results of the research on the determination of the power coefficient obtained a value smaller than 0.593, this shows that the blade with the twist angle still has limitations in converting energy (Figure 9). However, these results have shown satisfactory performance with Cp values of 0.468 and 0.449 which are obtained at 0° and 90° twist angles at a wind speed of 3 m/s. The results of this study also show that the increased wind speed does not produce an increased in Cp. It indicates that there is an energy loss during the conversion of wind energy into useful mechanical energy. This phenomenon can be caused by the negative flow of the blade turning against the wind direction. Maximum power extraction occurs at the optimal tip speed ratio [18].

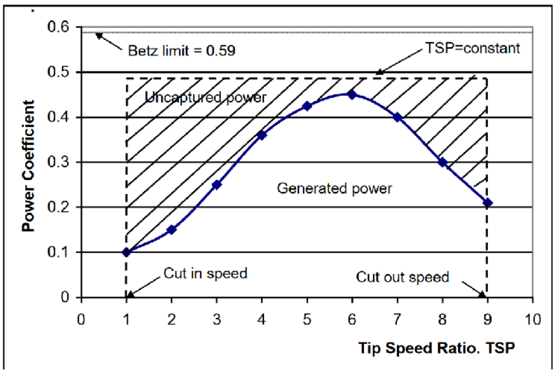

Figure 9: Power coefficient as a function of tip speed ratio for a two bladed rotor.

It has been reported by Jang [32], the drag-type Savonius wind turbine rotor was designed and tested with a diameter of 0.58 m and a height of 1.32 m. The rotor is modelled in a commercial CFD program and its aerodynamic performance is predicted through simulations. The simulation results show that the maximum power coefficient of the wind turbine is 0.17 with a tip speed ratio of 0.54. Based on this, a power curve with maximum power point tracking is obtained. The simulation results are compared with the wind turbine test results designed with a generator and controller. As a comparison, obtained aerodynamic power with tip speed ratio data from field tests based on the control strategy embedded in the wind turbine controller. Also found is the electrical conversion efficiency of the generator and motor-generator test controllers and is considered for comparison. From this comparison, the simulation results are validated with a maximum error of 4.32% at the power estimate of 12 m/s [32].

The differential resistance causes the Savonius turbine to rotate The Savonius turbine converts much less wind power than a lift-type turbine for the same size which makes the power coefficient low. Most of the Savonius rotor sweep area is probably below ground near the ground, if it has a small stand without extended masts, making overall wind energy conversion less effective due to lower wind speeds. Savonius turbines are used whenever cost or reliability is more important than efficiency and simple construction [28-31]. Modeling by using application of CAD/CAM technology present a challenge for researchers to investigate [33], thus this research.

4. Conclusions

Based on the experimental results of various blade models with differences twist angle at wind speed of 3 m/s and 4 m/s, it can be concluded:

1) The rotation speed increases as wind speed increase. The maximum rotational speed is obtained at twist angle of 90 °.
2) The maximum TSR is obtained at a twist angle of 90° with a value of 0.381 and 0.445 at a wind speed of 3 m/s and 4 m/s, respectively.
3) The maximum equal torques are obtained at an angle of 90° with a value of 0.33 Nm for both wind speed.
4) The greater the wind speed, the greater the energy converted. However, the actual power also depends on

the profile of the turbine blades. The highest actual power is obtained at blades with a twist angle of 90 °.

5) The highest values of Cp occur at twist angles of 0°, 90°, and 180° at wind speed of 3 m/s. The values are 0.468, 0.449 and 0.401, respectively. The Cp decreases as increasing wind speed.

5. Acknowledgements

The authors would like to thanks Directorate General of Higher Education, Ministry of National Education Indonesia, LLDikti V Yogyakarta, and Head of Department Mechanical Engineering Institut Sains dan Teknologi AKPRIND for providing the test facility and support during the experimental work.

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