Performance analysis of a H-Darrieus wind turbine for a Naca 0015 Airfoil: CFD and RSM-based design optimization

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Abstract. With the increasing demand for electrical energy and the depletion of fossil fuel reserves, this situation forces humans to look for alternative renewable energy. The Indonesian region has a very large wind energy potential because it is located in the tropics. The wind turbine is alternative energy based on kinetic energy into electricity. The purpose of this study was to analyze the effect of the number of blades, wind speed, and angle of attack on turbine performance in the form of the efficiency of the H-Darrieus wind turbine using Airfoil NACA 0015. Variations used in this study were the number of blades (3; 4; 5 pieces) and angle of attack (5º; 15º; 25º). The method used in this research is the Computational Fluid Dynamics (CFD) method and the response surface methodology (RSM). The CFD method is used to find the moment pressure and tangential velocity values, while the RSM method is used to find the most optimum variation. The results of this study indicate that a wind turbine with a number of blades 3 pieces, and a turbine angle of attack 11º is the most optimum H-Darrieus wind turbine design with an efficiency of 5.38%.

1. Introduction

Energy is one of the primary commodities needed by all people in the world. Due to the rapid growth of population and economic growth in the world, this is also in line with the increasing demand for energy. One of them is the need for electrical energy. With the increasing human needs, the sources of electrical energy will also increase. Especially for developing countries or regions, where most of what humans do requires electrical energy starting from small needs to large industrial worlds [1]. Wind as an energy source in abundance is a renewable energy source and does not cause air pollution because it does not produce exhaust gases that can cause the greenhouse effect. Indonesia is an archipelagic country which has about 17,500 islands with a coastline of more than 81.29 km and is located in a tropical area where monsoon winds pass each season. Indonesia has a very large wind energy potential, which is around 9.3 GW [2]. One way to utilize wind energy is to use a wind turbine.
Wind turbines are able to convert the kinetic energy of the wind into electrical energy with the help of a generator. One type of wind turbine is the H-Darrieus type wind turbine. H-Darrieus wind turbine is a vertical axis wind turbine that utilizes lift force when converting wind kinetic energy. The Darrieus-H turbine is also capable of receiving wind from all directions and rotating at low wind speeds [3]. Response Surface Methodology (RSM) is a mathematical and statistical method that is useful for analyzing problems, where several independent variables affect the response variable and the goal is to optimize the response. The basic idea of this method is to use a statistical-based experimental design to find the optimum value of a response [4]. While, CFD (Computational Fluid Dynamic) is a science that studies how to predict fluid flow, heat transfer, chemical reactions and other phenomena by solving mathematical equations or mathematical models. CFD can minimize time and cost in designing a product if the design process is carried out by experimental tests with high accuracy [5].

Hybrid turbine is based on a combination of two turbine technologies, namely Savonius and Darrieus [6] [7]. The main point of the study is that the asynchronous clutch (identical direction of rotation for the two rotors) provides the best performance compared to other hybrid configurations, as the built-in Savonius makes starting Darrieus easy, by providing additional power. The numerical results show that the hybrid design has important strengths over the range of tip speed ratios under consideration. The effect of variations in angle of attack on vertical axis wind turbines. It was found that the most optimum angle of attack on the turbine was between 0º-16º, the largest value was obtained at the angle of attack 6º [8] [9]. The Vertical Axis Wind Turbine (VAWT) has a good ability to extract more power from low winds than the Horizontal Axis Wind Turbine (HAWT). It is proven that 3 blades VAWT is more efficient than 2 or 4 blades. Solidity 0.2-0.4 is more efficient. Using the three-blade turbine power coefficient as a reference, it shows a 5% performance reduction for the four-blade design, while the five-blade design shows a 15% performance reduction [10].

2. Methodology

2.1. Optimization Method using RSM

The first step in this research is to enter the independent variables, namely the number of blades (3; 4; 5 pieces) and angle of attack (5º; 15º; 25º) mentioned above into the Minitab software with the RSM method. The wind velocity applied to the turbine is 5 m/s. It aims to test some variations that will be generated randomly variations. The dependent variables used in this study are moment pressure and tangential velocity, then the calculation is carried out until the torque, turbine power and efficiency of the wind turbine are obtained to obtain the optimum design. Design of experiment (DOE) obtained from the optimization process can be seen in Table 1. This study uses the RSM method with a second order model on the central composite design (CCD). Equation 1 shows the second order model of CCD method. In this study also used the CCD method with 3 factors and 3 levels which resulted in the regression equation in equation 2.

\[ \hat{y} = \beta_0 + \sum_{i=0}^{k} \beta_i x_i + \sum_{i=0}^{k} \beta_i x_i^2 + \sum_{i} \sum_{j} \beta_{ij} x_i x_j, \quad i < j \]  
(1)

\[ \hat{y} = b_0 + b_1 x_{i1} + b_2 x_{i2} + b_3 x_{i1}^2 + b_4 x_{i2}^2 + b_5 x_{i1} x_{i2} \]  
(2)

Where x represents the independence variable, y is the response variable, and is a constant. In equation 2, the code \( x_1 \) indicates the number of blades, \( x_2 \) indicates the angle of attack, \( i \) indicates the repeated number, and \( b \) is a coefficient from the test results. The independent variable codes were -1,0,1, and \( \pm 1.42 \). The value of \( \pm 1.42 \) was the result of the rotatability value \((2^k)^{1/4} = (2^3)^{1/4} = 1.42\), where \( k \) is the total independent variable. Table 2 shows the independent variable code of \( x_1 \), and \( x_2 \).
### Table 1. Design of Experiment (DOE) using CCD Method

| Std Order | X₁ Code | X₂ Code | Number of Blade (pcs) | Angle of Attack (°) |
|-----------|---------|---------|-----------------------|---------------------|
| 1         | -1      | -1      | 3                     | 5                   |
| 2         | 1       | -1      | 5                     | 5                   |
| 3         | -1      | 1       | 3                     | 25                  |
| 4         | 1       | 1       | 5                     | 25                  |
| 5         | -1.42   | 0       | 2                     | 15                  |
| 6         | 1.42    | 0       | 6                     | 15                  |
| 7         | 0       | -1.42   | 4                     | 1                   |
| 8         | 0       | 1.42    | 4                     | 29                  |
| 9         | 0       | 0       | 4                     | 15                  |
| 10        | 0       | 0       | 4                     | 15                  |
| 11        | 0       | 0       | 4                     | 15                  |
| 12        | 0       | 0       | 4                     | 15                  |
| 13        | 0       | 0       | 4                     | 15                  |

2.2. H-Darrieus Wind Turbine Design and CFD Method

The dimensions of the blades of the H-Darrieus wind turbine are showed in Table 2. Figure 1 shows the design of the H-Darrieus Wind turbine using the Autodesk Inventor and then imported into the ANSYS application to obtain the moment pressure and tangential velocity values using the CFD method. Figure 2 shows the design of the NACA 0015 airfoil used in a wind turbine. The steps in the CFD method are preprocessing, processing and post processing. The preprocessing step is making a model according to the design parameters that have been provided, meshing, and applying boundary conditions according to the fluid properties. The processing step is the input of material and wind speed, which is then applied to mathematical calculations. The postprocessing step is to organize and interpret the simulation data in the form of numbers, contour displays, vector displays, pathline displays, curves, and animations.

### Table 2. Design Specification of H-Darrieus wind Turbine

| Design                  | Specification            |
|-------------------------|--------------------------|
| Diameter of Blade       | 1 m                      |
| Height of Blade         | 1 m                      |
| Length of Cord          | 100 m                    |
| Type of Blade           | Airfoil NACA 0015        |
| Material                | Aluminium                |
Figure 1. H-Darrieus Wind Turbine Design with a number of blade variation (a) 2 pcs; (b) 3 pcs; (c) 4 pcs; (d) 5 pcs; and (e) 6 pcs

Figure 2. Airfoil NACA 0015

2.3. Performance Analysis
The value of moment pressure and tangential velocity obtained at the post-processing stage in the CFD method, then calculate the performance of the H-darrieus wind turbine according to equations 3-6 to calculate the torque, power and efficiency of the turbine. Then it was analyzed again using Minitab software using the RSM method to see which was the optimum variation of the 20 trials. Equation 3 shows the wind power generated from the rotational speed of the wind turbine [11] [12].

\[ P_{\text{wind}} = \frac{1}{2} \rho v^3 A^3 \]  

where \( \rho \) is the density of air (kg/m\(^3\)), \( v \) is the wind speed (m/s) and \( A \) is the sweep area of the turbine blades (m\(^2\)). Equation 4 shows the value of the mechanical power of the turbine [11] [12].

\[ P_{\text{mechanic}} = \frac{2\pi nr \tau}{60} \]  

where \( P_{\text{mechanic}} \) is the mechanical power of the turbine, \( n \) is the turbine rotational speed (rpm), and \( \tau \) is the torque. Equation 5 shows the wind turbine power coefficient [11] [12].

\[ C_p = \frac{P_{\text{mechanic}}}{P_{\text{wind}}} \]
where $C_p$ is the power coefficient, $P_{mechanic}$ is the turbine mechanical power (Watts) and $P_{wind}$ is the wind power (Watts). Equation 6 shows the efficiency of the wind turbine. Wind turbine efficiency can be calculated using the ratio of the power coefficient to the Betz limit, Betz limit = $16/27 = 0.593$. The value of 0.593 is the maximum value of the efficiency of a wind turbine that converts kinetic energy into mechanical energy [13].

$$\eta = \frac{C_p}{16/27}$$ \hspace{1cm} (6)

3. Results and discussion

The experimental design using Central Composite Design (CCD) method with 2 factors and 3 levels is shown in Table 1 which is then carried out using ANSYS simulation process to obtain moment pressure and tangential velocity to determine the performance of the H-Darrieus wind turbine, namely efficiency. Table 3 shows the test results using the design of experiment (DOE). Experiments were carried out for 13 variations and used a wind speed of 5 m/s. Efficiency contour from program simulation is shown in Figure 3.

Figure 3. Pressure Contour of H-Darrieus Wind Turbine with (a) Number of blade 3 pcs and angle of attack $5^0$; (b) Number of blade 5 pcs and angle of attack $5^0$; (c) Number of blade 3 pcs and angle of attack $25^0$; (d) Number of blade 5 pcs and angle of attack $25^0$
Figure 3. Pressure Contour of H-Darrieus Wind Turbine (e) Number of blade 3 pcs and angle of attack 15°; (f) Number of blade 5 pcs and angle of attack 15°; (g) Number of blade 4 pcs and angle of attack 1°; (h) Number of blade 4 pcs and angle of attack 29°; and (i) Number of blade 4 pcs and angle of attack 15°
Moment pressure simulation results in Figure 3, based on the standard order in Table 3, are used to find the efficiency value of the wind turbine. The optimum factors generated from the statistical software are shown in Figures 4 (a) and (b). The contour plot shows the maximum efficiency value indicated by a red contour. These results are in line with the contour plots and optimization plots where the results of the number of blades are 3 pieces and angle of attack 11.46º which are shown in Table 4. Equation 7 is a regression equation that can be used to determine the predicted turbine efficiency without performing simulation process to determine the value of efficiency. The comparison of actual and predicted efficiency is shown in Table 3 and Figure 5, where the efficiency value is not more than 5%.

$$\hat{y} = 30.88 - 14.40x_1 + 0.302x_2 + 1.793x_1^2 - 0.01204x_2^2 - 0.0087x_1x_2$$  (7)

| Std Order | Number of Blade (pcs) | Angle of Attack (º) | Moment Pressure (Nm) | Tangential Velocity (m/s) | Efficiency Actual (%) | Efficiency Predictive (%) |
|-----------|----------------------|---------------------|----------------------|--------------------------|-----------------------|--------------------------|
| 1         | 3                    | 5                   | 0.42                 | 2.4                      | 5.65                  | 4.89                     |
| 2         | 5                    | 5                   | 0.48                 | 2                        | 5.35                  | 4.69                     |
| 3         | 3                    | 25                  | 0.19                 | 2.2                      | 2.39                  | 3.18                     |
| 4         | 5                    | 25                  | 0.09                 | 3.4                      | 1.75                  | 2.64                     |
| 5         | 2                    | 15                  | 0.42                 | 2.2                      | 5.25                  | 5.25                     |
| 6         | 5                    | 15                  | 0.29                 | 3                        | 5.07                  | 4.87                     |
| 7         | 4                    | 1                   | 0.05                 | 3.95                     | 1.17                  | 3.03                     |
| 8         | 4                    | 29                  | 0.04                 | 2.7                      | 0.73                  | 1.12                     |
| 9         | 4                    | 15                  | 0.18                 | 3.18                     | 3.23                  | 3.27                     |
| 10        | 4                    | 15                  | 0.18                 | 3.18                     | 3.23                  | 3.27                     |
| 11        | 4                    | 15                  | 0.18                 | 3.18                     | 3.23                  | 3.27                     |
| 12        | 4                    | 15                  | 0.18                 | 3.18                     | 3.23                  | 3.27                     |
| 13        | 4                    | 15                  | 0.18                 | 3.18                     | 3.23                  | 3.27                     |

Figure 4. (a) Contour plot
Optimal Number of blade Angle of attack
D:0.9463 High 5.0 29.0
Predict Cur 3.0 11.4646
Low 3.0 1.0

Efficiency
Maximum
y = 5.3889
d = 0.94628

Figure 4. (b) optimum solution

Table 4. Optimum Solution using CCD Method

| Number of Blades | Angle of Attack | Efficiency |
|------------------|----------------|------------|
| 3                | 11.46          | 5.39%      |

Figure 5. Comparison of actual and predicted H-Darrieus wind turbine efficiency values

Based on data in Table 3, In Efficiency with 3 blades, the lowest value is 2.39% in an angle of attack of 25º and the highest value is 5.65% in an angle of attack of 5º. Meanwhile, with the number of blades 4, the lowest value is 0.73% in an angle of attack of 25º and the highest value is 3.23% in an angle of attack of 15º. The efficiency value on the number of blades 5 pieces, obtained the lowest value of 1.74% in an angle of attack of 25º and the highest value of 5.07 % in an angle of attack 15º. The number of turbine blades has a relationship with the turbine power coefficient (Cp). Where the fewer the number of blades, the Cp will increase, which indirectly also increases the turbine's effective power. Based on data from Figure 4(b), it was found that with the number of blades 3 pieces, it became the optimal condition in the Darrieus-H type turbine design on the Airfoil NACA 0015. In addition, the number of turbine blades also affects the rotation of the turbine rotor, where the more the number of blades it causes movement the turbine rotor will slow down and become heavier, whereas if the number of blades is
small, it causes the turbine rotor to rotate faster, so that the effective power generated from the turbine increases [14] [15] [16].

The angle of attack, lift (lift) and drag (drag) that work as the turbine rotates also changes. Lift and drag will form a resultant that can help the rotation or inhibit the rotation. In this study, as shown in Figure 6. Based on the data from the ANSYS simulation results of the CFD method and the optimization results of the RSM method, the highest efficiency performance was obtained on a turbine with an angle of attack of 15°. However, in angle of attack of 25°, efficiency decreased because the angle of attack has passed the critical angle or also called the critical angle of attack. The critical angle is the angle of attack where the lift generated reaches the maximum, above that angle the lift will decrease while the drag will increase rapidly, because the turbulent flow increases [17] [18].

![Figure 6. The performance of H-Darrieus wind turbine for efficiency](image)

4. Conclusion
In the test results of variations in the number of blades, it was found that an increase in the number of blades tends to reduce the efficiency of the Darrieus-H wind turbine. In the tests carried out using the CFD and RSM approaches, the best efficiency values were found in a turbine with 3 blades and an angle of attack of 11°. The best optimization design results according to the Darrieus-H wind turbine RSM method on Airfoil NACA 0015 is a number of blade 3 pieces and an angle of attack 11° which has maximum efficiency of 5.3889%.

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