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Performance Analysis of NACA2420 as Wind Turbine Propeller Blade

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***Abstract*— Wind is one of the popular renewable energy sources which is abundantly available either in land or at sea. The wind energy can be converted into electrical energy using wind turbines or wind energy conversion systems. However, the exploration and utilization of wind energy potential in Indonesia is not optimal yet. Therefore, in the present study, the performance of a NACA2420 airfoil as wind turbine blade is evaluated. The main objective of the present research is to determine the optimum angle of the propeller blade that can deliver the most optimum performance. In order to achieve the objectives, the wind turbine blade model was tested using a wind tunnel at wind speeds varying from 2 to 9 m/s. From this research, it is demonstrated that the tunnel has helped to increase the wind speed. The maximum wind speed was generated from the tunnel when the fan distance was 1.1 m. In addition, the experiment was also carried out by varying the pitch angles to be 0^0, 5^0, 8^0, 15^0, and 30^0. From the test measurements, it was found that the pitch angle of 5^0 produces the most optimal power which was at 221.039 watts with 0.401 of power coefficient.**

***Index Terms*— NACA2420, propeller blade, turbine power, power coefficient, wind energy, wind tunnel.**

I. Introduction

Electricity is a fundamental and essential requirement for a region to grow and develop. The chosen electricity sources should be available in large amounts but with the lowest possible cost for exploring it. Therefore, development of power plants using renewable energy as the main energy source has been popular. The renewable energy sources could be solar, water, geothermal, biomass, wind, etc.

It is a common knowledge that in contrast to the natural resources of fossil origin such as gas and oil, the wind is a natural energy resource that will never run out. Besides that, wind energy is the energy that is flexible because it can be harvested in many locations such as in the area of ramps, plateaus, and at sea. A tool that can be used to convert wind energy is wind turbine or known as the wind energy conversion system (WECS). The wind turbines use the kinetic energy of wind to drive a generator that will produce electrical energy.

Wind energy is one of the most developed renewable energy and widely used today. Based on data from WWEA (World Wind Energy Association), until 2007 the estimated electrical energy generated by wind turbines has reached 93.85 GW, or more than 1% of total global electricity. United States, Spain and China are among the countries leading in wind energy utilization both technology and science.

However, the utilization of wind energy potential in Indonesia is not yet optimal. Even though Indonesia has abundant wind energy potential especially in coastal areas, it is only recently has a total installed capacity of wind energy conversion system is currently less than 800 kW [1]. Across Indonesia, there are five new wind turbine power generation units with a capacity of 80 kW each which are already built. In 2007, seven units of the same capacity following a built in four locations, each three units in Selayar Island, North Sulawesi two units, and Nusa Penida, Bali, and the Pacific Islands, each one unit. Referring to the national energy policy, wind power plants (thermal power station) is targeted to reach 250 MW by 2025.

Based on research data and results of Mahmuddin [2], wind in Indonesia especially in sea areas has varying speeds, but generally categorized as moderate speed winds. Therefore, it is important to determine the locations which have optimal wind speeds and energy density in order to optimize the harvesting power produced by the conversion system.

In real condition, wind turbines always have problems when dealing with the wind/air flow rate changes. Therefore, the system optimization for load changes is important. In a previous study performed by Nur [3], parts of pipe were used as the propeller blade of a wind energy conversion system. An experiment was conducted in order to determine their performance. From the study, it was known that flat shape pipe with a certain pitch angle has a higher rotation compare to other pipes with twist.

In the present study, an uncambered and untwisted blade which has NACA2420 shape is used. The blade is made from wood for easy manufacturing and maximum generated power. Several pitch angles are tested and compared in order to determine the angle with maximum performance. The experiment is conducted by varying the wind speed from 2-9 m/s. Moreover, the experiment is conducted with support of a wind tunnel in order to obtain higher wind speed. From the experiment, it was found that the pitch angle of 5^o has the best performance compare to other angles because of larger lift to drag ratio.

II. WIND ENERGY

Wind turbine is also known as wind energy converter system (WECS) is a system with a rotating blade that converts kinetic energy of wind into mechanical energy. The mechanical energy is then converted to be electrical energy by a generator. This electrical energy would normally be stored in a battery before it can be used [4].

II.A. Propeller Blade

There are two kinds of propeller blade that drives the shaft of a wind turbine, they are lift and drag type. Lift type is the propeller blade where the force direction is in perpendicular to the direction of flow generated when the fluid moves through airfoil surface. If the air swept by the airfoil cross-section with a certain speed, the air pressure at the top of the wings will be smaller than the bottom of the blade, this causes the lifting force on the wing which is called the lift force. While the drag force has opposite direction to the direction of motion of the blade [5]. Both forces are illustrated in the following figure

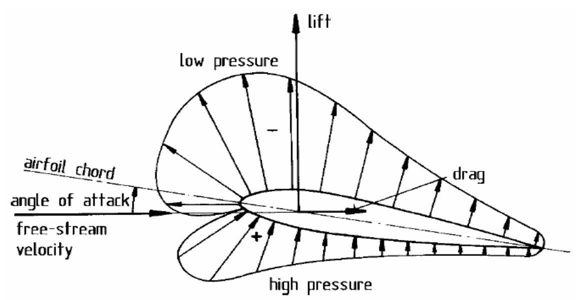

Figure 1. Aerodynamic blade pressures and forces experienced when airflow pass an airfoil surface [5].

The lift and drag forces can be computed using the following formulas

$$L = C_L \frac{\rho}{2} A v^2 \text{ (N)} \tag{1}$$

and

$$D = C_D \frac{\rho}{2} A v^2 \text{ (N)} \tag{2}$$

where ρ is air density, A blade swept area, v wind velocity, and C_L and C_D are the lift and drag coefficients, respectively.

II.B. Airfoil NACA2420

The ideal form of propeller airfoil shape is the one can absorb the kinetic energy of wind into mechanical energy with the maximum efficiency. Airfoil cross-section shape notation has been standardized by the NACA (National Advisory Committee for Aeronautics). Airfoil designed using this approach is known as NACA four-digit series. An example of the NACA notation is NACA MPXX so for example NACA 2420 has the meaning of notations is as follows

- M is the maximum camber divided by 100. In the example of M = 2 so that the camber is 0.02 or 2% of the chord.
- P is the maximum camber position divided by 10. In the example of P = 4 so that the maximum camber at 0.4 or 40% of the chord.
- XX Is the thickness divided by 100. In the example XX = 20 so the thickness is 0.20 or 20% of the chord.

In order to obtain a NACA series airfoil, the following design procedure steps are performed:

1. Select the value of *x* from 0 to maximum chord *c*.
2. Calculate the average camber line coordinates by substituting it into the values of *m* and *p*. The following equations can be used to find the camber line for each of *x* coordinate.

$$\eta_c = \frac{1}{10} x/c - \frac{2}{16}(x/c)^2 \qquad 0 \le x/c \le \frac{4}{10} \tag{3}$$

$$\eta_c = \frac{1}{90} + \frac{2}{45} x/c - \frac{2}{36}(x/c)^2 \qquad \frac{4}{20} \le x/c \le 1 \tag{4}$$

where:

- x = coordinate along the airfoil, from *0* to *c* (which stands for chord, or long).
- y = coordinates above and below the line extending along the airfoil.
- t = thickness in one-tenth the maximum airfoil chord (i.e. thicker airfoil would be 0.15)

The illustration of the coordinate positions can be seen in the following figure.

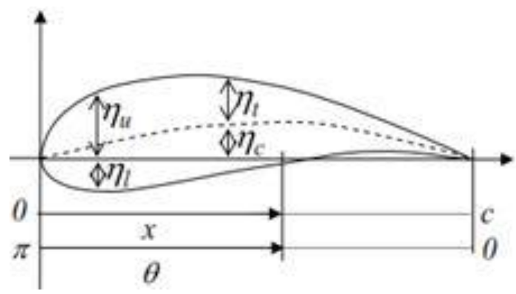

Figure 2. NACA airfoil camber line definition

3. Calculate the thickness distribution of the above (+) and down (-) average line by entering values of thickness *t* into the following equation for each *x* coordinate.

$$\pm y_t = \frac{t}{0.2}(0.2969\sqrt{x} - 0.1260x - 0.351x^2 + 0.2843x^3 - 0.1015x^4) \tag{5}$$

4. Determine the coordinates of the end of the airfoil upper surface (η_u , η_t) and lower surface (η_l , η_t) using the following relationship.

$$\eta_u = \eta_c + \eta_t \tag{6}$$

$$n_l = \eta_c - \eta_t \tag{7}$$

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II.C. Wind Tunnel

Wind tunnel is equipment that is used in aerodynamic research to study the effects of air moving past a solid object. This main function of a wind tunnel is as a testing tool for the aerodynamic properties of a model object. Components and an aerodynamic simulation are shown in the following figure [5]:

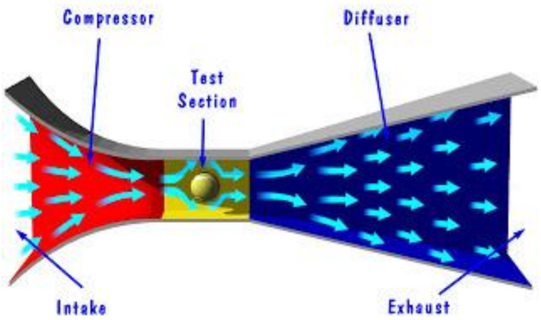

Figure 3. Simulation of aerodynamics in a Wind Tunnel.

The working principal of an aerodynamic test is to place a model which is usually much smaller than the original size, inside a tunnel that has air moving in the same direction. From there the aerodynamic performance of the model at certain points will be known, which in turn will lead to a conclusion whether the object has optimal performance or not. In the wind tunnel, the wind speed can be adjusted from low speed to high speed. Besides that, the wind direction can also be varied by changing the position of the model in the wind tunnel.

II.D. Turbine Power

Wind turbines harness the kinetic energy of the wind and convert it into electrical energy using a generator. For that purpose, wind rotates the turbine blades, the blades rotate the rotor of the generator at the rear of the wind turbines, which will produce electrical energy. The power P generated by the rotor can be calculated by the following formula [6]:

$$P = \frac{1}{2}\rho A v^3 \text{ (watt)} \tag{8}$$

where A is the blade swept area of the turbine. The kinetic energy of the wind is taken to reduce its speed. This means that the air speed behind the rotor will be lower than the speed of the air in front of the rotor.

II.E. Power Coefficient

Power coefficient is an important parameter in designing a wind turbine because it shows how much wind energy that can be extracted from the kinetic energy of the wind through the cross section of the rotor. The coefficient greatly affect the performance of the wind turbine, and is influenced by the construction of wind turbines and energy conversion principle. Power coefficient is the ratio between the power coming out of the rotor with the incoming power to the rotor [5].

Power coefficient Cp can be estimated using the following equation [7]:

$$Cp = 0.5(\lambda_r - 0.022\beta^2 - 5.6)e^{-0,17\lambda r} \tag{9}$$

where λ_r is tip speed ratio, β pitch angle, and e the natural number. Power coefficient of the rotor will be smaller than what is called Betz's limit, which says that value of the power coefficient shall not exceed the base value that is equal to 0.593.

Tip speed ratio (tip speed ratio) is the ratio of the rotor tip speed of the free wind speed. To a certain nominal wind speed, tip speed ratio will affect the rotational speed of the rotor. Lift-type wind turbines will have a tip speed ratio relatively larger than the drag-type wind turbine. Tip speed ratio is calculated by the equation [8]:

$$\lambda = \frac{\Omega R}{v} \tag{10}$$

where Ω is angular velocity and R is radius of the propeller blade. The angular velocity can be obtained by the following formula [8] :

$$\Omega = \frac{\pi n R}{30} \tag{11}$$

where n is the turbine rotation speed.

III. Propeller Blade Model

In order to conduct the experiment, a propeller blade model is constructed. The blade model is made from light wood in order increase its strength. The constructed model is shown in the following figure.

Figure 4. Propeller blade model [10]

As shown in the Fig. 4 above, the tested model model has 4 blades. Moreover, the blades shape is based NACA2420 airfoil with radius of 0.5 m.The model is installed in a turbine tower which has sketch and dimension shown in Fig. 5.

The main objective of the present study is to determine the pitch angle with optimum performance. Therefore, the experiment will be conducted for various pitch angles. In order to adjust the pitch angle, each blade is fixed to the turbine hub separately to make it easy to adjust the pitch angle as required.

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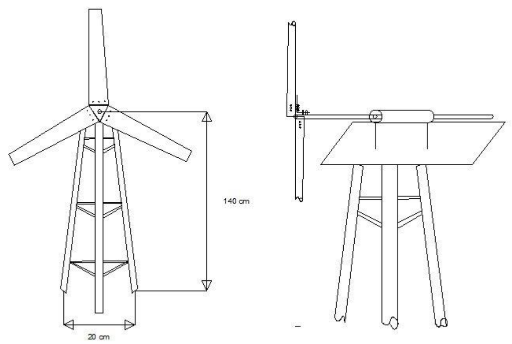

Figure 5. Turbine tower sketch and dimension

In order to generate required wind speed, a single fan is used and installed in front of the wind tunnel. The fan can generate wind speed from 2-9 m/s. Wind measurement is performed using an anemotor and rotor rotation is measured with a tachometer. The obtained data are recorded for analysis.

III. Results and Discussion

III.A. Effect of Wind Tunnel to Wind Speed

To determine the effect of the use of wind tunnel to the increase of wind speed, the wind speed is measured with and without the wind tunnel. Measurement results can be seen in the following graph [9]:

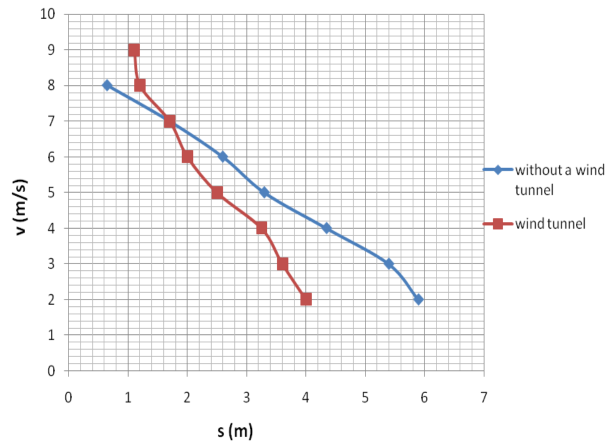

Figure 6. Wind speed measurement with and without wind tunnel

From the graph above, it is obvious that the use of wind tunnels produces higher speeds and distances that are closer than without the use of tunnels. This is because the winds generated by the fan is contained by the wall of the tunnel and focusing them ahead.

III.B. Effect of Pitch Angles to Turbine Performance

In order to determine the performance of the airfoil as the propeller blade on a wind energy conversion system (WECS), the performance of the airfoil for several pitch angles of the airfoil are measured. The measured pitch angles are 0°, 5°, 8°, 15° and 30°.

From the experiment of the blades with several different pitch angles, data are obtained and recorded. The experiment results can be seen in the following figure [9].

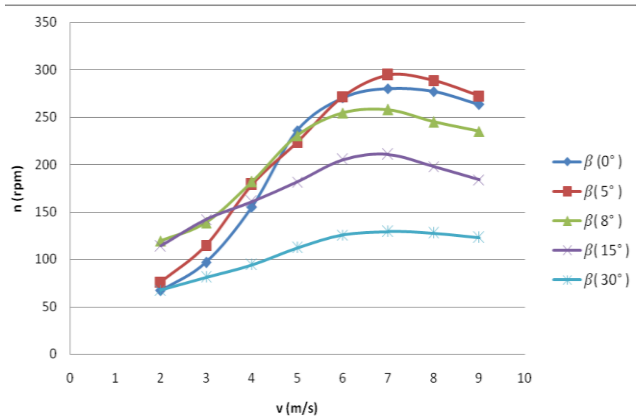

Figure 7. The airfoil test results with different pitch angles

From the figure above, it is clear that the pitch angle of 5° produces maximum propeller rotation speed especially in high wind region as compared to the ones from 0°, 8°, 15° and 30°. This is because the pitch angle 5° catches more wind to produce higher lift force than the other pitch angles.

Moreover, from the figure, it can also be noted that in the lower speed region, the wind speed increases gradually towards as the pitch angle increase. If the angle is too large, the boundary layer on the upper surface will split and create high turbulent region. This results in a reduced lift force and increased drag forces. This process is called stall. If the angle is slightly reduced, the optimal angle could be obtained. In addition, when the pitch angle becomes too large, it will reduce the ability of the blade to start the rotation for low tip speed ratio (TSR) [10].

III.C. Turbine Power Coefficient

From the experiment results shown in Fig. 7, the power coefficient of the turbine can be calculated using Eq. 9. The calculation results are shown in the following figure [9].

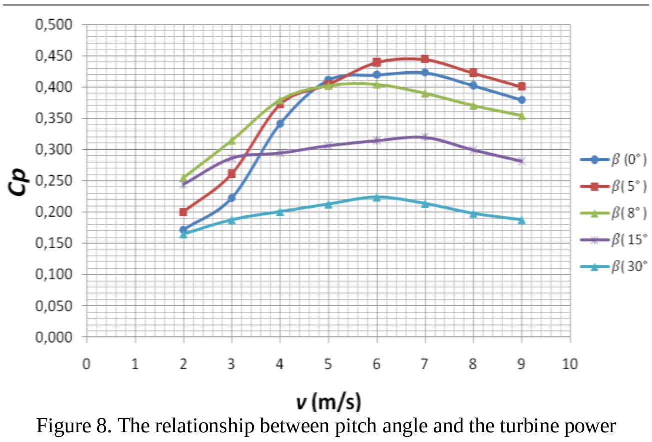

Figure 8. The relationship between pitch angle and the turbine power coefficient for varying wind speed

The figure above shows the relationship between the pitch angles and the power coefficient for each variation of wind speed. As can be seen from the figure, the largest power coefficient occurs at pitch angle of 5°. This is caused by the influence of the rotational speed of the turbine, where the faster the turbine rotation is proportional to the increase in the power coefficient.

From the calculation results of power coefficient, the power generated at each pitch angle can be calculated by multiplyng it with Eq. (8). The calculation results can be seen in the following figure [9].

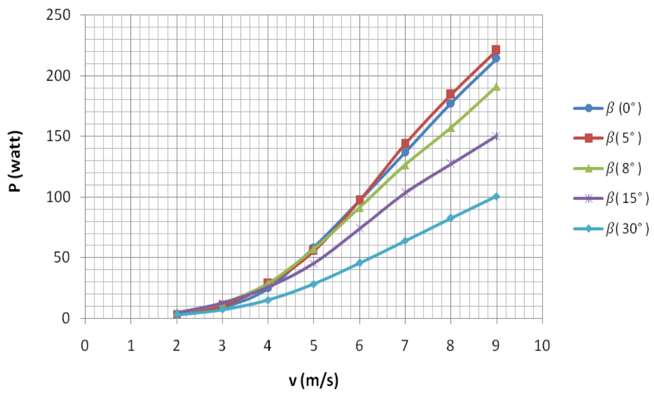

Figure 9. The relationship between wind speed and turbine power for different pitch angles

The figure above shows the relationship between the power turbine and the pitch angles on variation of wind speed, where the greatest power is produced on pitch angle of 5°.

Therefore, it can be concluded that the pitch angle of 5° is the most optimal pitch angle than other angles. This is due to the influence of wind catched area, where the catch area of wind at pitch angle of 5° is larger due to slope angle is not too large so that the lift is greater than other angles.

IV. Conclusion

Based on data analysis performed in this study, several conclusions can be drawn as follows:

a. Wind speed using a wind tunnel produces a higher speed which can be used as a validation test compared the wind turbine without the use of tunnels. This is because the winds were issued by the fan is limited by the walls of the tunnel and focused ahead.

b. Results of experiments and analysis of wind turbine propeller diameter is known performance and dimensions that can be used to generate the optimal wind turbine rotation is pitch angle of 5^o. This is due to the influence of the larger lift force.

c. Power obtained under optimal airfoil spin speed propeller blade produced is 294.44 rpm and generates a power of 221.039 watts which produced the maximum power efficiency of the experiment was 40.1%

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