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Experimental Study of the Effect of Winglets on Horizontal Wind Turbine (HAWT) Performance

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ABSTRACT

Horizontal axis wind turbine (HAWT) applications are primarily used for large wind energy capacities, and this is undoubtedly a problem for applications at a low-speed potential. However, developments related to improving performance for small-scale applications are still being studied, one of which is winglet blades. The application of winglets in aircraft provides advantages in reducing induced drag, leading to an increase in lift. Based on this case, the use of winglets in HAWT is an innovation that needs to be investigated to maximize its performance. In this study, the effect of winglet blades with the configuration of blades number and pitch angle was tested for their effect on wind speeds of 1.5 m/s to 5 m/s. In the results of the study, it can be seen that an increase in the pitch angle and wind speed affects the energy produced. In addition, it is known that an increase in the number of turbine blades will also increase energy and performance. In this case, the turbine performance with four winglet blades can produce the highest power, power coefficient (Cp), and tip speed ratio (TSR) of 11.34 Watt, 0.313 and 3.57, respectively.

1. INTRODUCTION

Wind energy is becoming renewable energy that has developed very fast in recent years [1]. An increase in wind energy use was recorded in 2009, with installed capacity reaching 159,742 Megawatts, increasing to 650 758 Megawatts in 2019. This increase has tripled in just ten years [2]. However, the global electricity generation from renewable energy in the world in 2019 only reached 28% of the total global electricity generation, implying that the remaining 72% is still generated from non-renewable energy [3].

The massive use of wind energy is influenced by the development of technology in wind turbines [4]. HAWT is one type of wind turbine that is widely used in the world today. HAWT uses an aerodynamic lift to rotate each rotor blade, like how an aeroplane fly. Lifting force occurs when the rotor blades are exposed to the wind, air flows around the top and bottom of the blade, so there is a difference in pressure between the upper and lower sides of the rotor blades [5], [6]. HAWT is one of the options for using wind energy in rural areas that are difficult to reach by electricity [3].

Several things influence HAWT performance, one of which is the shape of the rotor blades being one of the focuses in HAWT turbine research [7], [8]. In addition, the right airfoil design optimally increases the efficiency of the wind turbine. It maximizes the power generated, and the addition of blades affects the efficiency of the wind turbine [9]. Another influencing factor is the number of rotor blades [10]. A smaller number of blades has a higher flow speed, while a more significant number of blades provides more torque. The correct number of blades is important to match the generator performance curve for optimal performance and overall efficiency [2].

The use of winglets has also been investigated in addition to wind turbine rotors [11]. Winglet geometry has a significant effect on the effect of changes in the performance of the wind turbine. It is because the installation of winglets has an effect on diverging blade tip vortices away from turbine blades and reducing induced drag [12]. The effect of the ratio of turbine blade length and winglet length also affects performance. It was found that the ratio of 3.8 must be maintained to obtain maximum aerodynamic efficiency [13].

In Iswahyudi's *et al.* study [14], the winglet blade has a characteristic tip size of 10% of the radius of the blade with a modified tip with sweep and no anhedral, indicating the effect of blade tip modification on rotor performance. Swept blades without anhedral tend to produce slightly lower performance than straight blades if the sweep angle is small. The use of winglets can affect the aerodynamic performance of wind turbine blades used for small-scale wind generators [15]. In addition, these winglets affect the power generated by the turbine and reduce construction and configuration losses [16].

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Based on this background, research is needed to observe the relationship between the configuration of the number of rotors, winglets and pitch angle to variations in wind speed to find the highest level of efficiency in the HAWT turbine. In this research, HAWT is made on a lab scale, tested in a wind tunnel. This research was conducted with various configurations of predetermined research variables, and then this study analyzes the most optimal results from these various configurations.

2. METHODOLOGY

The wind is the air that has mass and motion, so it has speed. In this study, a power measurement was carried out, where the wind turbine power was directly proportional to the air density and wind speed cubic. The amount of wind power that passes through the turbine rotor is [17]:

$$P = \frac{1}{2}\rho A v_1^2 \quad (1)$$

Meanwhile, the comparison between the mechanical power of the rotor and the mechanical power of the wind that passes through the rotor can be found with the following equation [17]:

$$Cp = \frac{P}{P_0} = \frac{\frac{1}{4}\rho A(v_1 - v_2)(v_1^2 - v_2^2)}{\frac{1}{2}\rho A v_1^3} \quad (2)$$

In addition, another calculation is the tip speed ratio (TSR), which is formulated with the following equation [17]:

$$\lambda = \frac{\pi D n}{60 v} \quad (3)$$

In this study, the turbine blade used is NACA 4412 with chord lengths varying from 55 mm inside to 35 mm outside with a cross-section, as shown in Figure 1. Furthermore, the winglets used in this study have the same profile as the turbine blade profiles using fibreglass, with winglets attached to the turbine blades using an angle of 45° according to the configuration shown in Figures 2 and 3.

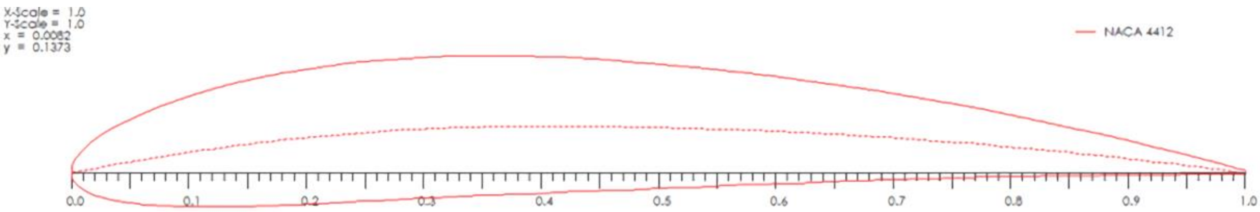
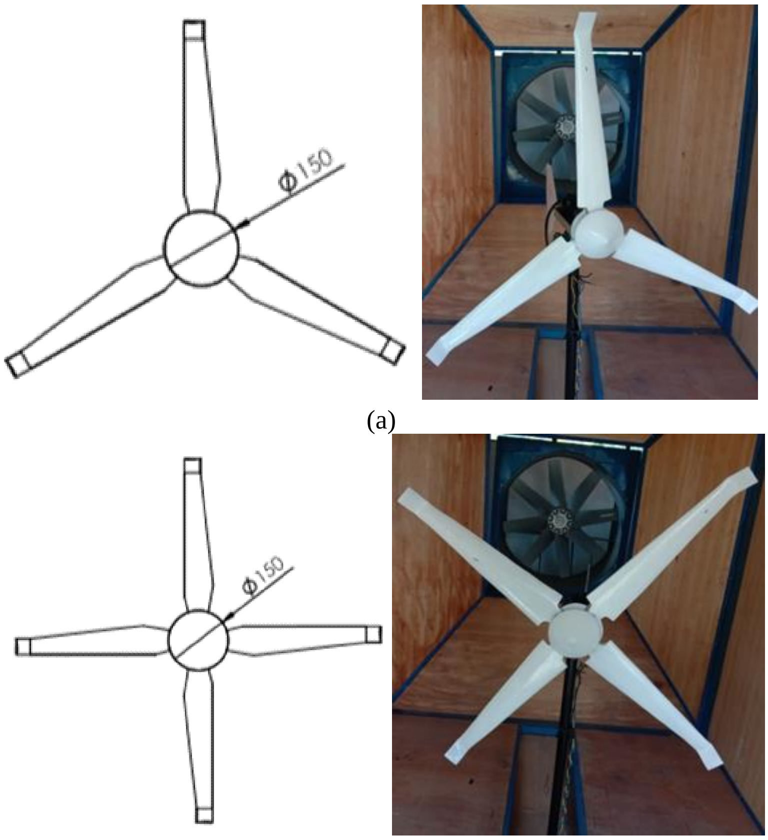


Fig. 1. NACA 4412 airfoil.



(a)

(b)

Fig. 2. HAWT using winglet blades configuration of (a) three winglet blades and (b) four winglet blades.

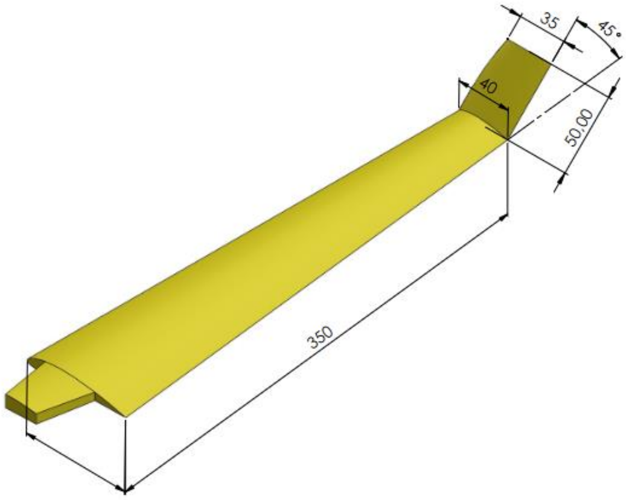


Fig. 3. Winglet and blade dimension.

Table 1. HAWT specifications using winglet blades.

Specifications	Detail
Tower height	1000 mm
Generator (PMG type)	200 watts
Transmission	Without Transmission
Rotor diameter	800 mm
Blade length	350 mm
The width of the blade	55 mm
End blade width	35 mm
Blade material	Fibreglass
Winglet width	35 mm
Winglet angle	45º
Winglet length	50 mm

This experiment was carried out in a wind tunnel with dimensions of 300 cm × 200 cm × 240 cm. Related to the specifications and dimensions of the wind turbine used in this study, it can be seen in Table 1.

Overall, the research flow in this experiment includes literature study and experimental device setup, then continued with experiments on various variable configurations, and ends with the analysis of research data. In more detail, the experimental design in this study can be seen in Figure 4.

3. RESULT AND DISCUSSION

3.1 Comparison of Generator Rotation Speed

Experimental data collection of generator rotation speed was carried out four times, with wind speed in 0.1 m/s intervals. The rotation of the horizontal shaft wind turbine generator with three winglet blades at the lowest wind speed or 1.5 m/s for each variation of the pitch angle from 0° to 10° is 0 rpm. In this condition, the generator has not rotated. A horizontal shaft wind turbine generator with three winglet blades starts rotating at a wind speed of 1.8 m/s for a 10° pitch angle variation.

Generator rotation at the highest wind speed or 5 m/s for each variation of the pitch angle is 75.3 rpm at an angle of 0°, 148.9 rpm at an angle of 2°, 183.6 rpm at an angle of 4°, 197.7 rpm at 6°, 223.6 rpm at 8°, and 264.6 rpm at 10°. On the other hand, rotation of the horizontal shaft wind turbine generator with four winglet blades with the lowest wind speed or 1.5 m/s for each variation of the pitch angle from 0° to 6° is 0 rpm, in this condition, the generator has not rotated, 56, 3 rpm at 8°, and 79.3 rpm at 10°.

Generator rotation at the highest wind speed or 5 m/s for each variation of the pitch angle is 109.6 rpm at an angle of 0°, 238.6 rpm at an angle of 2°, 357.2 rpm at an angle of 4°, 375.0 rpm at 6°, 382.9 rpm at 8°, 426.0 rpm at 10°.

These results can be seen in Figure 5, which showed the turbine generator rotation speed comparison with three winglet blades and four winglet blades based on variations in the pitch angle and wind speed.

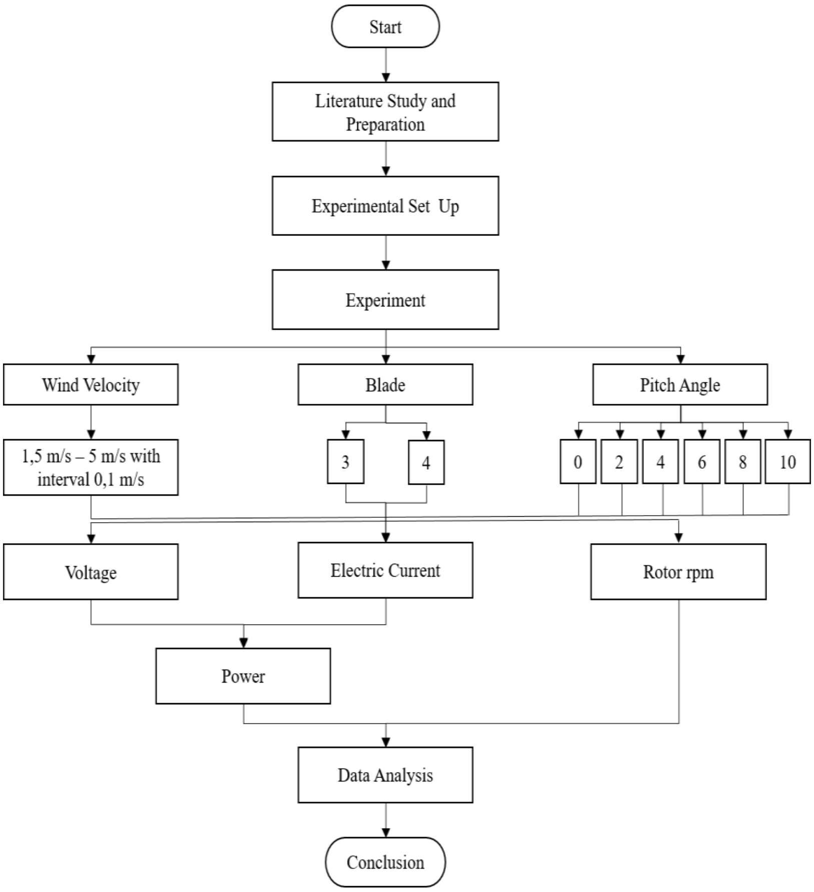
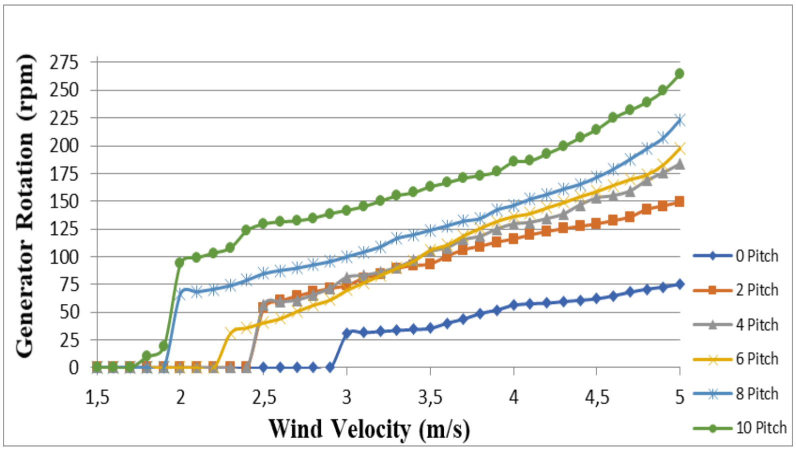


Fig. 4. Schematic experimental diagram.



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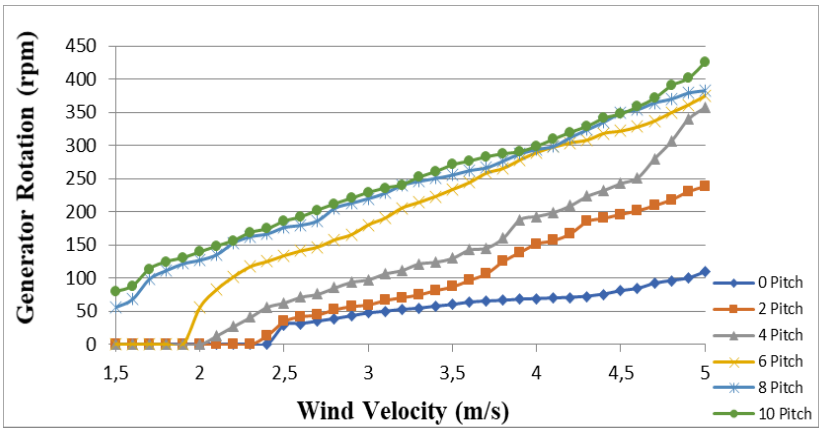


(b)

Fig. 5. Relation of wind speed to generator rotation speed (a) three winglet blades and (b) four winglet blades.

Based on the findings previously described, it can be seen that the addition of the pitch angle on the turbine blade can increase the rotation speed of the generator, with the highest speed obtained at an angle of 10°, which is 256.6 rpm for a turbine with three winglet blades and 426.0. rpm for four winglet blades in a wind speed of 5 m/s. In addition, the greater the pitch angle also affects the starting time of the turbine, the larger the pitch angle can rotate at lower wind speeds. An increase in the number of blades effectively results in higher starting torque, reduces cut-in speed, and provides sufficient blade area to convert wind energy [2], [18].

3.2 The Effect of the Number of Blades on the Power Produced

Figure 6 shows that a turbine with three new winglet blades generates electrical power in the wind speed range of 2 m/s to 3 m/s with an insignificant increase in the variation of the pitch angle of 2°-10°. Whereas in conditions with a wind speed range of 3.1 m/s to 5 m/s, the power generated by variations in the pitch angle of 6°, 8° and 10° has increased quite significantly. In addition, Figure 5 also shows the performance of a turbine with four winglet blades in a wind speed range of 1.5 m/s to 3 m/s. The electric power generated in this condition at variations in the pitch angle of 0º, 2º and 4º does not increase significantly. In the wind speed range of 3.1 m/s to 5 m/s, the electric power generated does not experience a significant increase in variations in the pitch angle of 2° and 4°.

The results of the turbine power test with a ratio of variations in the number of blades at a speed of 5 m/s are shown in Figure 7. The highest power results in testing three and four blades are 6.99 Watt and 11.34 Watt, respectively. At the wind speed of 3 m/s, the three blades produce the highest power 1.32 Watt, while the four-blade variation has the highest power 5.28 Watt. In addition, at a wind speed of 4 m/s, the three-blade variations produce the highest power of 1.64 Watts, and the four-blade variations produce the highest power of 8.50 Watts.

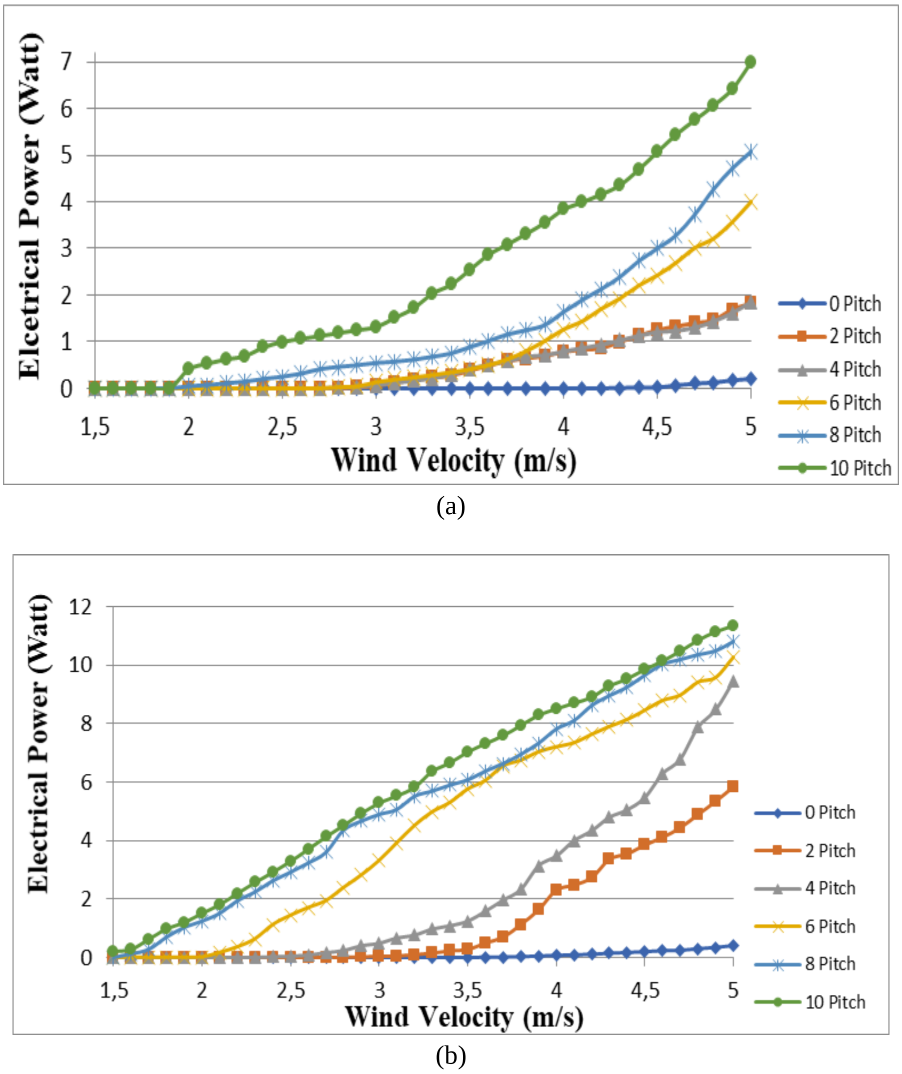


Fig. 6. The relationship of wind speed to electric power (a) three winglet blades and (b) four winglet blades.

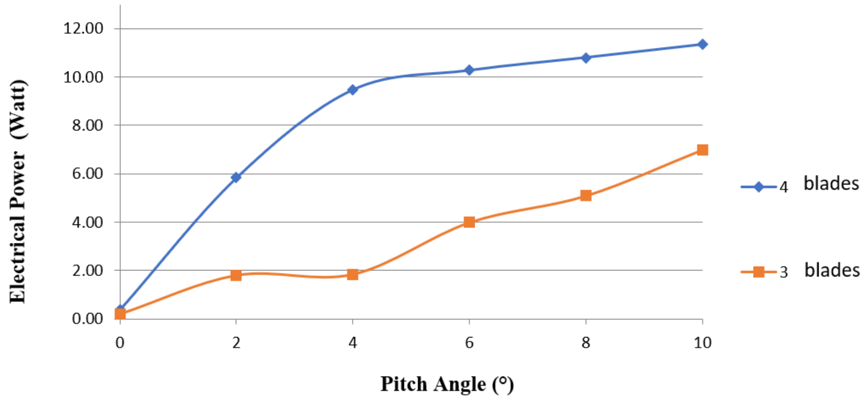


Fig. 7. The ratio of the number of blades to the electric power produced at a wind speed of 5 m/s.

These results indicate that the number of blades affects the electric power generated by the generator. The highest power from the variation of three blades and four winglet blades is obtained at a pitch angle of 10°, at a wind speed of 5 m/s. These results indicate that the greater the number of blades, the greater the power produced. The turbine rotates by utilizing lift so that the more blades installed, and the more lifting force acts on the turbine blades so that it will produce greater power [18], [19]. More blades will also make it easier for the turbine to work at low wind speeds.

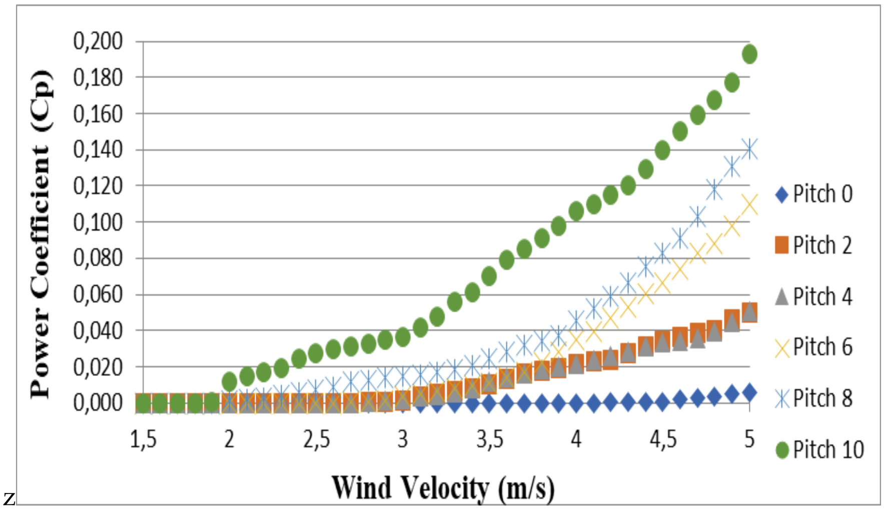
3.3 Effect of Winglet Angle Variations on Horizontal Shaft Wind Turbine Performance

Concerning the turbine's performance, the power coefficient and tip speed ratio (TSR) are the benchmarks of the influencing parameters. The power coefficient shows the amount of energy that can be converted from wind kinetic energy. In contrast, the tip speed ratio shows the ability of the turbine rotor rotation to convert wind kinetic energy into mechanical energy. These two things depend on the turbine construction, namely the rotor design and dimensions. In this research, the coefficient of power and tip speed ratio is the highest in the variation of the four blades and the pitch angle of 10°. TSR (λ) shows the ratio of the rotational speed of the turbine rotor with the wind speed, while the coefficient of power (Cp) is the ratio of the actual power produced to the ideal power of the turbine.

From Figure 8, the highest power coefficient (Cp) for the variation of the three winglet blades is obtained at a variation of the 10° pitch angle with a value of 0.193 at a wind speed of 5 m/s. At wind speeds of 2 m/s to 3 m/s, the power coefficient tends to increase, which is not too significant at variations in the pitch angle of 2°, 4°, 6°, 8°, and 10°. Meanwhile, the power coefficient value at a wind speed of 3.1 m/s to 5 m/s at 10° variation of pitch angle has increased significantly. Figure 4 also shows that in the variation of the four winglet blades, the highest power coefficient is obtained at a 10° pitch angle variation with a value of 0.313 at a wind speed of 5 m/s. In addition, these results indicate that the variation of the pitch angle of 6º, 8º and 10º in the wind speed range of 1.5 m/s to 5 m/s tends to increase significantly.

Figure 9 shows the highest tip speed ratio of the variation of the three winglet blades obtained at a 10° pitch angle variation with a value of 2.22 at a wind speed of 5 m/s. These results indicate that the TSR value in the wind speed range of 1.5 m/s to 5 m/s for all variations tends to increase. Figure 8 also shows the tip speed ratio for the highest variation of the four winglet blades obtained at a 10° pitch angle variation with a value of 3.57 at a speed of 5 m/s.

The results of this study indicate that the horizontal winglet wind turbine is very suitable for use at low wind speeds by adjusting the configuration of the number of blades and the size of the pitch angle. The most optimal configuration in the results of this study is obtained for horizontal wind turbines using a winglet variation with four blades and a pitch angle of 10°.

z 

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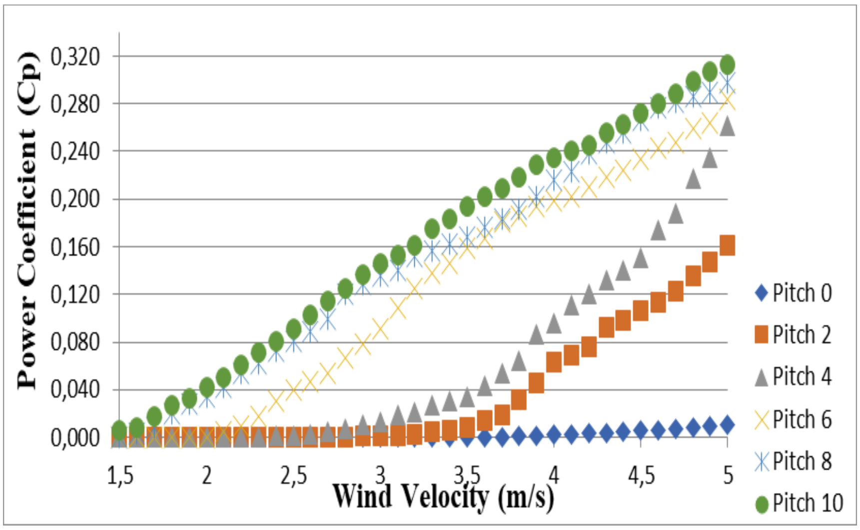
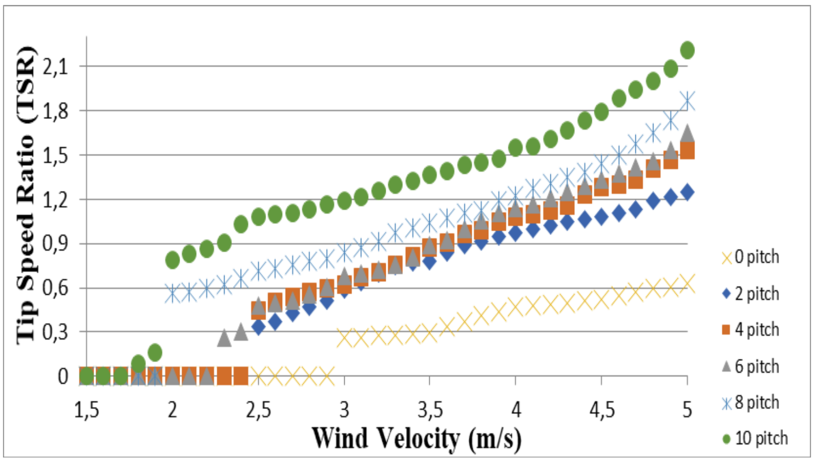


(b)

Fig. 8. Relation of wind speed to power coefficient (Cp) (a) three winglet blades and (b) four winglet blades.



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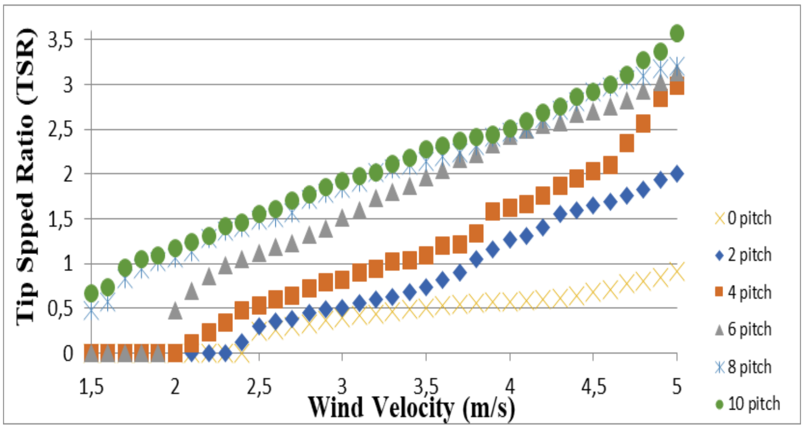


(b)

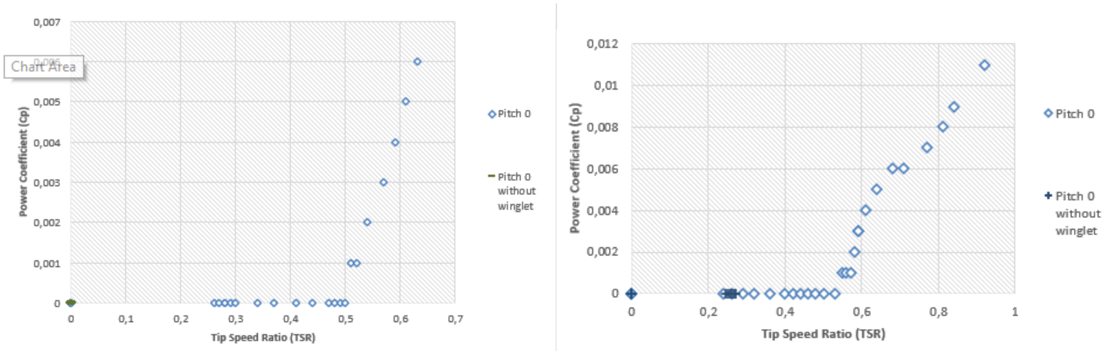
Fig. 9. Relation of wind speed to TSR of (a) three winglet blades and (b) four winglet blades.

3.4 TSR vs Cp on Horizontal Shaft Wind Turbine Performance

Figure 10 shows the correlation between TSR and Cp values for turbines with three and four blades. The maximum value of Cp at TSR for each blade was obtained. In three blades, it was obtained at Cp 0.193 and TSR 2.22 with winglet and Cp 0.192 and TSR 2.2 without winglet, while in four blades at Cp 0.313 and TSR 3.57 with winglet and Cp 0.284 and TSR 2.42 without winglet. The graph also shows that the higher the TSR, the higher the Cp produced, this is influenced by the pitch changes that were varied in this study. The winglet however clear show the influenced in both 3 and 4 blade turbines. In low angle pitch, the winglet increased TSR and can generate power while with the same wind speed where turbine without winglet cannot produced power. It also found that the winglet increased Cp in all pitch angle.

4. CONCLUSION

Horizontal axis wind turbine (HAWT) is a promising solution in its application to low-speed wind energy potential. In the configuration using winglet blades, it can be seen that there is an increase in performance with each increasing variation of the test, such as pitch angle and wind speed. The application of winglets reducing induced drag and increasing lift on turbine blades. The highest value is generated by a 10° pitch angle, which produces the most optimal power in the variation of three blades and four winglet blades, respectively 6.99 Watt and 11.34 Watt at wind speed 5m/s. In addition, the greater the pitch angle also affects the start time of the turbine, which makes it have the ability to rotate at lower wind speeds. It is also directly proportional to the wind speed. The higher the wind speed, the higher the electrical power generated due to the increase in the number of blades that can effectively generate higher starting torque, reduce the cut in speed, and provide sufficient blade area to convert wind energy. Based on this result, a turbine with four variations of winglet blades has a higher performance coefficient of power (Cp) and tip speed ratio (TSR) of 0.313 and 3.57 at a wind speed of 5 m/s with a pitch angle of 10°.



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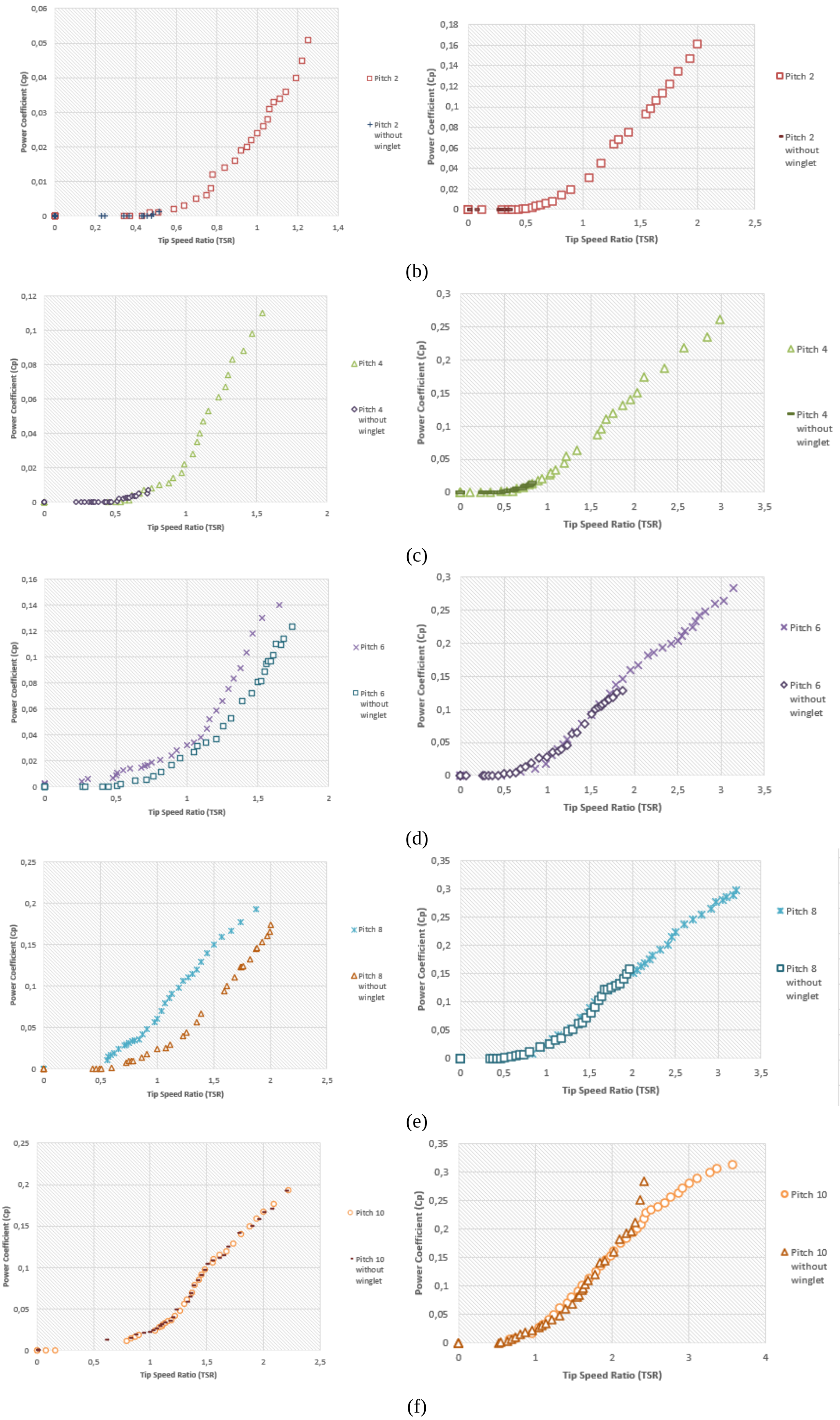

Fig. 10. Relation of TSR to Cp of three winglet blades and four winglet blades (a) pitch 0° (b) pitch 2° (c) pitch 4° (d) pitch 6° (e) pitch 8° (f) pitch 10°.

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