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Experimental Study Of The Performance Of A 5-Bladed Horizontal Axis Wind Turbine Of NACA 4415 Profile Using Winglets With Winglet Height Variation

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Abstract— **Horizontal axis wind turbine is one type of turbine used to convert wind energy into mechanical energy. The purpose of this research is to design, manufacture, test and analyze the performance of horizontal shaft wind turbine NACA 4415 airfoil blades that do not use winglets with those that use winglet height variations. The stages of this research include preparation of literature search, planning and making NACA 4415 airfoil blades both using winglets and not using winglets, assembling test equipment and assembling wind turbine installations, testing and taking wind turbine performance data, data processing and analysis, final results. The turbine diameter used is 1.1m with a blade thickness of 18 mm and a chord length of 38mm. Tests were carried out with winglet height test variables of 5%, 7%, 9%, and 11% of the rotor length at wind speeds of 4 m/s, 6 m/s, 8 m/s and 10 m/s. The test results show that the NACA 4415 airfoil horizontal shaft wind turbine using a winglet with a height of 7% has optimum performance at 4 m/s and 6 m/s with efficiencies of 23.68% and 8.75%, respectively, while when the wind speed is 8 m/s and 10 m/s the optimum turbine performance is achieved when using a 9% winglet with efficiencies of 6.12% and 3.64%, respectively. The most optimum turbine performance improvement is achieved when using a 7% winglet with an efficiency increase of 204.76% at a wind speed test of 4 m/s.**

Keywords— ***HAWT, NACA 4415 airfoil, wind turbine efficiency, winglet, vortex***

I. INTRODUCTION

Wind turbine can be defined as a device capable of converting wind energy into mechanical energy and then converted into electrical energy through a turbine generator [1]. Horizontal wind turbines have a main rotor shaft and an electric generator at the top of the tower and are directed towards the direction of the wind to be able to utilize wind energy [2]. Horizontal axis rotors are lift-based, have slender blades, and have high rotational speeds [3]. In principle, when there is interaction between the current flow and the turbine blades, two basic forces arise, namely lift and drag. Lift is a type of beneficial force to generate rotation in the turbine, while drag is a type of adverse drag force [4]. The mechanism of the formation of the elevator is due to the high pressure at the bottom and low pressure at the top. As a result of this imbalance, the flow at the tip of the wing tends to roll from the high pressure area at the bottom to the low pressure area at the top. Thus at the top of the wing there is a wing-length flow component from the tip towards the root, and at the bottom from the root towards the tip. This creates many small vortices distributed along the span, these small vortices merge into two large vortices at the wing tip (wing tip vortex). The vortex tends to attract the surrounding air and this secondary motion produces a downward velocity component behind the trailing edge called downwash. The appearance of this vortex and downwash structure produces a large amount of drag, which is due to the component of lift that is induced into drag or called induced drag. The addition of winglets is intended to improve performance by reducing induced drag on the blade by changing the downwash distribution [5]. Winglets are required that have aerodynamic loads such that the vortex sheet generated by the winglet can reduce the influence of tip vortex, reduce downwash and induced drag [6].

This research is expected to improve the performance of the NACA 4415 horizontal wind turbine profile so as to obtain optimal horizontal wind turbine performance.

II. METHODS

A. Blade and Winglet Design

The horizontal shaft wind turbine model used has a total of 5 blades in accordance with the NACA 4415 airfoil standard. For NACA 4415 blades that use winglets, it is designed to be removable between the blade and the winglet so that later 1 NACA 4415 blade can be used for various winglet height variations. The total blade length of NACA 4415 is 535 mm while the winglet length for each variation is 80 mm. So that the length of the NACA 4415 blade that uses the winglet before the winglet is installed has a total length of 455 mm. The design of the NACA 4415 blade is shown in Figure 1 below.

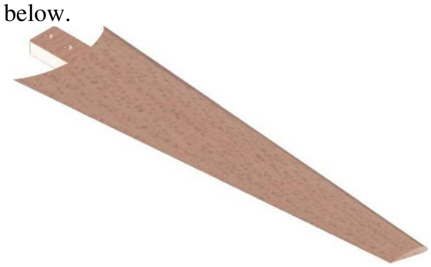

Fig. 1. NACA 4415 Horizontal Turbine Blade

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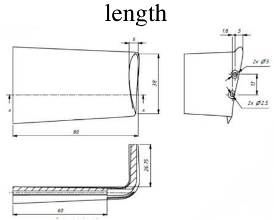
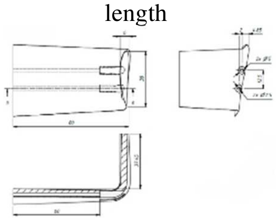
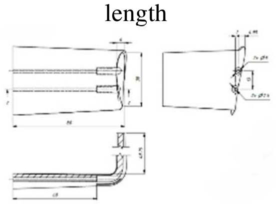
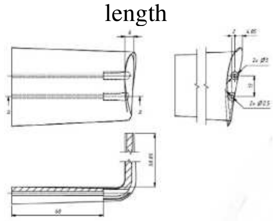
Winglets with a variation in height of 5%, 7%, 9%, and 11% of the blade length as shown in table 1. Winglets with a height variation of 5% have a height of 26.75 mm, for winglets with a height variation of 7% have a height of 37.45 mm, winglets with a height of 9% have a height of 48.15 mm, then for winglets with a height of 11% have a height of 58.85 mm.

Table. 1. 2D and 3D Design Winglet

	2D Design Drawing	3D Design Drawing
1.	Winglet 5% of the rotor length 	
2.	Winglet 7% of the rotor length 	
3	Winglet 9% of the rotor length 	
4.	Winglet 11% of the rotor length 	

B. Research Procedures and Data Presentation

The test was conducted by testing the NACA 4415 airfoil horizontal shaft wind turbine without using winglets with the NACA 4415 airfoil horizontal shaft wind turbine using winglets with variations in winglet height of 5%, 7%, 9%, and 11% of the turbine rotor radius. The wind speed variations used are 4 m/s, 6 m/s, 8 m/s, and 10 m/s. The wind is obtained from a blower that is already available at the Energy Conversion Laboratory State Polytechnic of Semarang as shown in Figure 2.

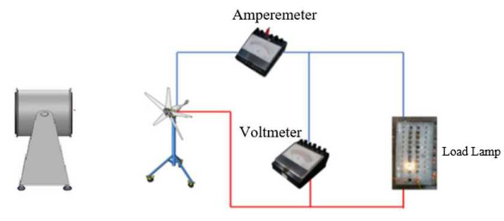


Fig. 2. Testing Scheme

The data taken in this test is free wind speed data (m/s) which will be used to rotate the turbine blade and also wind speed data in front of the turbine blade. Data collection of the two speeds using an anemometer tool. In addition, it is also necessary to collect data on the rotation of the turbine shaft (rpm) using a tachometer, collect voltage data (Volt) through a voltmeter, and also collect current data on the load that can be seen in the ammeter.

The data is processed so as to obtain the value of kinetic power (Watt), generator power (Watt) and also the efficiency of the wind turbine system (%). The variables in this test are wind speed and winglet height. Data presentation is made using a graph of wind turbine system efficiency characteristics against turbine rotation at varying wind speeds and a graph of system efficiency characteristics against turbine rotation at a fixed wind speed.

C. Data Analysis

The analysis was carried out by looking at how the effect of using winglets with variations in winglet height on the horizontal wind turbine profile NACA 4415 on the efficiency of the wind turbine system produced. After the analysis, the NACA 4415 airfoil wind turbine with a winglet that has a height of 7% of the radius of the wind turbine blade is the variation with the highest system efficiency.

III. RESULTS AND DISCUSSION

In principle, horizontal wind turbines can rotate because of the rotating force acting on the wind turbine. The force is the tangential force which is the simultaneous of the lift force and the drag force. The lift force depends on the laminar flow above the airfoil, which means that the air flows unhindered on both sides of the airfoil. Because the air at the top of the airfoil flows faster than the air flowing at the bottom of the airfoil, there is a pressure difference at the top and bottom of the airfoil. Because the upper air flows faster than the bottom of the airfoil, it causes a decrease in pressure, and this pressure difference causes the lift to occur on the airfoil.

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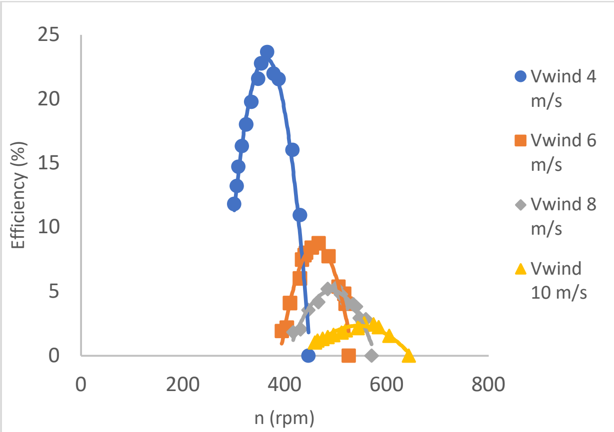

Fig. 3. Characteristic graph of the relation between efficiency and rotation of 5-bladed horizontal axis wind turbine NACA 4415 profile using winglets with a height of 7% of the rotor length

Figure 3 is a graph of the characteristics of system efficiency against rotation (rpm) on the research variables of horizontal shaft wind turbines using winglets with a height of 7% of the rotor length under different wind speed conditions. The highest system efficiency in the horizontal wind turbine model of 5 blades of NACA 4415 profile using winglets with a winglet height of 7% of the rotor length in each wind speed test is as follows. In the 4 m/s wind speed test, the highest efficiency was 23.68% in the 25 Watt load test, then for the 6 m/s wind speed test, the highest efficiency was 8.75% in the 25 Watt load test, for the 8 m/s wind speed test, the highest efficiency was 5.30% in the 40 Watt load test, and for the 10 m/s wind speed test, the highest efficiency was 2.52% in the 20 Watt load test. The efficiency of the system in this study tends to decrease as the wind speed increases.

When the wind speed increases, more airflow hits the turbine blades so that a greater force is needed to hold the turbine. The more airflow that hits the blade causes resistance because it becomes a blade load so that the efficiency of the wind turbine decreases when the wind speed increases [7].

In addition, the cause of the decrease in efficiency along with the increase in wind speed can also be seen from the results of the Reynold Number calculation, where the value increases when the wind speed also increases. The increase in Reynold Number value indicates that the airflow conditions are increasingly turbulent [8]. When turbulent airflow flows through a wind turbine, the irregularly moving air particles can cause irregular drag forces. When this phenomenon occurs, a lot of energy is not absorbed by the turbine so that the turbine cannot provide more output power while the input power (kinetic power) increases. When the turbine output power does not increase while the input power increases, the turbine efficiency will decrease. This happens because the efficiency value of the turbine is determined by the ratio between the input power and the output power of the turbine. Based on the research data and graph 3, it can be seen that the NACA 4415 airfoil blade model with a winglet height of 7% of the rotor length has the highest efficiency at 4 m/s wind speed. Likewise, the NACA 4415 airfoil blades that do not use winglets or those that use winglets with heights of 5%, 9%, and 11% of the rotor length produce the highest efficiency at 4 m/s.

Based on the data obtained, it can also be seen the effect of adding winglets with variations in winglet height on the performance of the 5-bladed horizontal wind turbine NACA 4415 profile.

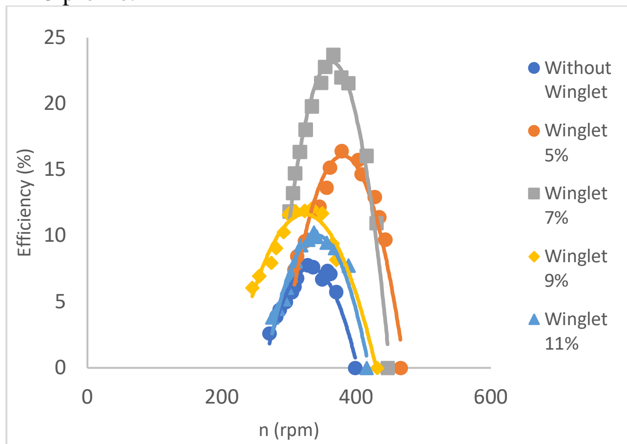

Fig. 4. Characteristic graph of the relation between system efficiency and NACA 4415 airfoil wind turbine rotation at 4 m/s wind speed.

Figure 4 is a characteristic graph of the relationship between system efficiency and rotation of the 5-bladed horizontal shaft wind turbine NACA 4415 profile at a wind speed of 4 m/s for each winglet variation. At this 4 m/s speed test, turbines that do not use winglets produce the highest system efficiency of 7.77% at a load of 30 Watt, for wind turbines using winglets with a height of 5% produce the highest efficiency of 16.42% at a load of 30 Watt, then for wind turbines that use winglets with a height of 7% of the rotor length produce the highest efficiency of 23,68% at a load of 25 Watt, for wind turbines using winglets with a height of 9% of the rotor length produces the highest efficiency of 12.08% at a load of 20 Watt, and for wind turbines using winglets with a height of 11% of the rotor length produces the highest efficiency of 10.25% at a load of 25 Watt. The five curves produce the same trend. The trend of the efficiency curve will decrease when it reaches its optimum point.

Based on Figure 4, it can be seen that wind turbines using winglets with a height of 7% of the rotor length produce the most optimum system efficiency while the highest turbine rotation is achieved by turbines using winglets with a height of 5% of the rotor length. In response to conditions like this, to determine which winglet variation is more optimum can be seen in the current produced not in the turbine rotation. Considering that this wind farm depends on natural conditions which during prolonged periods of weak winds in the rainy season means that not enough power comes from this wind farm while the demand for electricity remains high. To overcome these conditions, high-capacity battery storage facilities have been widely used as an important component of a successful energy transition leading to greater use of renewable energy.

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Battery charging requires optimal wind turbine output current, while the voltage is kept constant [9]. In testing wind turbines using both winglets with a height of 5% and 7% of the rotor length at a speed of 4 m/s, wind turbines using winglets with a height of 7% of the rotor length are considered to have the most optimal performance compared to turbines with a height of 5% of the rotor length because turbines with winglets 7% of the rotor length produce a greater current, namely at a load of 5 Watts, turbines with a winglet height of 7% produce a current of 0.366 A while turbines with a winglet height of 5% produce a current of 0.234 A, although the rotation of turbines with winglets 7% of the rotor length is lower than turbines using winglets with a height of 5%.

Based on graph 4, it can be seen that turbines using winglets have optimum performance compared to turbines that do not use winglets. The addition of winglets to this horizontal wind turbine can increase the efficiency of the system because the winglet can reduce induced drag on the blade by changing the downwash distribution. Induced drag is an aerodynamic drag that occurs because the wind turbine diverts the incident airflow. This drag is caused by vortex formation such as tip vortex. Meanwhile, downwash is a phenomenon where the airflow from the wind turbine decreases in the horizontal direction. This can affect the effective angle of attack of the airfoil which can affect the lift and drag generated by the wind turbine.

The addition of winglets to wind turbine blades can increase the output energy without increasing the projected rotor area [10]. This is done by spreading and moving the blade tip vortex (which rotates in the lower area of the rotor) away from the rotor plane, reducing downwash and decreasing the drag induced on the blade. The winglets convert some of the energy wasted in the rotor tip vortex into thrust.

Wind turbine blades utilizing winglets are seen that the lower pressure decreases from the base of the blade to its tip and along the winglet towards atmospheric pressure, which eventually results in less vortices at the wing tip and improves the aerodynamic performance of the wind turbine [11].

Based on Figure 4, wind turbines using winglets with a height of 7% of the rotor length have the most optimum performance. At a height of 7% of the rotor length, the winglet works at its optimum point in reducing induced drag so as to produce optimum output power. Winglets with higher heights can reduce induced drag but can also increase drag fraction and drag profile which will reduce system efficiency. Drag fraction is the drag produced due to friction between the air and the surface of the turbine blades. This is caused by the square factor of air velocity toward the wing tip which can increase the surface area exposed to friction. While the drag profile is the drag generated by the shape of the airfoil or wing section. A high winglet can increase the drag profile because a high winglet increases the surface area exposed to friction and increases the pressure at the tip of the blade which can produce a larger vortex and reduce the effective lift.

Taller winglets will increase the induced drag and concentrate the positive pressure towards the top of the rotor [12]. The drag induced by the winglets causes power losses and thus decreases the efficiency of the system. The use of winglets with higher heights will only increase the drag generated thereby degrading the performance of the horizontal wind turbine, besides the use of winglets that are too high will also concentrate extra positive pressure at the tip of the blades and increase the pressure difference in the rotor [13]**.**

The aerodynamic performance of horizontal wind turbines or the performance of horizontal wind turbines increases with the increase in winglet height up to a certain height, when it reaches its optimum height, the performance of horizontal wind turbines will decrease along with the increase in winglet height [11].

Based on the data from the research that has been done, testing the performance of horizontal wind turbines at a speed of 4 m/s can be concluded that wind turbines that use winglets with a winglet height of 7% of the rotor length have optimum performance with an increase in efficiency of up to 204.76% compared to horizontal wind turbines that do not use winglets.

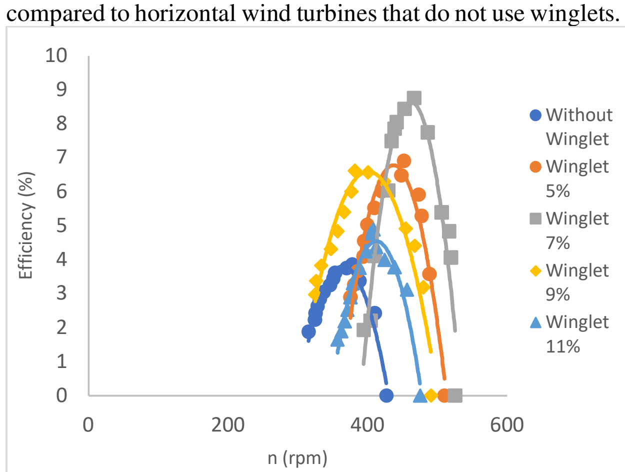

Fig. 5. Characteristic graph of the relation between system efficiency and NACA 4415 airfoil wind turbine rotation at 6 m/s wind speed.

Figure 5 is a characteristic graph of the relationship between system efficiency and rotation of the 5-bladed horizontal shaft wind turbine NACA 4415 profile at a wind speed of 6 m/s for each winglet variation. At this 6 m/s speed test, turbines that do not use winglets produce the highest system efficiency of 3.86% at a load of 15 Watt, for wind turbines using winglets with a height of 5% produce the highest efficiency of 6.90% at a load of 20 Watt, then for wind turbines that use winglets with a height of 7% of the rotor length produce the highest efficiency of 8,75% at a load of 25 Watt, for wind turbines using winglets with a height of 9% of the rotor length produces the highest efficiency of 6.61% at a load of 30 Watt, and for wind turbines using winglets with a height of 11% of the rotor length produces the highest efficiency of 4.88% at a load of 25 Watt. The five curves produce the same trend. The trend of the efficiency curve will decrease when it reaches its optimum point.

Based on the data from the research that has been conducted, testing the performance of horizontal wind

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turbines at a speed of 6 m/s can be concluded that wind turbines that use winglets with a winglet height of 7% of the rotor length have optimum performance with an increase in efficiency of up to 126.68% compared to horizontal wind turbines that do not use winglets. Based on the data obtained, although the wind speed increases to 6 m/s, the optimum performance of the horizontal wind turbine is achieved when using a winglet with a height of 7% of the rotor length. This shows that the winglet with a height of 7% is still optimum in reducing the increasing drag, which is considering that when the wind speed increases, the resulting drag profile will also increase [14].

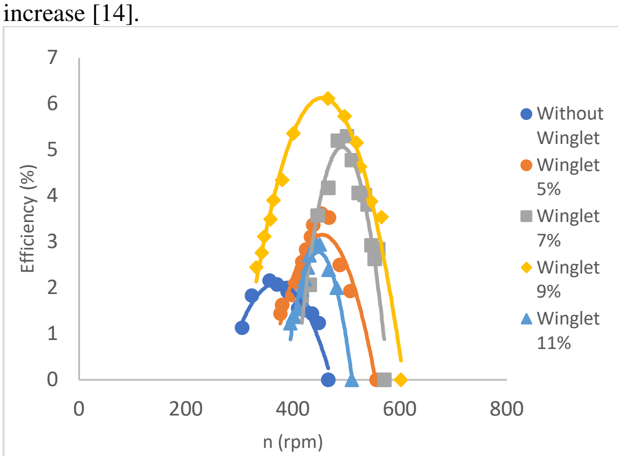

Fig. 6. Characteristic graph of the relation between system efficiency and NACA 4415 airfoil wind turbine rotation at 8 m/s wind speed.

Figure 6 is a characteristic graph of the relationship between system efficiency and rotation of the 5-bladed horizontal shaft wind turbine NACA 4415 profile at a wind speed of 8 m/s for each winglet variation. At this 8 m/s speed test, turbines that do not use winglets produce the highest system efficiency of 2.16% at a load of 55 Watt, for wind turbines using winglets with a height of 5% produce the highest efficiency of 3.61% at a load of 20 Watt, then for wind turbines that use winglets with a height of 7% of the rotor length produce the highest efficiency of 5,20% at a load of 40 Watt, for wind turbines using winglets with a height of 9% of the rotor length produces the highest efficiency of 6.12% at a load of 30 Watt, and for wind turbines using winglets with a height of 11% of the rotor length produces the highest efficiency of 2.97% at a load of 25 Watt. The five curves produce the same trend. The trend of the efficiency curve will decrease when it reaches its optimum point.

Based on the data from the research that has been conducted, testing the performance of horizontal wind turbines at a speed of 8 m/s can be concluded that wind turbines that use winglets with a winglet height of 9% of the rotor length have optimum performance with an increase in efficiency of up to 183.33% compared to horizontal wind turbines that do not use winglets. Based on the data obtained, when the wind speed increases to 8 m/s the optimum performance of the horizontal wind turbine is achieved when using a winglet with a height of 9% of the rotor length, no longer a winglet with a height of 7% of the rotor length as at a speed of 6 m/s. This shows that when the wind speed increases to 8 m/s the induced drag generated will increase [15] and winglets with a height of 7% of the rotor length are less than optimal in reducing induced drag so that the efficiency of the system is not optimal.

When the wind speed is high the air around the airfoil cannot flow following the shape of the airfoil surface as a result it will cause a large enough drag force so that a higher winglet is needed to reduce the induced drag [16]**.** The higher the winglet, the less vortex is generated so that it can improve the performance of the wind turbine.

For a certain wind speed, the aerodynamic performance of the horizontal wind turbine or the performance of the horizontal wind turbine increases as the winglet height increases to a certain height, when it reaches its optimum height, the performance of the horizontal wind turbine will decrease as the winglet height increases [11].

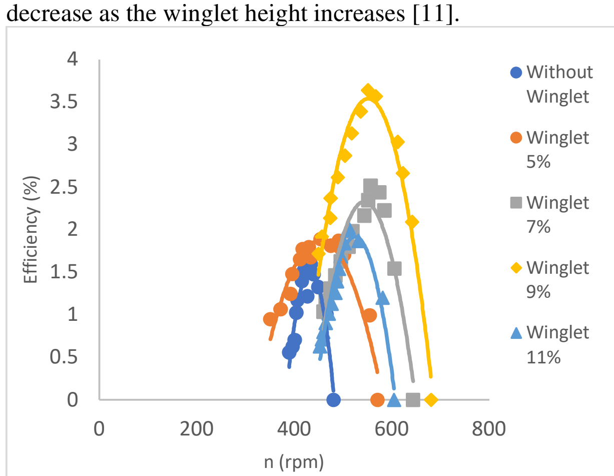

Fig. 7. Characteristic graph of the relation between system efficiency and NACA 4415 airfoil wind turbine rotation at 10 m/s wind speed.

Figure 7 is a characteristic graph of the relationship between system efficiency and rotation of the 5-bladed horizontal shaft wind turbine NACA 4415 profile at a wind speed of 10 m/s for each winglet variation.

At this 10 m/s speed test, turbines that do not use winglets produce the highest system efficiency of 1.60% at a load of 20 Watt, for wind turbines using winglets with a height of 5% produce the highest efficiency of 1.89% at a load of 25 Watt, then for wind turbines that use winglets with a height of 7% of the rotor length produce the highest efficiency of 2,52% at a load of 20 Watt, for wind turbines using winglets with a height of 9% of the rotor length produces the highest efficiency of 3.64% at a load of 25 Watt, and for wind turbines using winglets with a height of 11% of the rotor length produces the highest efficiency of 2.02% at a load of 15 Watt.. The four curves produce the same trend. The trend of the efficiency curve will decrease when it reaches its optimum point.

Based on the data from the research that has been conducted, testing the performance of horizontal wind turbines at a speed of 10 m/s can be concluded that wind turbines that use winglets with a winglet height of 9% of the

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rotor length have optimum performance with an increase in efficiency of up to 127.5% compared to horizontal wind turbines that do not use winglets. Based on the data obtained, although the wind speed increases to 10 m/s, the optimum performance of the horizontal wind turbine is achieved when using a winglet with a height of 9% of the rotor length. This shows that the winglet with a height of 9% is still optimum in reducing the increasing drag, which is considering that when the wind speed increases, the resulting drag profile will also increase [14].

IV. CONCLUSIONS

Based on the data obtained, it can be concluded that:

1. The performance of the 5-blade horizontal wind turbine with NACA 4415 profile increases with the addition of winglets.
2. At wind speeds below 6 m/s, the performance of the NACA 4415 horizontal 5-bladed airfoil turbine is
3. optimum when using winglets with a height of 7% of the rotor length.
4. At wind speeds above 6 m/s to 10 m/s, the performance of the 5-bladed horizontal wind turbine with NACA 4415 profile is optimum when using winglets with a height of 9% of the rotor length.

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