Effect of Tip Speed Ratio on the Performance of H-Darrieus Wind Turbine with NACA 0018 Airfoil

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Abstract. The effect of Tip Speed Ratio (TSR) to the performance of an H-Darrieus Vertical Axis Wind Turbine was studied using numerical method. The blade of the turbine was formed by using NACA 0018 mode. Three-dimensional governing equations are developed. The turbulent flow was modelled using \( k-\epsilon \) equation. The commercial code Computational Fluid Dynamic is employed to solve the problem. The focus in here is to explore effect of the TSR. The tip speed ratio is varied from 1.65 to 1.8. As a results, the contour velocity was generated and discussed. The average velocity of the wind leaving from the turbine is employed to estimate the power coefficient. The power coefficient for tip speed ratio 1.65 and 1.8 are discussed. The conclusion here is that tip speed ratio and the power coefficient strongly affected each other. Increasing the tip speed ratio will increase the coefficient power.

1. Introduction

Global warming catastrophe, critical fossil fuel sources, increases of oil price, climate change, etc. have gained the interest of many researchers to generate energy from renewable energy sources. One of the valuable renewable energy sources is wind power. A wind turbine is a structure that can be used to harvest the wind kinetic energy into rotational mechanical energy. This can be transformed into electric energy by using generator. There are several types of wind turbine that can be found in the wind farm. Those can be divided into Vertical Axis Wind Turbines and Horizontal Axis Wind Turbines. Mollerstrom [1] reviewed the performance vertical axis wind turbines that are found in the field with output power similar and more than 100 kW. The performances of the vertical axis wind turbines that have being operated were examined. It was revealed that many problems on development the vertical axis wind turbines mainly on metal fatigue and durability.

In the present study, the paper focuses on the study on the characteristics of H-Darrieus wind turbine. Some studies which focused on investigation of H-Darrieus wind turbine were reported in literature. Padmanabhan and Saravanan [2] compared NACA and NREL air foils of a wind turbine rotors with different tip speed ratio values. The two turbines showed the highest Cp values at an optimum tip speed ratio of 10 than the NREL at Cp=0.5, NREL has more Cp values for a bigger range of tip speed ratio. In addition, NREL is more efficient than NACA in order to get energy from the wind flow. Mc Cosker
[3] reported a design of three-blade horizontal axis wind turbine with a rotor radius of 2.5 m using turbine blade model NACA 4412 and NACA 23012, which follow Schmitz formula. In the study six different rotor designs are compared at different tip speed ratio. The comparisons are made by using BEM theory. The results reveals that rotor with NACA 23012 shows the bigger power coefficient at lower tip speed ratio. On the other hand, the rotor with NACA 4412 design shows the higher power coefficient for wide range of tip speed ratio especially for bigger tip speed ratio. The optimum is found to be at tip speed ratio of 10 for rotor with NACA 4412 with design tip speed ratio of 8. In addition, for rotor with NACA 23012 model the optimum tip speed ratio is 11 with design tip speed ratio of 8. It reveals that Schmitz formula and BEM theory can be employed to design the blade model with a proposed design tip speed ratio in order to get maximum power coefficient.

Vijayaragavan and Vijay [4] design of wind turbine blade using computer aided three-dimensional interactive application and analysis structural and flow characteristics using ANSYS. It shown the strain distribution, the stress distribution of blade for various materials with and without a notch. Salman Siddiqui et al. [5] investigated the tip speed ratio on wake stream specifications at operating conditions. It was plotted the vorticity and speed divisions in different locations in the downstream areas. Arian Hosseini and Navid Goudarzi [6] had designed, simulated and evaluated the characteristics of an innovative hybrid vertical axis wind turbine. In the study, a commercial computational fluid dynamics software was employed to estimate the performance parameter of the blade and structure system. It reveals an indication that when a Darrieus rotor shows that the highest power performance (Cp) it is loaded with high start-up torque demands. Pramono et al. [7] investigated the effect of chord length to the characteristics of an H-Darrieus Vertical Axis Wind Turbine (VAWT). The commercial computational fluid dynamic code is used to solve the problem. The results revealed that non-dimensional chord length strongly affects the power and adding the chord length will increase the power output of the turbine. Jerson and David [8] analyzed wind turbin performance at low tip speed ratio using the Betz-Goldstein model. Chaianant et al. [8] analyzed design factors like a material type, a number of blades height to radius ratios, design modifications, and turbine patterns by using CFD-based simulation. The number of blades and height to radius ratio has a significant effect on operating conditions of rotation due to inertia. Sobhani [10] compared NACA 0015 and J-NACA 0015 and investigated simple effects on Darrieus. Computational Fluid Dynamic was employed to estimate the forces employed on the wind rotor under turbulent flow regime conditions. It was shown that the averaged efficiencies of the turbine were enhanced for an optimal tip speed ratio which is varies from 18% to 25 % if the airfoil with a cavity was used.

Those reviewed literatures reveal that the performance characteristics of an H-Darrieus vertical axis wind turbine strongly affected on several design parameters. In addition, commercial Computational Fluid Dynamics code has mainly applied to examine the effect of tip speed ratio to the performance. The aerator is powered by H-Darrieus VAWT comprising NACA 0018 airfoil. In specific, the effect of the tip speed ratio on performance will be explored here.

2. Method and Governing Equations
In the previous section, it was mentioned that the H-Darrieus VAWT has been used in the developed aerator. The used H-Darrieus vertical axis wind turbine will be drawn as air foil design to be studied. The model of the H-Darrieus vertical axis wind turbine is depicted in Fig. 1 (a).

The structure is employed as a wind energy harvester to operate the rotor of the aerator. Figure 2(b) depicts the diagram of the H-Darrieus Vertical Axis Wind Turbine. The location of the blade in the rotating area is depicted in Figure 1(c). The NACA 0018 is used as model to develop the blade of the turbine as depicted in the Figure 4(d). The characteristic parameter design that is explored here is Tip speed ratio and chord length of the turbine blade. The tip speed ratio is outlined as comparison of the tangential velocity of the tip of an air foil and the actual velocity of the stream flow. It is calculated by the below equation.

\[ \lambda = \frac{\omega R}{v} \]

(1)
In this study, a commercial CFD code is employed to carry the examination. A two-dimensional computation domain is employed and the turbulent regime flow is taken into consideration. The continuity equation and momentum equations are shown below [9].

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

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

In the equation (3) the last term is known as the Reynolds-stresses and it will be given by

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

Figure 1 The model of H-Darrieus Wind Turbine used in this study

The stresses and the mean velocity gradients is combined by the Boussinesq hypothesis. Thus, the Reynolds-stresses can be calculated by the equation shown in equation (5).

\[ -\rho \bar{u}_i \bar{u}_j = \mu \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} - \frac{2}{3} \delta_{ij} \frac{\partial u_k}{\partial x_k} \right) \]  

To close the equations above, several complementary governing equations are needed. In this method, the standard \( k-\varepsilon \) turbulence formulation suggested by Lauder and Spalding [10] is employed. Furthermore, the two complementary governing equations are used in here. Those equations are the turbulent kinetic energy (\( k \)) equation and the turbulent dissipation rate (\( \varepsilon \)) equation. The mentioned equations are given in the below equations.

\[ \rho \frac{Dk}{Dt} = \frac{\partial}{\partial x_i} \left[ \left( \mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_i} \right] + G_k + G_b - \rho \varepsilon - Y \]  

\[ \rho \frac{D\varepsilon}{Dt} = \frac{\partial}{\partial x_i} \left[ \left( \mu + \frac{\mu_t}{\sigma_\varepsilon} \right) \frac{\partial \varepsilon}{\partial x_i} \right] + C_{1t} \frac{\varepsilon}{k} \left( G_k + C_{2t} G_b \right) - C_{2s} \rho \frac{\varepsilon^2}{k} \]
In those equations content two type of viscosities, they are the real dynamic viscosity and the proposed turbulent viscosity $\mu_t$. The proposed turbulent viscosity can be estimated as follow.

$$\mu_t = \rho C_{\mu} \frac{k^2}{\varepsilon}$$  \hspace{1cm} (8)

Where $G_k$ and $G_\varepsilon$ is known as generation of turbulent kinetic incorporated to mean velocity gradient, generation of turbulent kinetic energy incorporated to buoyancy. And $Y_\mu$ is defined as the contribution of fluctuating dilation in compressible turbulence to the overall dissipation rate. In addition, the symbol equation of $C_{\mu}$, $C_k$, $C_\varepsilon$ and $C_{\mu}$ are defined as constants. In this simulation, the original number from commercial Computational Fluid Dynamics code are employed. The mathematical symbol of $\sigma_k$ and $\sigma_\varepsilon$ are defined as the turbulent Prandtl numbers for $k$ and $\varepsilon$ equation, respectively.

The computational method used in this study, in the simple explanation, can be said as follows. The finite volume method is applied to discretize the developed governing equations. The SIMPLE algorithm is used to merge the speed field and other fields, iteratively. The errors of the continuity and $k$ and $\varepsilon$ equations are plotted. The trial and error process will be terminated if the highest total error reached a value of less than $10^{-3}$ or the total error seems to be constant.

3. The Results and Discussions

The numerical simulations airfoil NACA 0018 have been executed for 3 number of the blade. Here, the wind velocity at the inlet and the diameter of the rotation region is 5 m/s and 150 cm, respectively.

3.1. Validation of numerical method

A validation to the used numerical method has been carried out. The used parameter in the validation is Lift coefficient ($C_L$) of an air foil NACA 0018 that is tried in experimental work in a wind tunnel at different angle of attack ($\alpha$). Figure 2 shows the comparison. In the figure parameter resulted in the experiment shown by the blue color. The present CFD method was also employed to calculate the Lift coefficient at different angle of attacks. The results are also presented in Figure 2 by read color. The comparison reveals that the numerical result in the proposed method do agree with the experimental result. Based on this fact, the proposed numerical method can be employed to explore the effect of tip speed ratio to the performance of the wind turbine.

![Figure 2 Numerical validation of NACA 0018](image-url)
### 3.2. Velocity field

Figure 3 depicts the speed value in the computational domain given by the CFD results for all cases. Figure 3 and Figure 4 shows the contour velocity. To be noted, the red colour related to big speed and the blue colour shows low velocity. It shows that the wind speed lower in the inner region of rotating areas. Furthermore, on the inner regions of the turbine blade the speed almost zero (shown by blue colour). In contrast, the outer surface the velocity higher (shown by red colour). The difference of speed from the two surfaces results in power of the turbine. The effect of the tip speed ratio can be shown by making comparison of Figure 3 case with the velocity with 1.65 of tip speed ratio and Figure 4 with the speed with 1.8 of tip speed ratio.

The influence of tip speed ratio to the performance is examined by using comparing those two figures. The figure reveals that if the of tip speed ratio increase, the performance will increase. This is related to the energy of the wind flow drawn by the air foil to become mechanical kinetic energy in the rotor.

![Figure 3 Contour velocity with 1.65 tip speed ratio](image1)

![Figure 4 Contour velocity of 3 blade with 1.8 tip speed ratio](image2)

Figure 5 shown air flow inlet and outlet. It has shown contour of velocity wind turbine. The blue one was the lower flow and the red one was the highest flow. It shown the air flow with tip speed ratio 1.65 had higher velocity than turbine with 1.8 tip speed ratio.
Figure 5 Correlation of velocity and tip speed ratio

3.3. Power coefficient
The characteristic of the velocity of the wind when it is leaving the air foil will be examined to calculate the power coefficient. The coefficient of the turbine power \(c_p\) is calculated by the equation formulated in the following.

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

(9)

Here, the parameter \(P\) [Watt] and \(P_0\) [Watt] is the mechanical power drawn from the stream of the air flow and power in the air stream flow, respectively. In addition, the speed \(v_2\) and \(v_1\) is the air flow velocity before entering the turbine and the wind velocity after leaving the turbine, respectively. The average velocity leaving the turbine is given in Table 1. It shows that the average speed of the wind lower as tip speed ratio higher. In addition, as expected, the Power Coefficient higher as tip speed ratio higher.

| Tip Speed Ratio | Average velocity \(v_1\) [m/s] | Power coefficient \(c_p\) | Power Pt [watt] | Efficiency [%] |
|----------------|--------------------------------|--------------------------|-----------------|---------------|
| 1.65           | 2.095                          | 0.553                    | 50.778          | 55.284        |
| 1.8            | 2.005                          | 0.562                    | 51.608          | 56.203        |

4. Conclusions
The aim of this study was to explore a numerical simulation in order to explore the influence of tip speed ratio on the performance of the H-Darrieus Vertical Axis Wind Turbine. The turbine has the following specification: diameter of rotating region 1.5 m, the length of the blade is 1.55 m and number of blade is 3. The tip speed ratio was varied from 1.65 and 1.8. The velocity contour and the velocity profile of the wind leaving the turbine are shown. The conclusion can be drawn here is that the non-dimensional tip speed ratio strongly affects power. In addition, increasing the tip speed ratio will increase the coefficient of power.
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