Simulation analysis of Venturi-Vertical Axis Wind Turbine (V-VAWT)

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Abstract: - The simulation analysis of a new concept in vertical axis wind turbine was carried out in this study using the CFD simulation. A secondary blade was attached to each blade of the conventional vertical axis wind turbine to create a venturi-effect, to ensure increasing the cut-in speed of the wind turbine by increasing the wind velocity attacking the main blade especially for low wind speed area such as Malaysia and other tropical regions, where the average wind speed is 2.0m/s. In addition, the corresponding CFD analysis has been made to get an optimum size, shape, and position of the secondary blade. The simulation analysis gave useful indication about the flow between the main and the secondary blades. Besides that, the improvement in the output power of the V-VAWT has a value of 45% more than the bare vertical axis wind turbine.

Key-Words: - Wind turbine; Vertical Axis Wind Turbine; Venturi-Effect; CFD; Simulation; low wind speed.

1 Introduction

The kinetic energy generated from the movement of atmospheric air is called the wind energy[1]. Many years ago, the using of this type of energy was very extensive in grain grinding, sailing, and water irrigation[2]. The wind turbine converts the kinetic energy to mechanical energy which is then used to generate power[3]. In modern models of wind turbines, the mechanical energy is converted to electrical energy utilizing a generator connected to the rotating shaft of the turbine. In the field of generating electricity power from the wind energy, there are two main types of wind turbines, the horizontal axis and vertical axis wind turbine[1]. The advantages of the vertical axis wind turbine which made it more reliable than the horizontal axis wind turbine, is the ability of accepting wind from any direction, since the horizontal axis wind turbine must face the direction of the wind[4]. The other advantage is the ability of producing energy at steady state, so there is no fluctuating in electrical power generated. Besides all these advantages mentioned, is the simplicity of the vertical axis wind turbine, as there is no yawing component must add[5]. The blade of the vertical wind turbine may construct as simple as like a flat plate, i.e. no need to twist like the horizontal axis wind turbine blades[6]. But for higher efficiency, the twisted blades are needed.[7]Designed a new model of vertical axis wind turbine to investigate the characteristics and performance obtaining aerodynamic load estimation. The model was combined with a synchronizing generator to examine the gyroscopic effects, the structural damping, and the power generation. The computer code used for that study in FORTRAN, and was developed to analyze the dynamic effects of the vertical axis wind turbine. Then the results were compared with other theoretical and experimental studies. A diffuser augmented vertical axis wind turbine was represented by [8], the study was considered to obtain a theoretical approach of that type of wind turbine. A mathematical model was built using some assumptions to estimate the augmentation ratios. The results showed those maximum power coefficient and augmentation ratios are directly proportional the pressure factor, turbine factor, and the maximum velocity. Andy Grant and Nick Kelly[9] developed and tested a mathematical model of a ducted wind turbine and described the integrations of the turbine according to various domain of building simulation. The study was investigated the concept of ducted wind turbine, and the integration of the wind turbine model mounted inside the building using the simulation tools. Highly efficient horizontal axis wind turbine mounted in a diffuser was described by [10]. The study indicated that the output power of the diffuser type wind turbine is much higher than the conventional wind turbine. The diffuser increased the wind speed passing through the wind turbine blades, this yield to increase the rotational speed of the turbine and then increasing the output power. An investigation of numerical simulation for flow filed around a diffuser wind turbine using the CFD was presented by[11]. In order to develop this model, a small wind turbine of 1.5kW was used. A comparison between the computed results of the study with the experimental results has been presented. The study presented various diffuser angles with load coefficient. A suggestion was made so that the load coefficient for maximum performance is small compared with the bare wind turbine. for the flow field behind the diffuser augmented wind turbine, [2] presented an experimental and numerical model to investigate the flow filed behind a small wind turbine augmented by a diffuser. A hot wire technique was utilized to measure the velocity of air behind the wind system. considering the mechanism effects of the diffuser on the aerodynamic behavior of the wind attacking the turbine blades, it is found that there is a difference in vortex tip between the diffuser and the bare type wind turbine.

[12]Described a model of wind turbine utilized for the generation of electricity power in Malaysia. The main purpose of the study was to make a 1/3 scaled prototype of vertical axis wind turbine. The study also indicated that there are two major parameters that influence the performance of the vertical axis wind turbine, which are the wind speed, and the transmission system of the turbine. The velocity range was between 5.8m/s to 7m/s, and from the experimental work, it was found that the output power was 132.19W to 223.8W. another type of vertical axis wind turbine was developed by [13], where a preliminary development of a Savonius prototype wind turbine was built to test the performance of low wind speed wind turbines. The overall size of the prototype was 1.0m diameter and 1.5m height.

Considering the mentioned background about the wind turbine used in generating electricity power and its characteristics, in this study, a CFD simulation of a vertical axis wind turbine is presented. Besides that, the analysis of applying the venturi-effect on each turbine blades by adding a secondary blade connected to the main blade acting together as a virtual duct or diffuser. In addition to the simulation process, an experimental work has been done using the wind speed range recorded by weather data station in the same location of the wind turbine.

2 Low wind Speed

Small wind turbines require less wind speed source than the large commercial horizontal axis wind turbines, so the vertical axis wind turbine is considered as a feasible in many places[13]. Much of the land mass in Malaysia gets low wind speed and this speed is not enough to start the turbine. Figure (1) shows an annual average wind speed distributed at 14 weather stations in Malaysia. The data presented in the figure show that the average wind speed is about 2-3m/s. Mainland of Malaysia and many parts of ASEAN countries receive an average annual less than 3.0m/s of wind speed, therefore the need for designing a low wind speed wind turbines is occurred. For many islands and places in these regions, the electricity power transmission is not justifiable with the tropical climate which is almost cloudy, so there is no way to take the solar energy as the main source[13]. In the other side, ASEAN countries have a large population, so that the ability of building wind farms of large horizontal wind turbine is not possible.

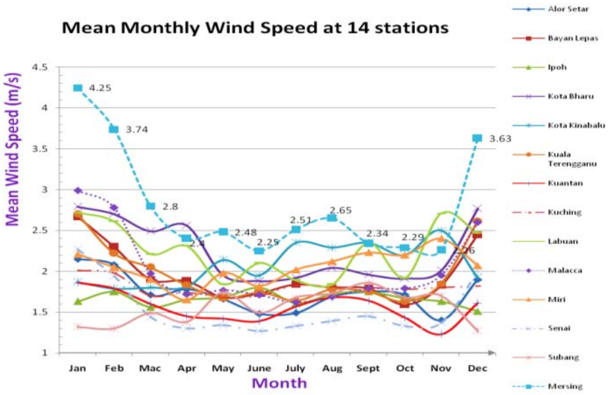

Fig. 1. Average annual wind speed in Malaysia

3 Numerical analyses

To verify the mathematical behavior of the air flow between the secondary and the main blades, the consideration of duct analysis (venturi-effect) will be assumed. Figure (2) below represents a top view section of the main blade attached with the secondary blade. The control volumeis the area between the two blades which is considered as a duct profile with different area ratio, the venturi-effect will take place in section (2), where the area ratio was taken in different values to get the optimum area ratio. Using Bernoulli's equation and assume that the flow is homogenous, incompressible, and steady state:

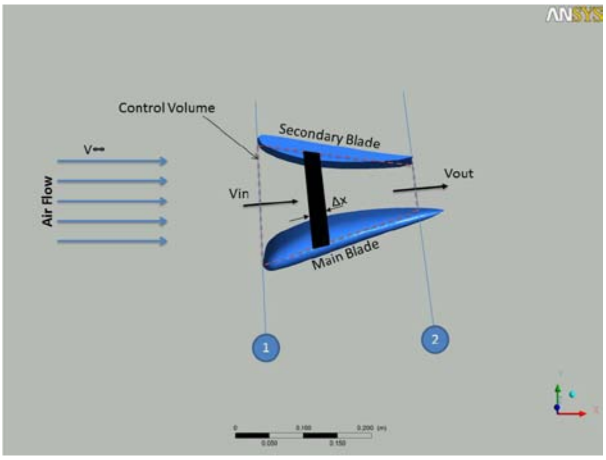

Fig. 2. Top view section and control volume of main and secondary blades

Giovanni Battista Venturi (1746 – 1822), find the effect of venturi according to the Bernoulli's equation for incompressible flow where the acceleration of the air flow is occur in the shrinkage part[14]:

$$P + \frac{1}{2}\,\rho\, V^2 + \,\rho\, g\, h = constant \tag{1}$$

From this equation we can derive:

$$P_1 - P_2 = \frac{1}{2}\,\rho\,(V_2^2 - V_1^2) \tag{2}$$

And:

$$A_1 V_1 = A_2 V_2 \tag{3}$$

Where:

A = area, V = velocity, ρ = density of air, g = gravitational acceleration, h = height, and P = air pressure.

Form the above equation, it is found that the effective parameter is the wind speed, from figure (2) V_2 is very important in the equation of power, as the power generated from the wind turbine is proportional to the cubic of the wind speed attacking the blade of the turbine, which is in this case V_2.

Now, the power of the wind can be estimated from the kinetics energy equation of any particle by the following formula:

$$KE = \frac{1}{2}\, m\, V^2 \tag{4}$$

Where the amount of the air flow is given form: $m = \rho\, A\, V$, m is the mass of air, A is the swept area by the turbine blades, ρ is the air density, and V is the velocity of air.

By substituting the mass of air in the above equation, the kinetic energy will be:

$$KE = \frac{1}{2}\,\rho\, A\, V^3 \tag{5}$$

The equation that expressed the amount of air indicated that the power of the wind turbine is proportional to the density of air and the swept area, where the density of air is 1.225 kg/m^3, and the area is equal to $\pi D^2/4$, so that the equation will be:

$$KE = 0.48(D^2 V^3) \tag{6}$$

For example, the velocity attacking the conventional vertical axis wind turbine VAWT is 2.0m/s; by substituting this value in the above equation we found that the power from the wind will be 5.53 Watt. Now by using the venturi vertical axis wind turbine V-VAWT, the velocity will be 2.6m/s, therefore, the power will be 12.15 Watt. Form the above example, the efficiency improvement for the new turbine will be 45% more than the conventional VAWT.

4 CFD Analyses

Considerable improvements in the understanding of the vertical axis wind turbine VAWT can be achieved through the use of CFD and experimental measurements. The scope of this study is to illustrate the improved understandings of the aerodynamic of VAWT performance through wind tunnel testing and computational simulation of the flow field around both the blade and the turbine. ANSYS CFD v.14 was used to create 2D and 3D models of the blades and the meshing. One main blade of the VAWT was scanned by 3D laser scanning device and converted to a geometry file. Then the geometry was imported using ANSYS CFD where an enclosure was built surrounding the blade to act as a domain, as shown in figure (3). The input wind speed to the domain was 2.0m/s, with high mesh accuracy for the elements number was 2727595 elements. Then, the pressure contour was captured to be studied and spot the effective area on the surface of the main blade as shown in figure (4).

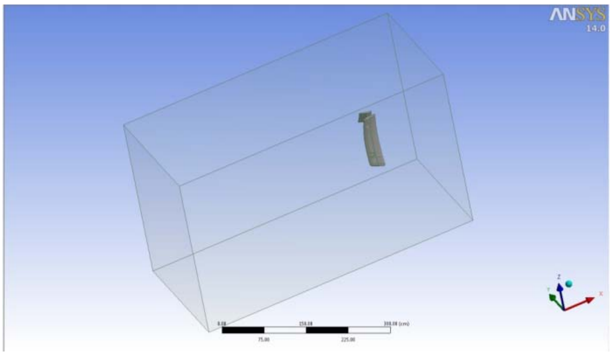

Fig. 3. CFD analysis domain with main and secondary blades inside

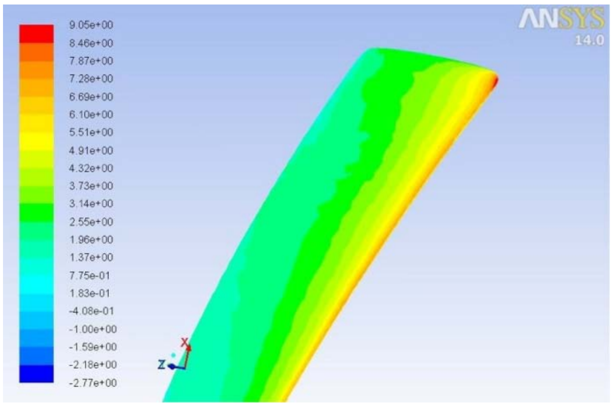

Fig. 4. Effective area of pressure at the main blade

The pressure distribution on both front and back sides of the main blade was calculated from the CFD simulation results. Then the effective area showed in figure (4) above estimated by the large pressure difference between the front and the back side in which this difference will create the rotational vector. The design of the secondary blade was modified several times to get the optimum profile. Then both the main and the secondary blades were simulated using the same procedure with an average input wind velocity of 2.0m/s.

5 Results and discussion

The analysis of a venturi-vertical axis wind turbine V-VAWT was taken into consideration in both CFD simulation and experimental analysis for the prototype. At an average minimum wind speed of 2.0 m/s and an ambient temperature of 30°C. based on the simulation results for the actual size of the main and secondary blades, the model was divided into six planes at six different distances between the secondary and the main blades to cover all the volume between them, as shown in figure (5).

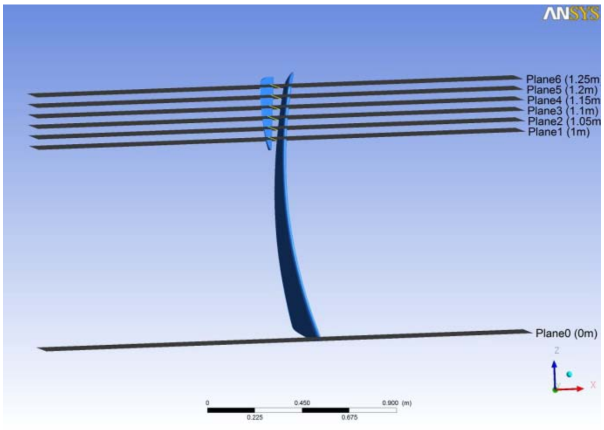

Fig. 5. CFD analysis of different planes height

All the planes were name from (plane 0 which represents the base of the main blade) to (plane 6 which is at the top of both the secondary and the main blades). Then it was found that from the simulation results, the difference between closed plane is not considered, so the number of planes then minimized to three planes only as shown in figure (6).

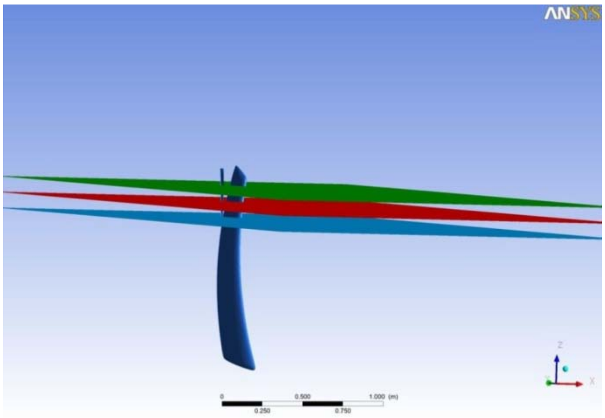

Fig. 6. CFD analysis of three main planes

In figure (7) below, it was found that the velocity profile of the wind speed at the three planes as defined before. The velocity profile for the bottom plane showed that the maximum value of the velocity is 2.61 m/s, and for the middle plane 2.52 m/s, finally for the top plane is 2.35 m/s. by taking the mean value for the velocity profile in the three planes, which is about 2.50 m/s. the increasing of the wind velocity in this figure represents the venturi-effect in which the velocity entering the front area between the main and the secondary blades at 2.0 m/s, and then leaving from the back area at 2.57 m/s.

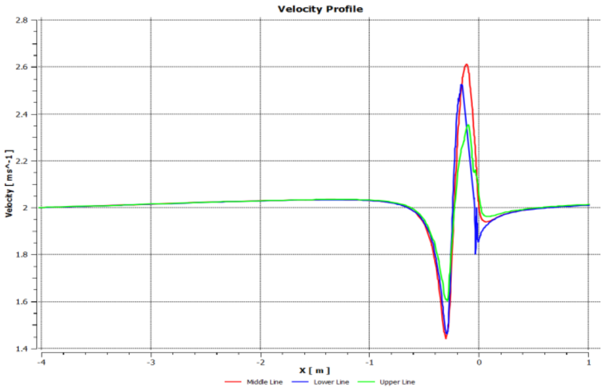

Fig. 7.Velocity profile of the three planes

The other simulation result is about the velocity vectors of the wind profile between the main and the secondary blades. Figure (8) shows the velocity vectors of the wind flow, where the direction of the vectors represent the direction of the wind. The velocity is gradually increased as the vectors reach the venturi area, where it can be noticed that the vectors reach a velocity value of 2.5 m/s. this increasing in velocity is very important, because most of the vertical axis wind turbine have a cut-off speed (which is the minimum wind speed must occurs to make the turbine rotate) of 2.5 m/s. on the other hand, from figure (9) which represents the velocity contour of the model, it can be conclude that the exist velocity from the venturi-area could reach a value of 2.74 m/s. this value is useful for this design especially when this is will be the input velocity or the attacking wind speed to the second blade of three blades vertical wind turbine.

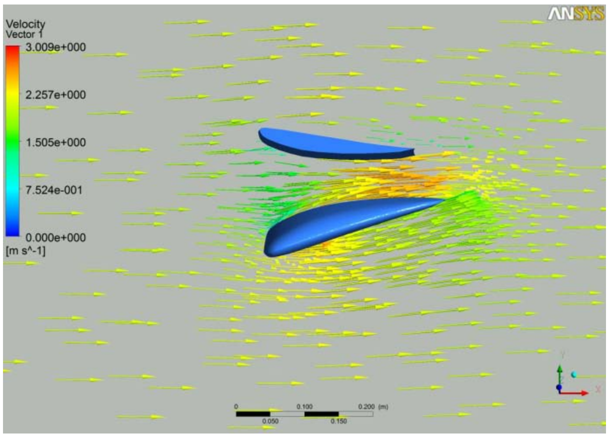

Fig. 8. Top view of velocity vector

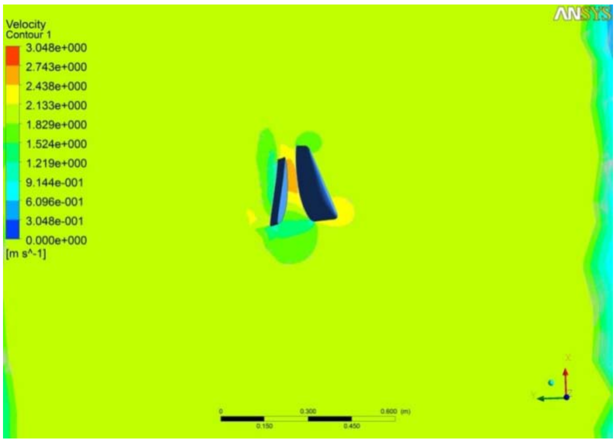

Fig. 9. Top view of velocity contour

Figures (10, and 11) below show the 3D CFD analysis of velocity vectors, where the vectors presented between the main and the secondary blades in different plane's height. This can indicates that the velocity attacking the first surface of the main blade will reduces its speed; this is due to the venturi-effect. On the other hand, the vectors rapidly changed the direction when entering the venturi-zone where the speed is maximized and attacked the main blade; therefore, the cut-in speed will be increased.

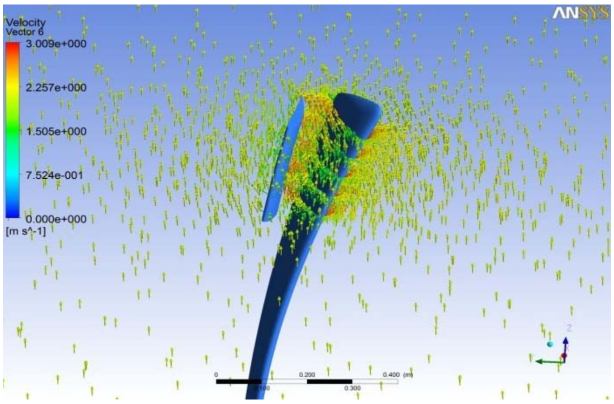

Fig. 10. CFD analysis of 3D velocity vectors

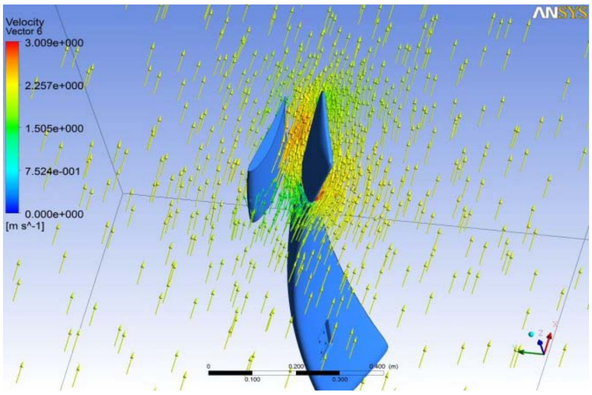

Fig. 11. CFD analysis of 3D velocity vectors inside the domain

4 Conclusions

This study demonstrated an optimization and development of a conventional vertical axis wind turbine VAWT by adding a secondary blade attached to each blade of the turbine. The developed system first analyzed using the CFD ANSYS simulation to get the optimum size and position of the secondary blade to ensure a full optimization of the venturi-effect would occur between the main and the secondary blades. As the power from the wind, or the kinetic energy of the wind turbine is proportional to the third power of the wind speed; therefore, the venturi-effect leads to increase the velocity attacking the main blade and hence increasing the power. The improvement of the power for the novel venturi-vertical axis wind turbine V-VAWT was calculated to be 45% more than the conventional VAWT.

5 References

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