Effect of Chord Length on the Performance of H-Darrieus Wind Turbine with NACA 4415 Airfoil

Indro Pramono¹, Himsar Ambarita¹,²,*, and Koki Kishinami³

¹Mechanical Engineering Department, Universitas Sumatera Utara, Jl. Almamater, Kampus USU, Medan 20155, Indonesia
²Sustainable Energy Research Centre, Universitas Sumatera Utara, Jl. Almamater, Kampus USU, Medan 20155, Indonesia
³Mechanical Engineering Department, Muroran Institute of Technology, 27-1 Mizumoto, Muroran 8585, Hokkaido, Japan

*Email: himsar@usu.ac.id

Abstract. The effect of chord length to the performance of an H-Darrieus Vertical Axis Wind Turbine (VAWT) was investigated numerically. The turbine blade made of NACA 4155 airfoil. A set of governing equations has been developed. In order to incorporate the turbulence effect, $k-\varepsilon$ model was adopted. A Computational Fluid Dynamic code has been used to solve the problem. The non-dimensional chord length of 0.2, 0.3, 0.4, and 0.5 are investigated. The contour velocity in the computational domain was plotted and discussed. By using the average velocity of the wind leaving the turbine, power coefficient is estimated. The results show that the power coefficient for non-dimensional chord length of 0.2, 0.3, 0.4, and 0.5 is 0.51, 0.57, 0.59, and 0.59, respectively. The conclusion here is that non-dimensional chord length strongly affects the power. Increasing the chord length will increase the coefficient power. However, there exists an optimum chord length it is 0.4. Thus, it is suggested to use the non-dimensional chord length of 0.4.

1. Introduction

There is a growing commitment to increase utilization of renewable energy sources to reduce the Greenhouse gas emission worldwide. One of the potential renewable energy resources is wind power. A wind turbine is an engineering innovation that can be used to convert the kinetic energy of wind into useful mechanic energy. There are many types of wind turbine can be found in the field. Those can be segregated into Vertical Axis Wind Turbines (VAWTs) and Horizontal Axis Wind Turbines (HAWTs). Mollerstrom [1] has reported a historical review of VAWTs rated 100 kW and above. The performances of VAWTs projects has been reviewed. It was stated that there are many barriers on development of VAWTs mainly on metal fatigue and durability.

In this work, we focus on the exploring characteristics of H-Darrieus wind turbine. Several works related to investigation of H-Darrieus wind turbine have been found in literature. Hashem and Mohamed [2] investigated the effect of airfoil shape and wind-lens type to improve the performance of H-Darrieus wind turbine. It was stated that S1046 airfoil showed the highest output performance. Ali et al. [3] explored the effects of instantaneous tangential velocity on the aerodynamic performance of an H-Darrieus wind turbine. CFD simulations were used for five different values of tip speed ratios i.e. 1, 2, 3, 4, and 5. The results showed that instantaneous tangential velocity has significant effect to the...
performance depend on the speed tip ratio. Abdalrahman et al. [4] studied the effect of blade pitching on performance of straight-bladed Darrieus vertical axis wind turbine (H-type VAWT) in term of power output. The investigation was performed numerically using CFD commercial code on 2D variable. The results showed that for H-type VAWT, compared to a conventional controller, a multilayer perceptron artificial neural network method results in superior power output. Bianchini et al. [5] proposed a new design criterion for H-Darrieus turbines based on the energy-yield maximization. The proposed design criterion has shown interesting prospects in terms of energy production improving. Lanzafame et al. [6] explored a strategy to develop a two-dimensional CFD model of H-Darrieus VAWT. The model has been compared with experimental work and show a good agreement. Mohamed et al. [7] employed CFD commercial code to analyze H-Darrieus VAWT at low speed. In the study, blade pitch angle has been investigated and the results indicated that the zero-pitch angle gives best performance. Asr et al. [8] investigated the start-up characteristics of H-Darrieus VAWT comprising NACA 4-digits series blade airfoils. The optimum start-up characteristics were observed with the use of a medium-thickness cambered airfoil, NACA 2418, put to use with an outward pitch angle of 1.5°.

The above literatures show that the performance of an H-Darrieus VAWT strongly depend on many parameters. CFD commercial code is widely used to explore the effect of design parameter to the performance. As a note, our research group is developing an aerator for agricultural uses. The aerator is powered by H-Darrieus VAWT comprising NACA 4155 airfoil. In this paper the effect of chord length will be examined numerically. The objective is to explore the effect of the chord length to the performance of the turbine.

2. Mathematical Model and Method
As mentioned above, in this study the developed of the H-Darrieus VAWT will be used as model to be investigated. The developed H-Darrieus VAWT is shown in Figure 1(a).

![Image](c) Rotating region

![Image](d) NACA 4155 airfoil

![Image](a) Developed H-Darrieus Turbine

![Image](b) Model of the H-Darrieus VAWT [8]

**Figure 1.** The developed H-Darrieus Wid Turbine and Models
It is used as an energy converter to power the aerator blade. Figure 2(b) shows the schematic of the H-Darrieus VAWT. The position of the air foil in the rotating region is shown in Figure 1(c). The blade of the turbine is developed by using NACA 4155 as shown in the Figure 4(d). The design parameter that is explored here is the chord length of the air foil. The non-dimensional chord length is defined as comparison of cord length to diameter of the rotating region. It is calculated by the below equation.

\[ \tilde{c} = \frac{c}{D_R} \]  

(1)

In this work, Computational Fluid Dynamics commercial code is used to perform the analyses. Two-dimensional model was used and the turbulent flow is considered. The mass conservation and momentum equation can be written as follows [9].

\[ \frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_i} \left( \rho u_i \right) = 0 \]  

(2)

\[ \rho \frac{D u_i}{D t} = -\frac{\partial \rho u_i}{\partial x_j} \left[ \mu \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} - \frac{2}{3} \delta_{ij} \frac{\partial u_i}{\partial x_j} \right] + \frac{\partial}{\partial x_j} \left( -\rho u_i u_j \right) \]  

(3)

The last term of equation (3) is named as the Reynolds-stresses and calculated by

\[ -\rho \tilde{v}_i \tilde{v}_j = -\rho \left( \tilde{v}_i \tilde{v}_j - \tilde{v}_i \tilde{v}_j \right) \]  

(4)

The Boussinesq hypothesis is used to combine the stresses with the mean velocity gradients. As a result, the Reynolds-stresses is given by the below equation.

\[ -\rho u_i u_j = \mu \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) - \frac{2}{3} \left( \rho k + \mu \frac{\partial u_i}{\partial x_j} \right) \delta_{ij} \]  

(5)

To complete those equations, additional governing equations are proposed. Here, the standard \( k-\varepsilon \) turbulence model proposed by Launder and Spalding [10] is applied. Thus, two additional governing equations are employed; they are the turbulent kinetic energy \( (k) \) equation and the turbulent dissipation rate \( (\varepsilon) \). These equations are defined in the followings.

\[ \rho \frac{D k}{D t} = \frac{\partial}{\partial x_i} \left( \mu + \frac{\mu_t}{\sigma_k} \frac{\partial k}{\partial x_i} \right) + G_k + G_b - \rho \varepsilon - Y_M \]  

(6)

\[ \rho \frac{D \varepsilon}{D t} = \frac{\partial}{\partial x_i} \left( \mu + \frac{\mu_t}{\sigma_\varepsilon} \frac{\partial \varepsilon}{\partial x_i} \right) + C_{1\varepsilon} \frac{\varepsilon}{k} \left( G_k + C_{2\varepsilon} G_b \right) - C_{2\varepsilon} \frac{\varepsilon^2}{k} \]  

(7)

In the above equations, there are two types of viscosities, the actual dynamic viscosity and the turbulent viscosity \( \mu_t \). The turbulent viscosity is given by

\[ \mu_t = \rho C_{\mu} \frac{k^2}{\varepsilon} \]  

(8)

The parameter \( G_k, G_b \) and \( Y_M \) is defined as generation of turbulent kinetic related to mean velocity gradient, generation of turbulent kinetic energy related to buoyancy and the contribution of fluctuating dilation in compressible turbulence to the overall dissipation rate, respectively. While, the parameter \( C_{1\varepsilon}, C_{2\varepsilon}, C_{3\varepsilon} \) and \( C_{\mu} \) are constants. Here, the default number from CFD code are used. The parameter \( \sigma_k \) and \( \sigma_\varepsilon \) are the turbulent Prandtl numbers for \( k \) and \( \varepsilon \) equation, respectively.

The method, in glance, explained as follows. All of the governing equations are discretized based on finite volume method. To couple the velocity field and other fields, iterative SIMPLE algorithm is employed. The residual of the continuity and \( k \) and \( \varepsilon \) equations are monitored. The iteration will be terminated when the maximum residual reached a value of less than \( 10^{-3} \) or the residual reached a constant value.
3. Results and Discussions

The simulations have been carried out for chord length 30 cm, 45 cm, 60 cm, and 70 cm. Since the diameter of the rotation region is 150 cm, the non-dimensional chord length is 20%, 30%, 40%, and 50% respectively. In all cases the pitch angle was fixed at $\phi = 8^\circ$ and the tip speed ratio was also fixed at $\lambda = 2$. The velocity of the wind at the inlet was 5 m/s.

3.1. Numerical Validation

In order to make sure that the developed numerical method is acceptable, a numerical validation has been performed. Lift coefficient ($C_L$) of an airfoil NACA 4155 has been tested in a wind tunnel at different angle of attack ($\alpha$) [11]. The results are presented in Figure 2 by blue mark. The present method was used to estimate the Lift coefficient at different angle of attack and the results are also shown in figure 2 by read mark. The figure shows that the present numerical method shows some discrepancies with the experiment at angle of attack higher than $8^\circ$. However, for angle of attack less than this value the numerical results do agree well with experiments. Based on this fact, it can be said the results of the present numerical method is acceptable. Thus, it can be used to investigate the effect of chord length.

![Figure 2. Numerical validation of NACA 4155](image)

3.2. Velocity field

Figure 3 shows the velocity fields resulted by numerical simulation for all cases. Figure 3(a), figure 3(b), figure 3(c), and figure 3(d) shows the contour velocity at non-dimensional chord angle 20%, 30%, 40%, and 50%, respectively. As a note, the red colour indicates high velocity and the blue colour indicates low velocity. It can be seen that the wind velocity decrease in the inner area of rotating regions. In addition, on the inner surface of the air foil the velocity close to zero (dominated by blue colour). On the other hand, the outer surface the velocity increases (dominated by red colour). The difference of velocity from both surfaces results in power of the turbine. The effect of the chord length can be explored by comparing Figure 3(a) the lowest chord length and Figure 3(d) the highest cord length. Figure 3(a) shows that after the rotating region the velocity of the wind is relatively high (shown by green colour). On the other hand, Figure 3(d) shows that after rotating region the velocity of the wind is relatively low (shown by the blue colour).

In order to examine the effect of chord length to the performance, the velocity of the wind leaving the rotating regions are shown in Figure 4. The profile for all chord lengths are shown in the figure. The figure shows that if the chord length increase, the velocity of the wind leaving the turbine decreases. This is because the energy of the wind extracted by the turbine to become mechanical energy in the shaft. However, the velocity profile for chord length 40% and 50% show the almost similar values.
3.3. Power coefficient
The velocity profile of the wind leaving the wind turbine will be used to estimate the power coefficient. The power coefficient \((c_p)\) is estimated using the below equation.

\[
c_p = \frac{P}{P_0} = \frac{1}{2} \left[ 1 - \left( \frac{v_2}{v_1} \right)^2 \left( 1 + \frac{v_2}{v_1} \right) \right]
\]  

(9)

Here, \(P\) [Watt] and \(P_0\) [Watt] is the mechanical power extracted from the wind and power in the wind stream, respectively. The velocity \(v_2\) and \(v_1\) is the wind velocity before entering and after leaving the turbine. Table 1 shows the average velocity leaving the turbine. It can be seen that the average velocity of the wind decreases as chord length increase. However, the average velocity leaving the turbine for chord length 0.4 and 0.5 is similar. Power coefficient for all cases are calculated using equation (9) and
the results are presented in Table 1. It can be seen that, as expected, Power Coefficient increases as chord length increases. However, the Power Coefficient for chord length 0.4 and 0.5 is the same.

| Non-dimensional Chord Length | Average at inlet $v_1$ [m/s] | Average velocity leaving the turbine $v_2$ [m/s] | Power coefficient $c_p$ |
|-------------------------------|-------------------------------|-----------------------------------------------|------------------------|
| 0.2                           | 5                             | 3.01                                          | 0.51                   |
| 0.3                           | 5                             | 2.42                                          | 0.57                   |
| 0.4                           | 5                             | 1.99                                          | 0.59                   |
| 0.5                           | 5                             | 1.97                                          | 0.59                   |

4. Conclusions
Numerical simulation has been carried out to study the effect of chord length to the performance of the H-Darrieus VAWT. The turbine has diameter of rotating region of 1.5 m and the length of the blade is 1.55 m. The non-dimensional chord length (comparison of chord length to the diameter of rotating region) was varied from 0.2 to 0.5. The velocity contour and the velocity profile of the wind leaving the turbine are plotted. The conclusion here is that non-dimensional chord length strongly affects the power. Increasing the chord length will increase the coefficient power. However, there exists an optimum chord length it is 0.4. Thus, it is suggested to use the non-dimensional chord length of 0.4.

References
[1] Mollerstrom E, Gipe P, Beurskens J and Ottermo F 2019 Renewable and Sustainable Energy Reviews 105 1-13.
[2] Hashem I and Mohamed MH 2018 Energy 142 531-545
[3] Ali A, Lee S-M and Jang C-M 2018 Energy Conversion and Management 171 1322-1338
[4] Abdalrahman G, Melek W, and Lien F-S 2017 Renewable Energy 114 1353-1362
[5] Bianchini A, Ferrara G and Ferrari L 2015 Energy Conversion and Management 89 690-707
[6] Lanzafame R, Mauro S and Messina M 2014 Energy Procedia 45 131-140
[7] Mohamed MH, Ali AM and Hafiz AA 2015 Engineering Science and Technology, an International Journal 18 1-13
[8] Asr MT, Nezhad EZ, Mustapha F and Wiriadidjaja S 2016 Energy 112 528-537
[9] Ambarita H, Siregar M R and Kawai H 2018 2018 IOP Conference Series: Materials Science and Engineering 343 012025
[10] Launder BE and Spalding DB 1974 Computer Methods in Applied Mechanics and Engineering 3(2) 269 – 289
[11] Abbot IH and Von Doenhoff AE 1959 Theory of the Wing Sections, Dover Publication Inc., New York