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THE EFFECT OF AIRFOIL TYPE AND WIND SPEED ON HAWT WIND TURBINE PERFORMANCE USING QBLADE SOFTWARE

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ABSTRACT

Energy transition is critical in the context of the current global climate situation. It is also important for Indonesia to achieve Sustainable Development in the Clean and Affordable Energy sector; given that the country's primary energy mix is still dominated by fossil energy, which accounts for around 90% of energy production. Wind is a new renewable energy that can be utilized to produce electrical energy through energy conversion. In addition, wind power is a type of renewable energy that has the lowest price compared to other types. This study aims to determine the characteristics of the selected airfoil types, including; NACA 2412, NACA 4412, NACA 6409 and SG6043. These characteristics included lift and drag coefficient. The BEM (Blade Element Momentum) method approach was used to obtain the performance parameter values of the airfoil and wind turbine, which include; lift and drag coefficient, lift-to-drag ratio, power coefficient, torque coefficient, turbine rotation, and power with variations ranging from angle of attack, tip speed ratio and wind speed. The results obtained for the highest lift coefficient value produced by SG6043 airfoil of 1.838 at an angle of attack of 16 °, and the lowest value produced by NACA 2412 of 1.529 at an angle of attack of 16 °. For the drag coefficient value, all types of airfoils produced values that increased as the angle of attack increased. Then, the highest power coefficient value produced by the SG6043 airfoil of 0.496 at TSR 5, and the lowest value produced by the NACA 6409 airfoil of 0.481 at TSR 5. Then, the power generated was based on the results of the power coefficient, where the SG6043 airfoil produced the greatest power for each wind speed used, and the NACA 6409 airfoil produced the lowest power. From the results of this study, it can also be concluded that the SG6043 airfoil produced the best performance compared to other types used.

Keywords: wind turbine, HAWT, airfoil, tip speed ratio, QBlade, SDGs.

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1. INTRODUCTION

By the end of 2020, Indonesia had a total installed power generation capacity of 70 gigawatts (GW) connected to the grid. Coal-fired power plants account for half of the total installed capacity. Energy transition is critical in the context of the current global climate situation. It is also important for Indonesia, given that the country's primary energy mix is still dominated by fossil energy, which accounts for about 90% of energy production. Indonesia has abundant renewable energy resources of more than 3,000 GW, mostly solar, but also wind, water, bioenergy, ocean, and geothermal. The capacity of renewable energy power in 2020 was modest, with a total of 165 megawatts (MW) added [1]. Wind is a new renewable energy that can be utilized to produce electrical energy through energy conversion. In addition, wind power is a type of renewable energy that has the lowest price compared to other types of renewable energy [2].

According to the Ministry of Energy and Mineral Resources, in 2020-2024, the average annual speed in Indonesia will only be between 3 m/s - 6 m/s, only half compared to countries in the northern and southern hemispheres that have wind speeds of more than 8 m/s. The low speed occurs due to Indonesia's location on the equator with warm air and low pressure. Based on the wind speed data, the technical potential record of wind power at the Ministry of Energy and Mineral Resources is around 60.6 GW, with a utilization of around 0.15 GW until 2020. This utilization is still far from the target in RUEN (National Energy General Plan), which, at least by 2020, Indonesia has installed 0.6 GW of wind power [3]. As of 2020, the total installed capacity of onshore wind energy connected to the country's grid was only 153.83 MW. The development of wind power for electricity is projected to be 1.8 GW by 2025 and 28 GW by 2050 [4]. In 2021, the installed wind energy capacity amounted to 154 MW out of 19.6 GW total capacity [1]. An example of the utilization of wind energy is in wind power plants that use wind turbines to generate power. Wind turbine development must be based on airfoil characteristics to obtain a good coefficient of performance. In addition, the geometry of the airfoil is also influential in generating power. Wind speed also affects the power output of wind turbines. Samosir and Riszal's research [5] stated that the higher the wind speed, the higher the power generated. In addition, the tip speed ratio also affects, where the higher the TSR, the power coefficient will increase, and when producing the maximum power coefficient, the higher the TSR, the power coefficient will decrease.

Suresh and Rajakumar [6] conducted research related to the design of airfoils for HAWT types that can produce the best performance. The simulation results show the influence of turbine performance, including angle of attack and tip speed ratio. In addition, airfoil selection also affects turbine performance. Another study was also conducted by Fajar Romadlon *et al*., [7]; simulating standard and modified airfoil types with different variables, namely wind speed, airfoil, and angle of attack. From the analysis, it was found that wind speed is a factor that affects the results of turbine performance.

Research conducted by Shubham Raut *et al*. [8] analyzed the type of airfoil and geometry, which included twist angle and chord length optimized to get the best performance. This was also done by Alaskari *et al*. [9], where the twist angle and chord length were optimized.

Pyungho Shin and Keonhoon Kim [10] researched to analyze the aerodynamic performance of the SG6043 airfoil for horizontal wind turbines. The simulation results showed that this type of airfoil was the type that could generate the most optimal power.

Based on the discussion of the above studies, some researches are related to studies to determine airfoil characteristics. Related research has different variables so that if the same type of airfoil is used, it will produce different performance. The main factors of wind turbine performance are wind speed and tip speed ratio, as well as the terminology or shape of the airfoil. Thus, further study is needed to determine the characteristics of airfoil types with several parameters that affect them. This research describes the performance parameters of wind turbines, which include lift coefficient, drag coefficient, lift-to-drag ratio, and the power produced. The purpose of this study is to determine the influence of these factors so that the best airfoil type is obtained, which can later be used as a reference in the development of wind turbines, especially HAWT. To determine the selection of a suitable airfoil, the results of the performance parameters are analyzed, starting from the terminology and the influence of related variables.

2. MATERIALS AND METHODS

2.1 Research Model

To obtain the performance parameters, steps need to be taken to obtain the values. In wind turbine development, one method that is often used is BEM (Blade Element Momentum). In the process, this method has advantages in calculation time and cost [11] in computation compared to the CFD (Computational Fluid Dynamics) method. QBlade uses the Blade Element Momentum (BEM) method for horizontal axis simulation and the Double Multiple Streamtube (DMS) algorithm for vertical axis wind turbine performance simulation. QBlade includes modules that include airfoil design and analysis, lift and drag polar extrapolation, blade design and optimization, and turbine definition and simulation [12].

2.2 Airfoils Selection

The selection of airfoil type used for wind turbine development should be based on its characteristics to get the best performance from the turbine itself. The selection of airfoil types must be based on terminology. The commonly used type is based on NACA (National Advisory Committee for Aeronautics). In Figure-1 [13], the selected airfoil types include NACA 2412, NACA 4412, NACA 6409 and SG6043. The selected types are airfoils that are suitable for use at low to medium wind speeds. Based on terminology, NACA 2412 has a maximum thickness of 12% of the chord length and a maximum chamber value of 2% (of chord line) located at 40% of the leading edge, NACA 4412 has a maximum thickness of 12% of chord length and has a maximum chamber value of 4% (of chord line) located 40% of the leading edge, NACA 6409 has a maximum thickness of 9% of chord length and has a maximum chamber value of 6% (of chord line) located 40% of the leading edge and SG6043 based on data from airfoils. Com and UIUC Airfoil Coordinates Database, this airfoil has a maximum thickness of 10% located at 32.1% of the chord length and a maximum chamber of 5.1% located at 53.3% of the chord length [13].

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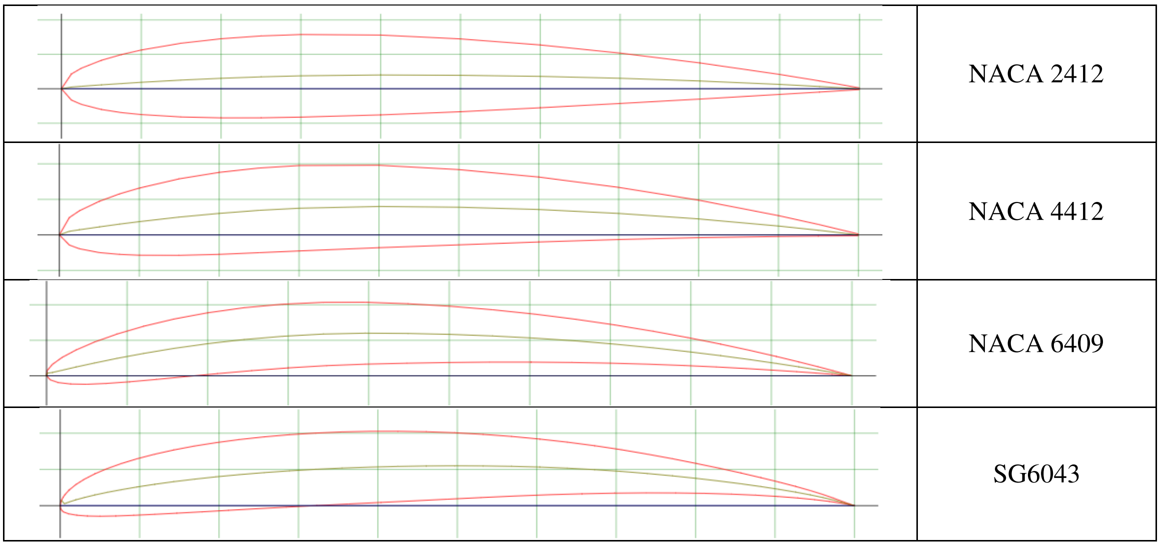

Figure-1. Selection of airfoils used.

2.3 Lift and Drag Coefficients

In the case of a wind turbine, the value of lift and drag can be determined through the calculation of the direction of wind flow passing through the airfoil (equations 1 and 2) [14]. The lift and drag coefficient values are parameters that affect an airfoil to work properly. The value is influenced by the angle of attack as in Figure-2. (a) and (b) [15], where the higher the angle of attack value, the lift coefficient value will increase, and at a certain angle of attack, the lift coefficient value will reach a maximum and stall.

To get efficiency, in this case, a wind turbine, the drag coefficient value must be smaller. To get the lift value, an airfoil must have a good lift coefficient and speed value to convert the lift coefficient into lift [15].

$$C_L = {}^{L}/_{0.5\ x\ \rho\ x\ A\ x\ v^2} \tag{1}$$

$$C_D = {}^{D}/_{0.5\ x\ \rho\ x\ A\ x\ v^2} \tag{2}$$

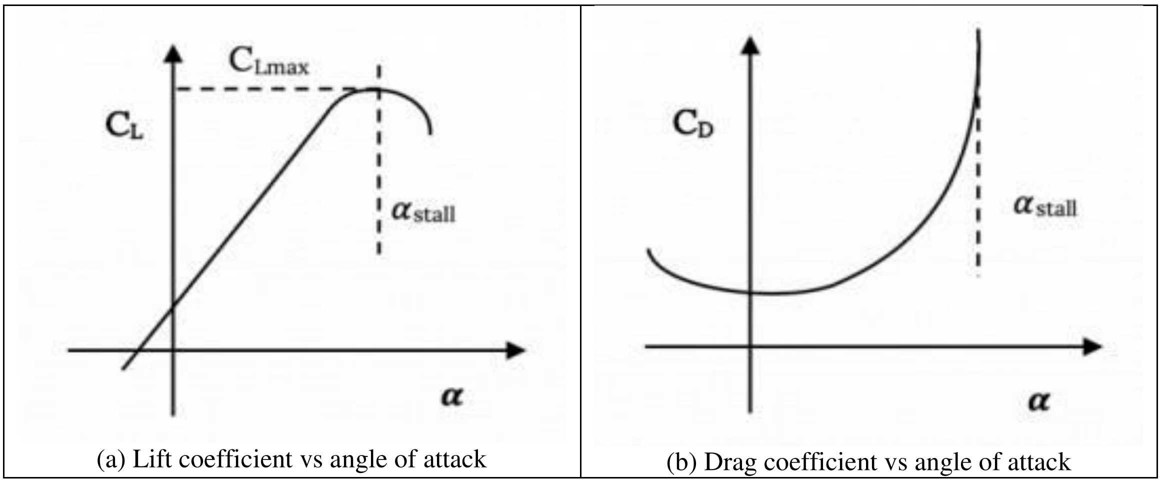

Figure-2. Lift and drag curve coefficient vs angle of attack.

Figure-3 explains how the airfoil works against the angle of attack and produces lift and drag values. When an airfoil reaches the maximum lift coefficient value, the airfoil will have the ability to lift. However, the airfoil also has drag which can cause a speed reduction. As the velocity decreases, the lift value will also decrease [15].

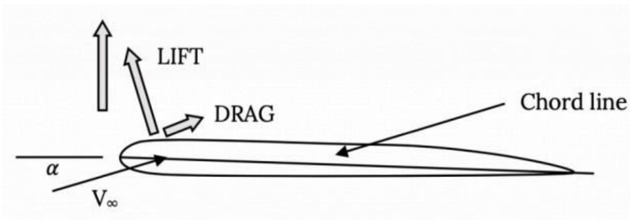

Figure-3. Lift and drag of an airfoil.

$$L = {C_L . \rho . v^2 . A}/{2} \quad (3)$$

$$D = {C_D . \rho . v^2 . A}/{2} \quad (4)$$

Where, ρ is density (kg/m3), A is swept area (m), and v is wind speed (m/s) [15].

2.4 Wind Turbine Geometry

To make a wind turbine, a blade geometry or size is required, which will be used to design and provide specifications of the wind turbine blades. In this research, wind turbines were devoted to the development of horizontal axis wind turbines for small to medium scale. Geometry or size is made in QBlade software with 3 blades. The design parameters of the turbine blades amounted to 7 segments, with each position (length of each segment) determined based on Table-1. Figure-4 shows a wind turbine blade with a radius of 0.520 m and a sweep area of 0.85 m^2.

Table-1. turbine segments.

Post/segment (m)	Chord (m)	Twist (deg)
0.00	0.050	0
0.05	0.050	0
0.10	0.070	0
0.20	0.050	0
0.30	0.040	0
0.40	0.030	0
0.50	0.020	0

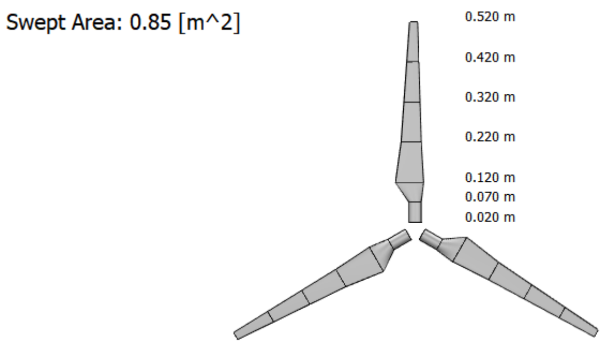

Figure-4. Blade geometry.

2.5 Power Coefficient and Turbine Power

The maximum efficiency or power coefficient that a wind turbine can produce is only 0.593 or 59.3% based on the Betz Limit [16]. The higher the wind speed, the higher the power generated. This can be seen in equations (5- 7) [17].

$$C_p = {Pout}/{Pin} \quad (5)$$

$$Pin = 0.5\, x\, \rho\, x\, A\, x\, v^3 \quad (6)$$

Where, C_p is the power coefficient, Pout is output power (W), Pin is wind power (W), ρ is density (kg/m3), A is swept area (m), and v is wind speed (m/s). Wind turbine power is the amount of mechanical energy that can be generated by the wind turbine rotor after getting power from the wind gusts. Wind turbine power is not the same as wind power because the power coefficient affects it.

$$Pout = 0.5\, x\, \rho\, x\, A\, x\, v^3 x\, C_p \quad (7)$$

2.6 Simulation Parameters

2.6.1 Angle of attack

The angle of attack (α) value will affect the lift and drag coefficient values. As seen in Figure 2. (a) and (b), where the higher the angle of attack, the lift coefficient value will increase, and at a certain α value, the lift coefficient will reach the maximum value. At the same time, the drag coefficient value will increase as the angle of attack increases. This study uses an angle of attack of 4° to 8° with Δ = 2°.

2.6.2 Angle of attack

Wind speed is an important parameter in wind turbines. If there is no wind, the wind turbine cannot rotate properly. Site selection for windfarm development should be based on wind speed potential. This study takes data on low to moderate wind speeds of 4 m/s to 10 m/s based on locations in Indonesia that have the potential to be developed for wind turbines.

2.6.3 Tip speed ratio

The difference between the speed of the blade tip and the speed of the wind through it is called the tip speed ratio. A TSR of more than 1 indicates that more of the blade is experiencing lift, while a TSR of less than 1 indicates that more of the blade is experiencing drag [18].

$$\lambda = {\omega \cdot r}/{v} \quad (8)$$

Where, r is the radius of the turbine (m) and v is the wind speed (m/s) and the angular velocity ω is obtained from

$$\omega = {2 \cdot \pi \cdot rpm}/{60} \quad (9)$$

The TSR used in this study ranges from 3 to 8.

2.7 Data Analysis

The simulation data was used for analysis and discussion. The data presented were performance parameters, including lift coefficient, drag coefficient, lift-to-drag ratio, power coefficient, and power of the turbine. The data was taken based on variations in angle of attack and tip speed ratio as well as wind speed.

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3. RESULT AND DISCUSSIONS

3.1 Lift Coefficient

Figure-5 shows the lift coefficient of the type of airfoil used with the angle of attack variation. The results showed that the higher the angle of attack, the lift coefficient value would increase, and when it reached the maximum value, the lift coefficient value would decrease. At an angle of attack close to zero, the lift coefficient value of all airfoil types would increase, while the greater the angle of attack, the higher the value would decrease.

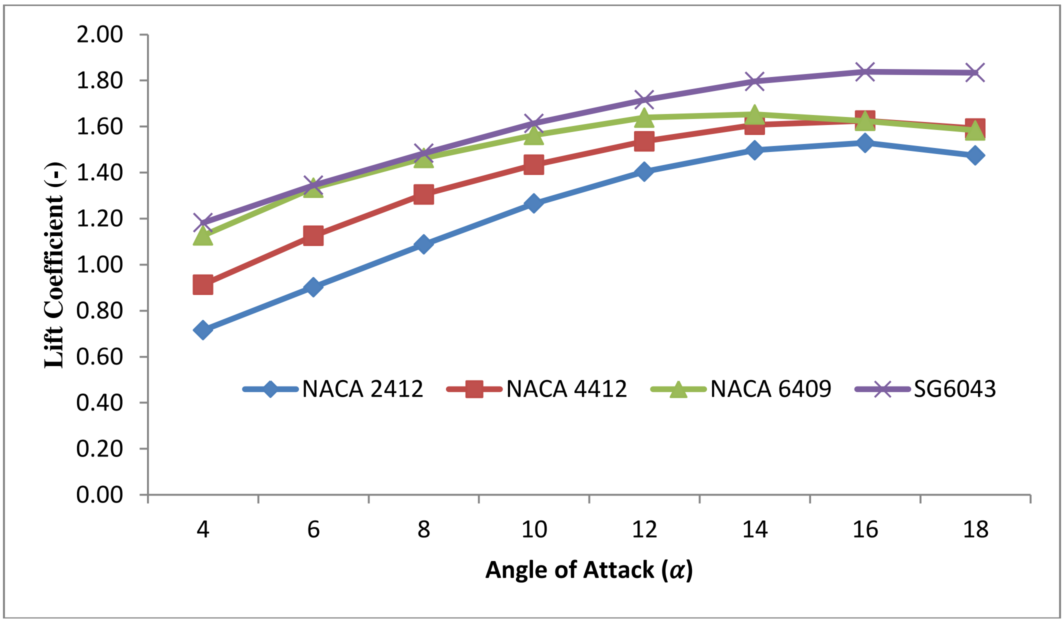

Figure-5. Effect of angle of attack on lift coefficient value.

It can be explained that the highest lift coefficient at each angle of attack was obtained in the NACA 2412 airfoil of 1.529 at an angle of attack of 16°, NACA 4412 of 1.626 at an angle of attack of 16°, NACA 6409 of 1.653 at an angle of attack of 14° and SG6043 airfoil of 1.838 at an angle of attack of 16°. Of all the airfoil types used, SG6043 was the type that produced the highest lift coefficient value compared to other types.

3.2 Drag Coefficient

Figure-6 shows the drag coefficient of the type of airfoil used with the angle of attack variation. The results showed that the higher the angle of attack value, the higher the drag coefficient value. In the figure, it can be explained that the higher the angle of attack value, the higher the drag coefficient value. Figure-6 shows the difference in drag coefficient values for each type of airfoil. Figure-5 and Figure-6 show the lift curve and drag curve, which have an increasing and decreasing trend similar to Figure-2.

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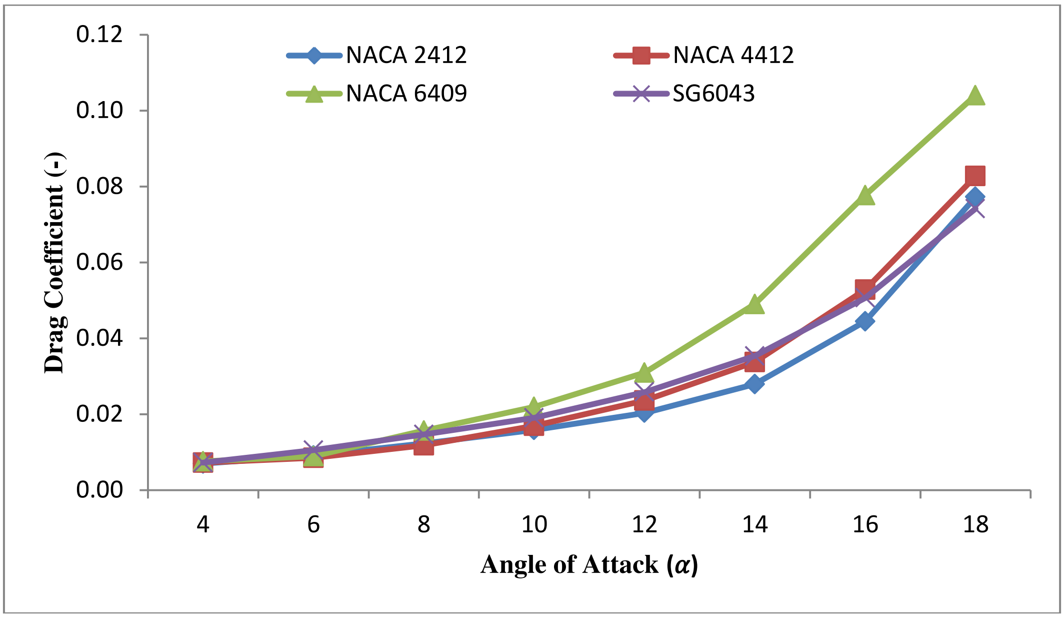

Figure-6. Effect of angle of attack on drag coefficient value.

3.3 Lift-to-Drag Ratio

Figure-7 shows the lift-to-drag ratio where the maximum value is at an angle of attack close to zero, and the greater the angle of attack value, the value of the lift-to-drag ratio will decrease. This was due to the higher drag coefficient value, so that the value would decrease. The lift-to-drag ratio value had an influence on the torque and rotation of the turbine, the higher the value, the better the efficiency of the turbine blades so that it will affect the value of the power coefficient and the power produced. To get a high lift-to-drag ratio value, the drag coefficient value must be smaller than the lift coefficient value.

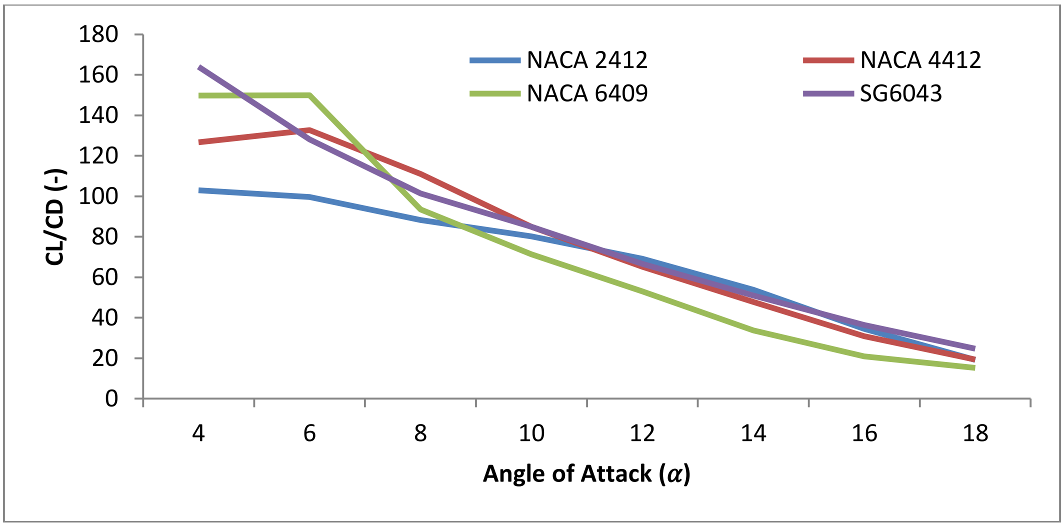

Figure-7. Effect of angle of attack on lift-to-drag ratio value.

In Figure-7, it can also be explained that the SG6043 airfoil type produced the highest lift-to-drag ratio value compared to other airfoil types. This was due to the comparison of high lift coefficient and low drag coefficient values. Other airfoil types, namely NACA 2412 and NACA 4412, had similarities with the SG6043 airfoil type, where the comparison of lift and drag values was not so far away so that at high angles of attack the resulting lift-to-drag ratio values tend to be the same, unlike the NACA 6409 airfoil type which produced a smaller lift-to-drag ratio value than other airfoil types because the drag coefficient value tended to be greater as the angle of attack increases than other airfoil types. Based on NASA institutions [19], airfoils that have a high lift-to-drag ratio value, in this case, can rotate constantly for a long time.

3.4 Power Coefficient

Figure-8 shows the power coefficient based on tip speed ratio variations of 3 to 8. The average increase in power coefficient occurred at a low TSR of 3 to 4 and reached the maximum power coefficient at TSR 5 and 6,

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and the decrease in power coefficient occurred at a high TSR of 7 to 8. The comparison between tip speed ratio and power coefficient for all airfoils used in this study. At TSR 3, the highest power coefficient of 0.271 was found in the SG6043 airfoil and the lowest power coefficient of 0.191 in the NACA 6409 airfoil. At TSR 4, the highest power coefficient was 0.436 in SG6043 airfoil, and the lowest power coefficient was 0.363 in NACA 2412 airfoil.

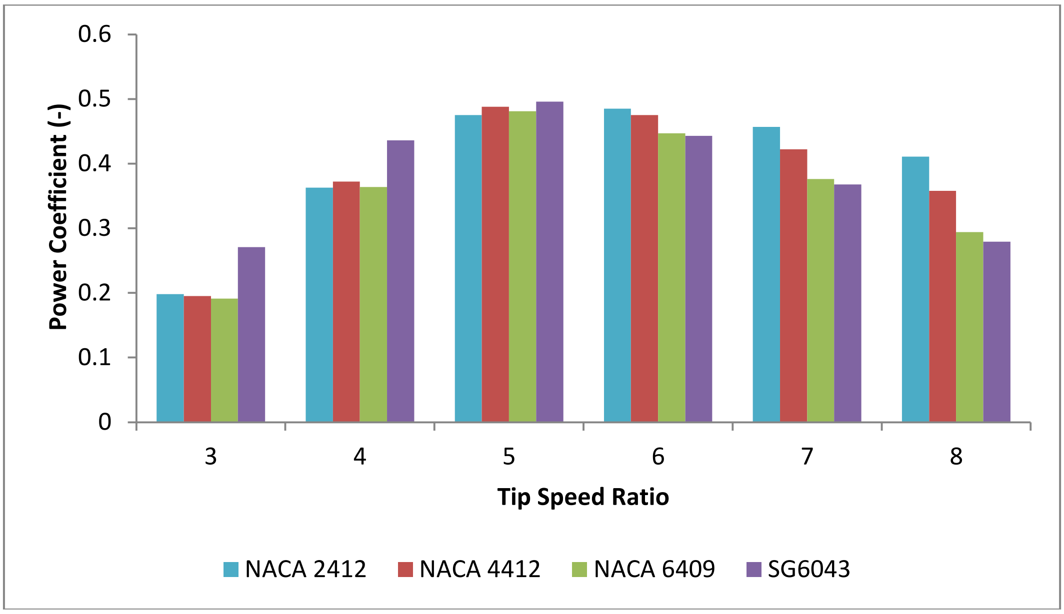

Figure-8. Effect of tip speed ratio on power coefficient value.

At TSR 5, the highest power coefficient was 0.496 on SG6043 airfoil, and the lowest power coefficient was 0.475 on NACA 2412 airfoil, then TSR 6, the highest power coefficient was 0.485 on NACA 2412, and the lowest power coefficient was 0.443 on SG6043 airfoil. Then, at TSR 7, the highest power coefficient was 0.452 on NACA 2412 airfoil. The lowest power coefficient was 0.368 on the SG6043 airfoil, and, for TSR 8 the highest power coefficient was 0.411 on NACA 2412 airfoil, and the lowest power coefficient was 0.279 on the SG6043 airfoil. This research found the same trend of research conducted by Samosir and Riszal [5].

3.5 Relationship of Turbine Turning and Torque to Power

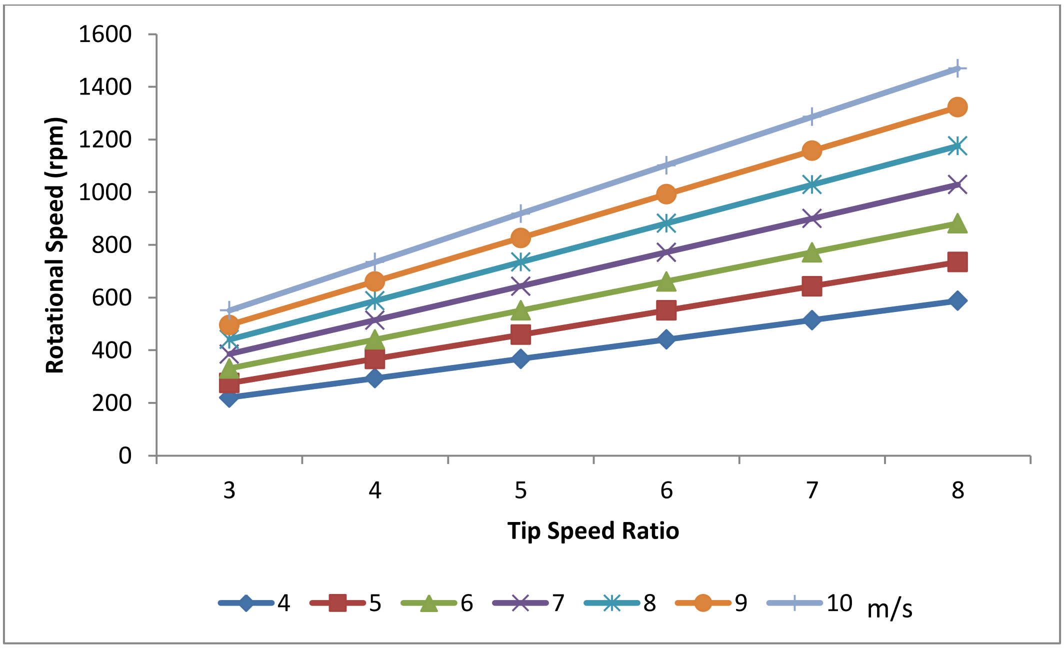

Figure-9. Turbine rotation at each wind speed.

To efficiently convert wind energy, the rotor must have a rotational speed relative to the size of the wind turbine rotor diameter used and sufficient wind speed to turn the turbine. In other words, the rotor must have an efficient tip-speed ratio. The rotation of the turbine is influenced by the wind speed coming towards the blades.

Table-2. Turbine rotation.

Wind Speed (m/s)	Rotational Speed (rpm)	Optimal Rotation (rpm)
4	220 - 588	367 - 441
5	276 - 735	459 - 551
6	331 - 882	551 - 661
7	386 - 1029	643 - 772
8	441 - 1176	735 - 882
9	496 - 1323	827 - 992
10	551 - 1470	919 - 1102

Figure-9 shows that the higher the wind speed, the higher the turbine rotation. In this study, all airfoil types produced the same rotation. However, each wind speed produced a different rotation, and when it reached the optimal rotation where at this rotation the turbine produced the highest power coefficient and power. Table-2 shows the rotation results for each wind speed used. Figure-10 shows that the turbine rotation of all types of airfoils would produce different torque coefficients so that the torque produced would be different, too. In this study, the maximum torque coefficient was generated at TSR 4 for the SG6043 airfoil type of 0.109, then at TSR 5, for the NACA 2412 airfoil type of 0.09503, NACA 4412 of 0.09756 and NACA 6049 of 0.09627.

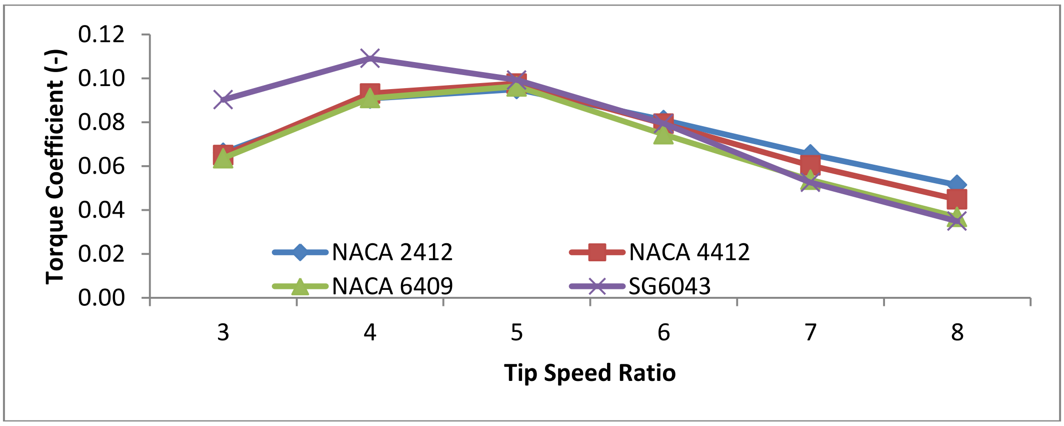

Figure-10. Torque coefficient airfoil.

3.6 Turbine Power

Wind speed is a parameter that affects the performance of wind turbines. The higher the wind speed, the higher the amount of power generated. In addition to wind speed, another parameter that affects is the tip speed ratio. Figure-11 shows the power generated from all types of airfoils at speeds of 4 m/s to 10 m/s with TSRs of 3 to 8. Based on Figure-11, the higher the wind speed, the higher the power generated, with an average increase of 6 W to 20 W, however, TSR also affected the power generated. The increase in TSR would result in an increase in power as well, where the maximum power that occurred at a wind speed of 10 m/s produced by NACA 2412 occurred at TSR 6 of 253 W, NACA 4412 occurred at TSR 5 with a power of 254 W, NACA 6409 occurred at TSR 5 with a power of 250 W and SG6043 occurred at TSR 5 with a power of 258 W. Airfoil SG6043 produced the highest power compared to other types due to the value of the lift-to-drag ratio - which affects the torque and efficiency of the wind turbine. This also showed the similarities in the research of Samosir and Riszal [5] and Fajar Romadlon *et al.*, [7], stating that based on wind speed variations and rotational speed variations show that the higher the wind speed, the higher the power generated and states that wind speed is the factor that most affects wind turbine performance.

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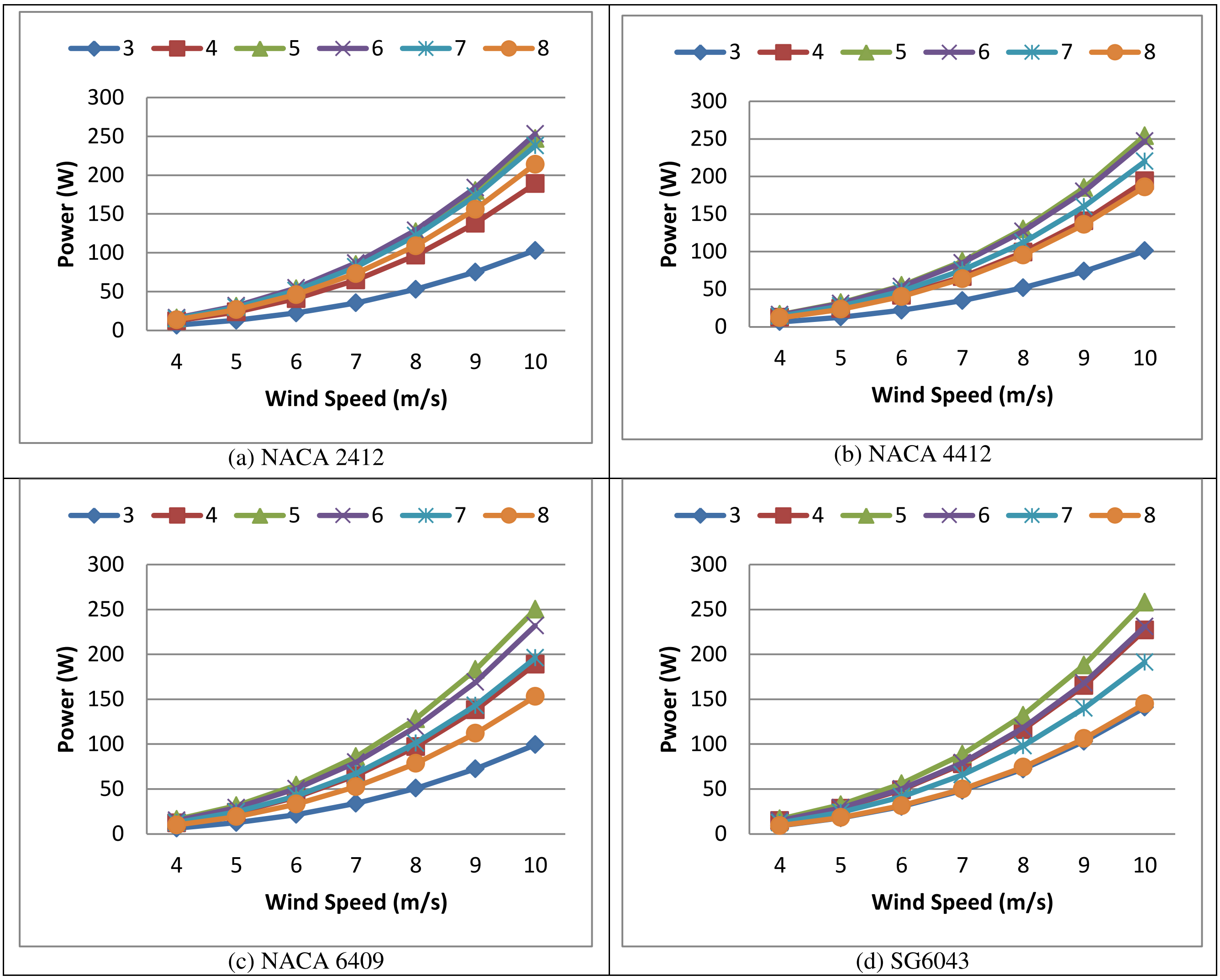

(a) NACA 2412 (b) NACA 4412

(c) NACA 6409 (d) SG6043

Figure-11. Power generated by each type of airfoil against wind speed and tip speed ratio.

3.7 Airfoil Types

Based on Figure-5 to Figure-11, the lift coefficient, drag coefficient, lift-to-drag ratio, power coefficient and power released showed different values. This was because the selection of airfoils in the development of wind turbines was something that must be considered because each type of airfoil will produce different output power. Figure-12 shows the difference in the value of wind turbine performance parameters of all types of airfoils, including lift coefficient, drag coefficient, lift-to-drag ratio, power coefficient, and power. In Figure-12. (a) and Figure-12. (b) explained that each airfoil had different lift and drag values. Where the largest lift coefficient value was on the SG6043 airfoil of 1.838. This was due to the terminology of this type, where the maximum chamber was larger than other types. While the lowest value was in the NACA 2412 airfoil of 1.529 because the maximum chamber value was smaller than other types. The highest drag coefficient value at an angle of attack of 18° produced by the type of airfoil used was 0.1040 on the NACA 6409 airfoil, this was because the NACA 6409 type was thinner and the maximum value of the chamber was higher than other types. In contrast to the SG6043 type, which produces the lowest drag at the same angle of attack of 0.0741.

This was because the thickness and chamber line of this airfoil were larger than NACA 6409 and smaller than NACA 2412 and NACA 4412. In Figure-12 (c), each TSR value had a different power coefficient value. This showed that TSR affected the magnitude of the power coefficient. The highest power coefficient results from this study were obtained from SG6043 airfoil with a power coefficient of 0.496 or 49.6%, then NACA 4412 of 0.488 or 48.8%, and NACA 2412 of 0.485 or 48.5%, and NACA 6409 of 0.481 or 48.1%. In Figure-12 (d), it can also be explained that each type of airfoil produced different power. The highest power from this study was obtained in the SG6043 airfoil type with a power of 258 W, then NACA 4412, NACA 2412, and NACA 6409 of 254 W, 253 W, and 250 W, respectively. The value of the power produced was influenced by the magnitude of the power coefficient. The difference in simulation results was

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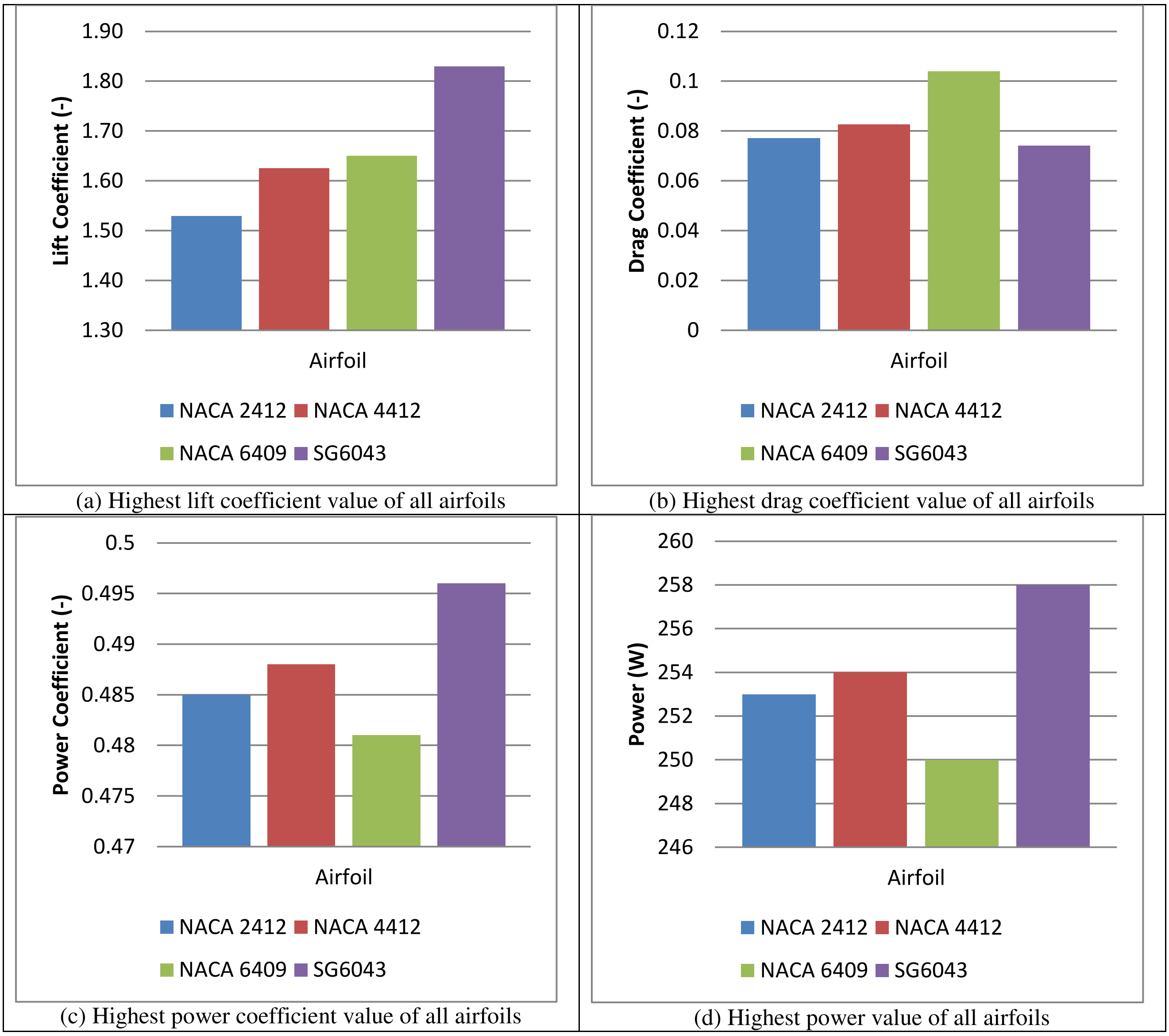
because each airfoil had different terminology where SG6043 airfoil produces the most power. This is in line with D. Wood's statement [20] and the research by Ali Said *et al.*, [21] and by Giguere and Selig [22], where the SG-series airfoil type is made specifically for wind turbines.



(a) Highest lift coefficient value of all airfoils
(b) Highest drag coefficient value of all airfoils
(c) Highest power coefficient value of all airfoils
(d) Highest power value of all airfoils

Figure-12. Results of performance parameters of all airfoil types used.

CONCLUSIONS

Wind turbines had several parameters that affected their performance, one of which was airfoil selection. In this study, the airfoils used were NACA 2412, NACA 4412, NACA 6409 and SG6043. The angle of attack influenced the value of lift and drag coefficient. While the value of power coefficient and power was influenced by wind speed and tip speed ratio resulting from turbine rotation. In addition, the thickness and maximum chamber of the airfoil also affected the value of the lift and drag coefficient, which would produce a lift-to-drag ratio, and this value had an influence on torque and turbine rotation. In this study, it was obtained that the SG6043 airfoil type produced better performance compared to other airfoil types. Where the highest lift coefficient was obtained in the SG6043 type of 1.838 at $\alpha = 16°$ while the drag coefficient of all types of airfoils increased as the angle of attack increases. The highest power coefficient and power generated were 0.496 and 258 W at TSR 5.

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