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Numerical Investigation on the Effect of Profile and Blade Numbers in a Savonius Vertical Axis Wind Turbine

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ABSTRACT

Small-scale wind turbines are considered recently as an attractive source of renewable energy, especially at remote area with respect to city centre. The design and characterization of a small vertical wind turbine are introduced through this work. A CFD analysis has been used as a first step in design to simulate the flow around the vertical blades of the small wind turbine. Different parameters have been taken into account in this work such as blades number, shape, and existence of stator blades deflector. Three different versions depend on blade profile have been examined. The turbulence model with sliding mesh in CFD have been performed. In this paper, a performance of small-scale of vertical wind turbine represented by CFD results of power coefficient, and optimal freestream velocity of this model are presented. The results showed that using 8 blades of VAWT instead of 4 blades with the same profile of blade has enhanced VAWT performance up to 64%. Also, increasing the concave profile of the blade can rise the torque produced by approximately 8%, however more increase in concave shape cause drop down by 5.6 %. Moreover, including stator deflector to the VAWT design has ability to increase the torque produced by 70 %. The output of these results will help to choose the optimum configuration of the small vertical wind turbine to implement this design experimentally as a next step.

1. Introduction

Small-scale wind turbines have recently gained popularity as a viable source of environmentally friendly power, particularly in far off zones regarding the downtown area [1]. However horizontal axis wind turbines have grown to such an extent that they are now used in all large-scale wind farms. Due to their simplicity in design, and a low cost gain the vertical wind turbine many advantages over the horizontal axis wind turbine. For example, vertical axis wind turbines are in need to less expensive towers [2, 3]. The rotor shaft is mounted vertically and can be positioned near the ground, which is an advantage of vertical axis wind turbines over horizontal axis wind turbines.

Extensive studies on both horizontal axis wind turbines (HAWT), and vertical axis wind turbine (VAWT) can be found in the literature [2, 4–10], however, more investigations are in need to further

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understanding of VAWT most dominant design parameters that lead to improve its performance. Horizontal Axial Wind Turbines (HAWT) are used widely due to their high efficiency [11], however, the Vertical Axial Wind Turbine (VAWT) has advantages over HAWT, low cost, lower noise, independent on wind direction, and easy to tilt to a range of angles [9]. These advantages have motivated many researchers in the literature to conduct researches in this area to improve VAWT low efficiency [7, 12].

Both experimental and numerical approaches were used to study the performance of VAWT [9]. Generally, VAWT can be classified into different type according to the rotor design. The impact of blade profile, number of blades, rotor design of VAWT on turbine performance were studied in the literature [13]. Integrating an external design element, such as, windshields, guides, and nozzles, to the turbine rotor lead to improve its performance [14–16].

Adding collection-shield boards to the vertical wind turbine structure with S-type blade profile has increased the power output to three times higher than the case without [10]. In different study, adding a wind deflector in front of the rotor, has shown increase in the system performance to about 16 % [13]. Parameters such as, number of blades, tip-speed ratio, and turbine solidity, have shown a significant impact on turbine performance [2]. Increasing the number of blades at a constant solidity, has a significant impact on the generated power [17]. Changing in solidity shows an influence on the value of the coefficient of performance (CP) of the VAWT. By changing the blades number, chord length, and radius, cp shows a reduction in its value with increasing solidity magnitude [17].

Other studies relayed mainly on numerical simulations CFD [6, 9, 18, 19]. The CFD studies of VAWT relied mainly on solving Unsteady Reynolds Averaged Naiver Stokes (URANS) equations [19], [20]. A comparison between two URANS models, k-w and SST k-w to simulate the flow conditions within VAWT at low Reynolds number, has shown an accurate result of SST k-w rather than results that obtained with K-W [18].

CFD simulations are used in some studies to optimize and predict the VAWT efficiency at different design parameters. Generally, two approaches were adopted in the literature with CFD studies, (1) reference frame; and (2) dynamic mesh. In the first method, the blades are considered fixed and the air flows within the domain. This approach is relatively simple and time efficient and can be used within steady state models. In the dynamic mesh simulations, the wind turbine blades are considered to be in motion, and the air acts according to this motion. The latter approach can be considered higher accuracy than the first method [20]. The influence of different working conditions on VAWT of NACA00XX performance were tested. The results have shown that, the CP values were fluctuated a cross the constant value of CP as the wind fluctuated at any blade thickness [21]. A mesh independent study and its effect on CP, the CP magnitude was found to be very sensitive to the mesh size in CFD simulations [22]. Therefore, selecting right mesh size must be considered. CFD studies [23] which adopted different rotor design was carried out with two models A (Benesh type) and model B (Semicircular type) which were different in blades layout. The simulation results showed that Cp was obtained from model A higher that mode B in 4.8 times at same speed ratio. Other study has investigated the effect of different aerofoil profile [24]. The performance of VAWT was obtained with NACA0018 and S1046 aerofoil profiles. The outcomes showed that VAWT with S1046 aerofoil with 2 degree of blade pitch can offer best performance.

Adding additional surfaces such as shield boards around the rotating rotor, has shown an improvement in the turbine efficiency to three times higher than the typical design [10]. The flow structure around VAWT blades was simulated using CFD tool. The flow pattern and the generated vortex were predicted and the validation with experimental data has shown good agreement [18, 25].

Blade tips plays also an important role on VAWTs efficiency due to vortices generate at the tips. A study was conducted at the literature [26] to add an endplate to reduce these effect. Different designs were adopted at different speed ratios. The study concluded that semi-circular inward endplate shows an improvement in the Cp by 7.45 %, 5.79 % at speed ratio at 2.19 and 2.58 respectively.

According to the above, more numerical investigation is still in need to fill the gap in the literature, and to help in developing and designing an optimal VAWT. This work aims to set the first step toward designing and fabricating a small scale vertical wind turbine and minimizing the manufacturing costs. In this paper, CFD simulations were adopted to study the impact of blade number in term of using dynamic mesh simulations.

2. Main Description of the Wind Turbine

The main idea of the wind turbine is to extract the kinetic energy from the oncoming air, so the wind turbine starts rotating due to the energy transfer between the wind and the blades of the wind turbine. Through a gearing mechanism coupled to the rotating shaft, this rotational motion is changed to mechanical energy, which is then turned to electrical energy via the generator box. The maximum power which can be extracted from the wind is:

$$P_{max} = \frac{1}{2}\rho A {V_\infty}^3 \tag{1}$$

where ρ is the density of the air, A represents rotor swept area perpendicular to the wind direction, and V_∞ is the freestream air velocity.

The rotor of a wind turbine cannot absorb all of the energy from the flow path since this would need the wind to become stagnant on the rotor's leeward side.

The important coefficient in the power calculation related to the wind turbine is a power coefficient which represent a function of the collective blade pitch and the tip-speed ratio (TSR). The TSR is calculated by dividing the blade tips' tangential speed by the wind speed perpendicular to the rotor plane as:

$$TSR = \frac{\omega R}{V_\infty} \tag{2}$$

where ω is the angular velocity of the rotor, and R represents the radius of the wind turbine rotor.

The wide variety of attack angles and profiles that the blades encounter are considered the VAWT's biggest challenges. The turbine's blades even sense the reverse when it starts at zero rotational speed. The greatest angle of attack decreases as rotational speed increases. For this reason, it is so important to investigate the status of blades profile and positions respect to the rotate center.

3. Computational Fluid Dynamics (CFD)

Computational Fluid Dynamics (CFD) simulations to aid in the design process of the small scale vertical wind turbine were performed using ANSYS Fluent 20. The flow field has been assumed to be 2-dimensional, transient, incompressible, and fully turbulent. The working fluid is air and is treated as an ideal gas. The Fluent model employs a finite volume technique to solve the Reynolds averaged

Naiver-Stokes equations. The standard k-ε epsilon turbulence model with double precision was selected to define the turbulent energy and dissipation rate. The adopted solution method which is used in the CFD simulation includes an implicit method for pressure-linked equations, the simple algorithm for the velocity-pressure coupling, and the second order upwind approach for all transports equations except the turbulence dissipation rate, which was first order. The aim residuals for continuity, momentum, and turbulence equations were less than 1×10^{-4}.

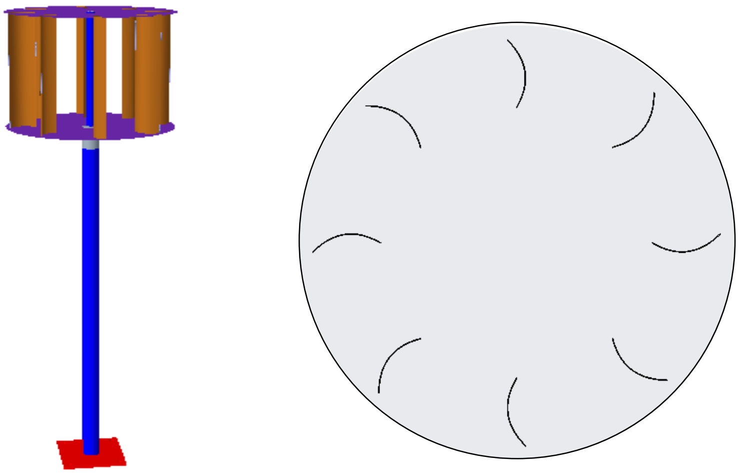
The k value is determined using the following equation in the k-epsilon turbulence dissipation model:

$$k = \frac{3}{2}(VI)^2 \quad (3)$$

The terms V and I in this context stand for reference velocity of 12 m/s and turbulence intensity, respectively. The expected turbulence intensity is 1%. The kinetic energy of turbulence is 0.00526 m^2/s^2.

4. VAWT Geometrical and Operational Characteristics

The goal of this study is to examine different feasible 3-bladed VAWT configurations and choose the most appropriate one, taking into account the number of blades. A *Savonius*-type VAWT with two different numbers of blades (four and eight blades) is used in this study. Figure 1 shows the schematic diagram of the proposed power VAWT. The diameter of the rotor D is set 2 m and the height of the rotor H is set 2.5 m. Figure 2 shows the cross-sectional view of the blade geometrical shape of this turbine. Three types of geometrical blade shape (version A, version B, and version C) have been investigated in this study as shown in Figure 2. The angle θ can control the blade direction respect to centreline of the rotor, and r represents the distance between the rotor centreline and the highest peak of the blade which is responsible of concave shape of the blade. Table 1 show the characteristics dimensions of blade profile.



(a) (b)

Fig. 1. Schematic diagram of the proposed power VAWT; (a) isometrics view (b) 2D VAWT rotor

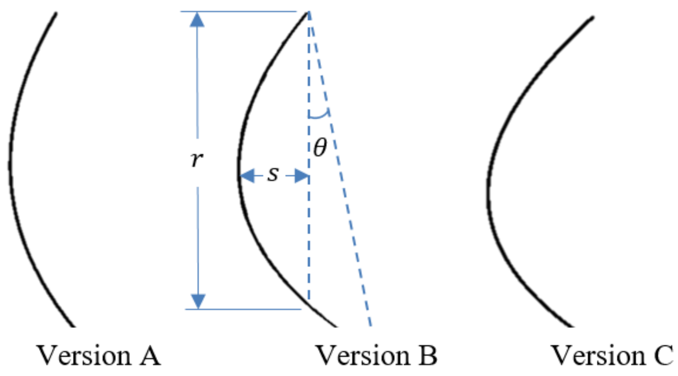


Fig. 2. cross-sectional view of the blade geometrical shape

Table 1
Characteristics dimensions of blade profile

Version/parameter	Version A	Version B	Version C
s/r	0.15	0.25	0.35
θ	9°	13°	6°

5. Computational Domain and Boundary Conditions

Figure 3 shows the computational domain of the turbine flow field which is involves of a rotating domain covering the turbine area and stator domain surrounding the rotating area. A non-conformist interface with sliding mesh between the stator region and the rotating domain allows rotation motion of the turbine and transfer the flow data between two domains. As shown in Figure 4, the whole computational domain is occupied L×W (7D ×4D). The rotational domain is located at the centre of the whole domain.

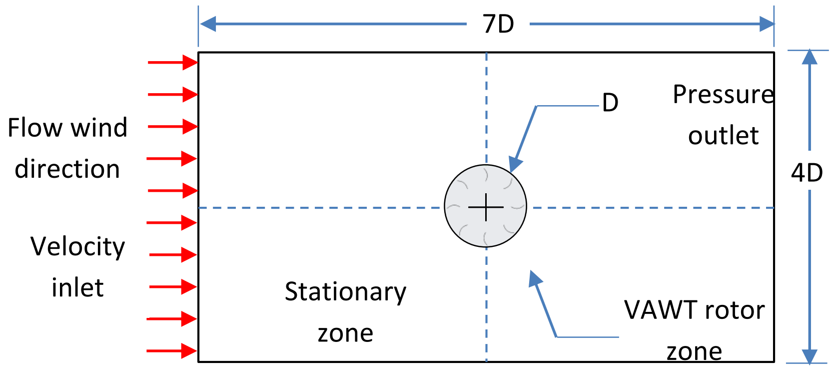


Fig. 3. Computational domain of VAWT

The boundary condition of the computational domain used uniform freestream velocity inlet of 12 m/s at the inlet and atmospheric pressure at outlet. The blades wall set to be stationary wall and no slip shear condition while the horizontal walls of the stator domain specified zero shear.

6. Mesh

The mesh quality plays an important role in the convergence and accuracy of the CFD solution. A triangular mesh elements have been used in this case. The options of refine surface mesh with edge sizing were selected to improve the results. The inflation option was set for all solid walls of the turbine blades using three layers. Sliding mesh with the mesh motion teqnique has been used to simulate the rotational speed of the wind turbine blades. Two zones: stator and rotor zone have been implemented to simulate the vertical wind turbine case. A grid sensitivity analysis was conducted for the wind turbine model to assess the numerical results. The mesh was modified and refined within the regions of particular interest: the blades wall in the wind turbine, and the mesh interface between stator and rotor domains as shown in Figure 4.

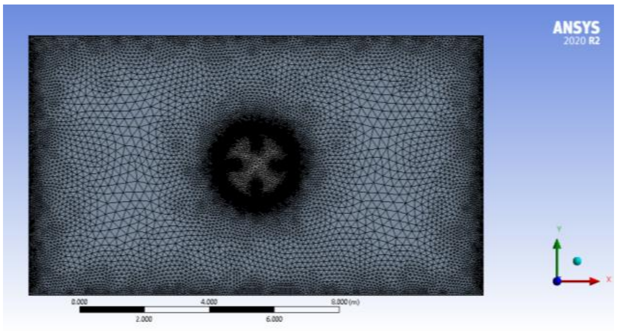


Fig. 4. Whole mesh domain

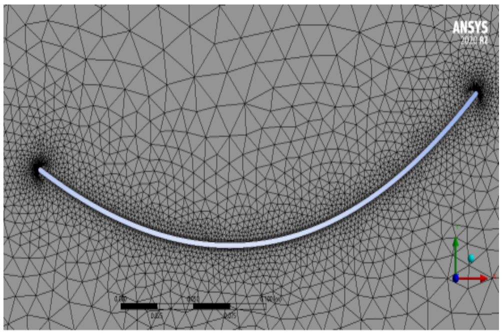


Fig. 5. Mesh domain vicinity of blade boundary

7. Numerical set up

The incompressible unsteady standard k-e model equations with Enhanced wall treatment are solved using the commercial CFD software package ANSYS Fluent 20. The SIMPLE scheme is used for pressure-velocity coupling and second order discretization is employed both in time and space [27]. Also, second order upwind is used for momentum, turbulent kinetic energy and turbulent dissipation rate in spatial discretization. The rotational speed of the rotor has set to be 10 rad/s for all cases in this study. Pressure based solver with transient mode is selected for all the simulations.

Convergence in the unsteady state of VAWT takes a long time to achieve. To make it feasible, under relaxation is used to achieve convergence in an acceptable amount of time. For the velocity equation the under-relaxation factor has set 0.6, for the pressure equation the factor has set 0.2, and for the turbulent kinetic energy, k, has set 0.5.

8. Results

Figure 6 shows velocity magnitude distribution for the four Blades Vertical Axis Wind Turbine (4B-VAWT). As showing in the Figure 6, in instance time (certain rotational angle) the higher flow velocity concentrate in such two blades due to the way in which they direct the flow (windward) which can extract the maximum energy in this position while the other two blades have lower flow velocity because they alter the flow direction at this position. Also, the maximum flow velocity can be seen at the outer tip of blades respect to the rotational axis, and this demonstrate that the wind turbine rotates in the correct direction and has both positive and negative torque.

To show the behaviour of flow velocity direction in both windward and leeward blades, flow velocity vector has been presented in Figure 7 and 8 respectively. Figure 7 shows the flow hit the inner surface of the blade which is directed to the wind flow and the blade extract the energy and at the same time alter the flow direction toward tips of the blade. The maximum concentration of the velocity vectors has been seen at the outer tip of the blade and this indicates that the wind turbine works properly and efficiently.

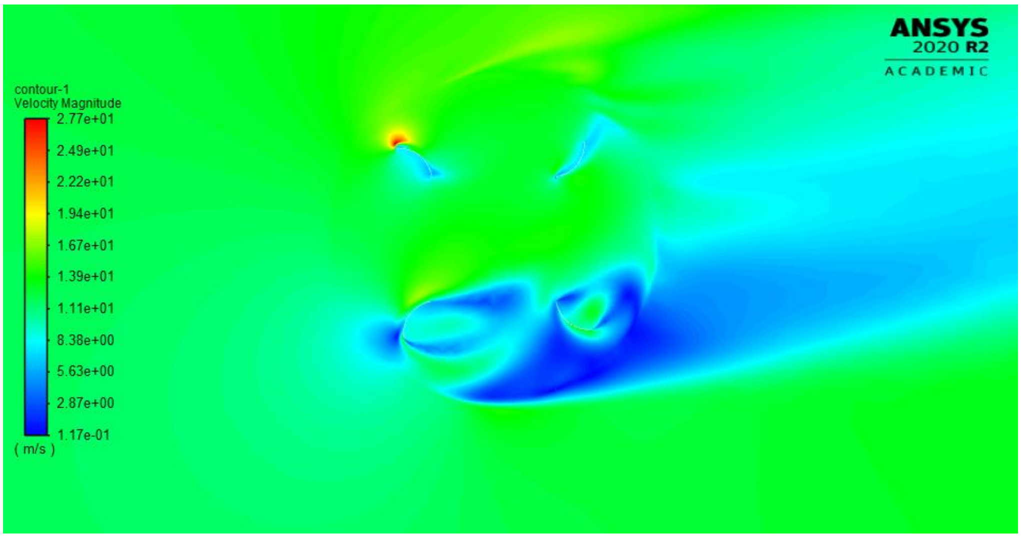


Fig. 6. Flow velocity magnitude of 4B-VAWT

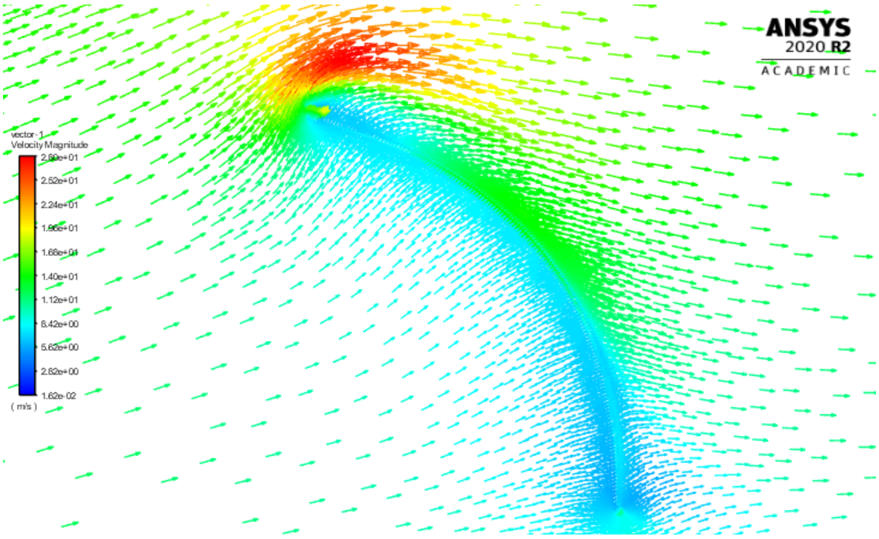


Fig. 7. Flow velocity vector for blade faced the wind flow of 4B-VAWT

Figure 8 shows the flow velocity vector at the blade where positioned against the flow wind. The flow alters his direction due to outer surface blade profile to the region of the inner surface same blade which is assisting the overall positive torque of the 4B-VAWT. Two vortices region were generated in behind of the blade, the inner region near to the rotational centre of the wind turbine acts as a wake while the outer region acts as scavenged the flow outside the rotational region.

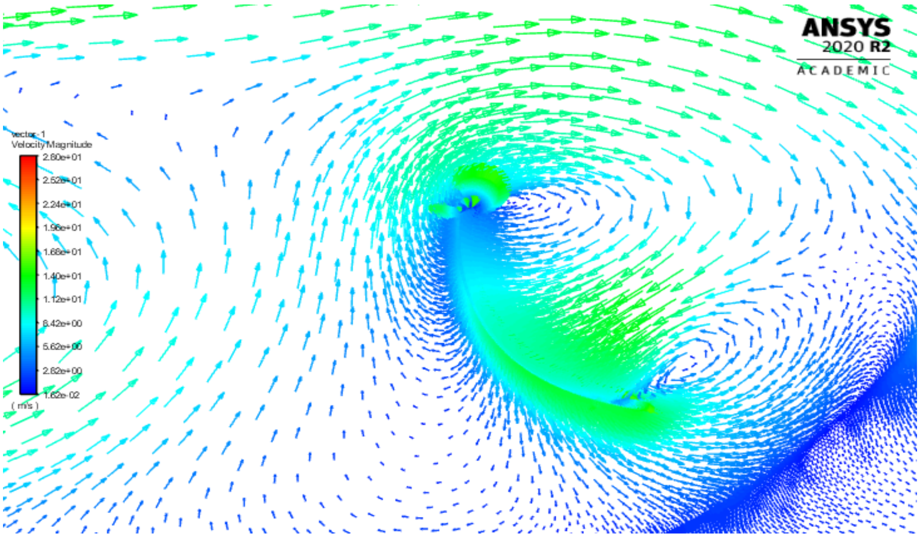


Fig. 8. Flow velocity vector for blade against the wind flow of 4B-VAWT

Figure 9 illustrates the predicted CFD results of torque output of four blades of 4B-VAWT. The results have been recorded for period of 10 seconds. As it shown in Figure 9 the torque produced from this type varied between approximately 45 to 65 N.m.

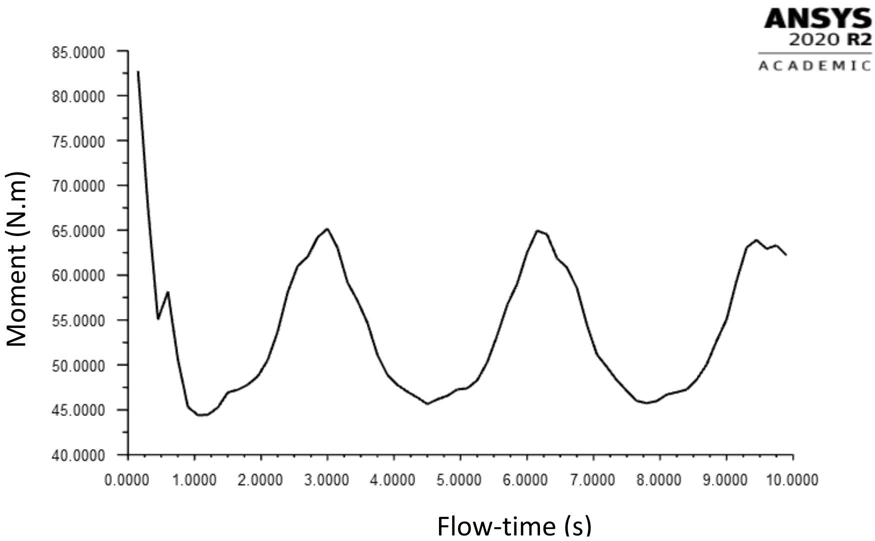


Fig. 9. Variation of torque of four rotor blades with respect to time

Figure 10 shows velocity magnitude distribution for the eight Blades Vertical Axis Wind Turbine (8B-VAWT) version A. As showing in the Figure 10, in certain rotational angle the higher flow velocity concentrates close to five blades which are more than half of total number. It seems to be the flow velocity distribution more promoted compared with case of 4B-VAWT.

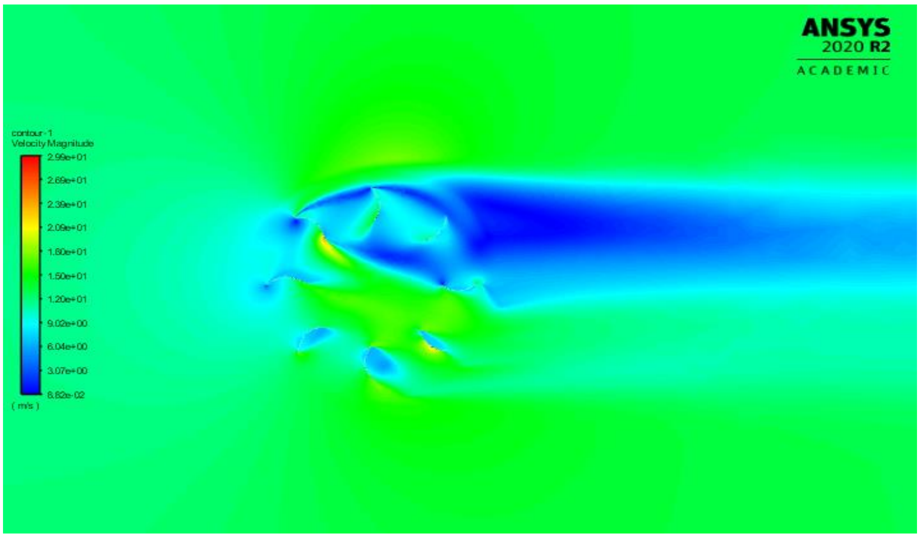


Fig. 10. Flow velocity magnitude of 8B-VAWT version A

Figure 11 shows flow velocity vector vicinity to the two blades of 8B-VAWT version A. It can be seen that the air flow can easily change its direction towards both centre and outside rotational region. Also, the maximum flow velocity appeared at two tips of the blade as shown in Figure 11. This makes a high mixing flow area at blades tips region and this can explain the maximum flow turbulent intensity as shown in Figure 12.

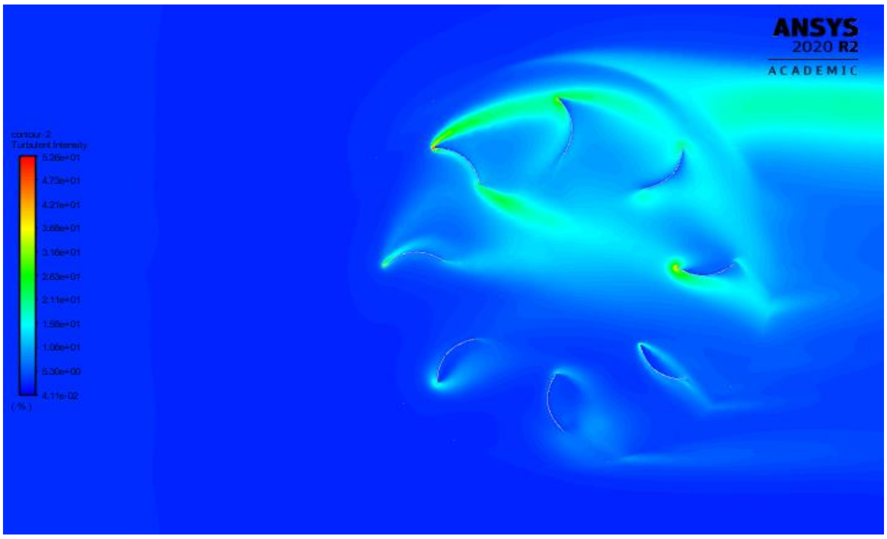


Fig. 11. Flow velocity vector for blade faced the wind flow of 8B-VAWT version A

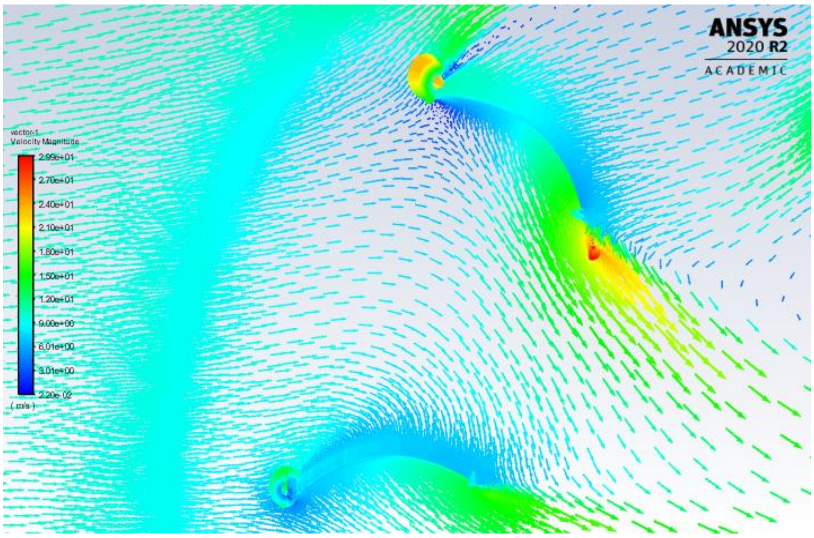


Fig. 12. Flow turbulent intensity of 8B-VAWT version A

The predicted CFD results of torque output of eight blades of 8B-VAWT version A has been presented in Figure 13. The results have been recorded for period of 10 seconds and the torque produced varied between approximately 125 to 143 N.m. These figures showed that using 8 blades of VAWT instead of 4 blades with the same profile of blade has ability to improve VAWT performance up to 64%.

To investigate the influence of blade shape on the performance of the VAWT, extra versions B and C have been simulated. Figure 14 shows torque produced comparison between three proposed versions. The torque produced increases as the distance r increases and the blade gets more concave as shown in Figure 13. The simulated results showed that the torque produced from version VAWT version B was 8% higher than version A and this because increasing in the concave profile. It has to be noted, however, when the r distance increased more in version C, the torque produced drop down by 5.6% compared with version A. This demonstrates that there is an optimum profile gives a maximum torque, but this also may be linked with the angle of attack (AoA) of the blade.

To improve the performance of the VAWT, the stator deflector blades has been added around the rotor as shown in Figure 15. Sixteen stator blades in opposite direction respect to the rotor blades have been distributed around the VAWT rotor. The new results showed that including stator deflector to the VAWT design can increase the torque produced by 70 % compared with VAWT without deflector Figures 13 and 16.

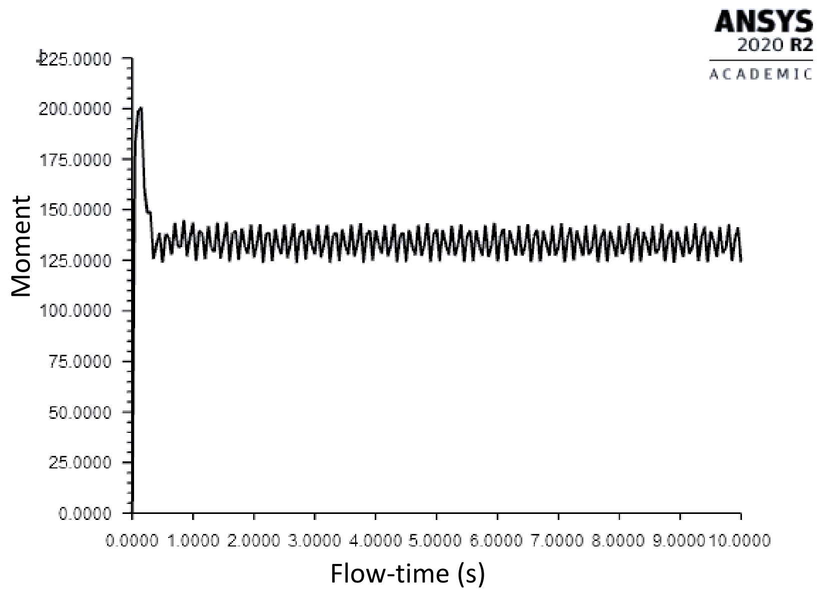


Fig. 13. Variation of torque of eight rotor blades with respect to time

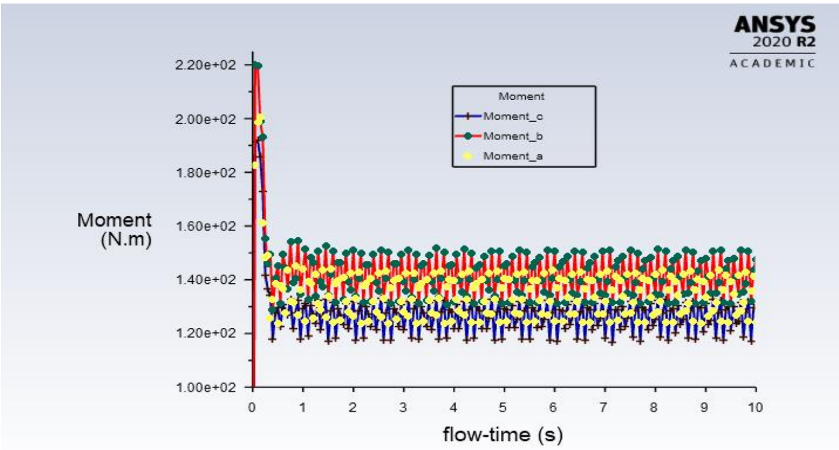


Fig. 14. Comparison of torque produced from VAWT different versions

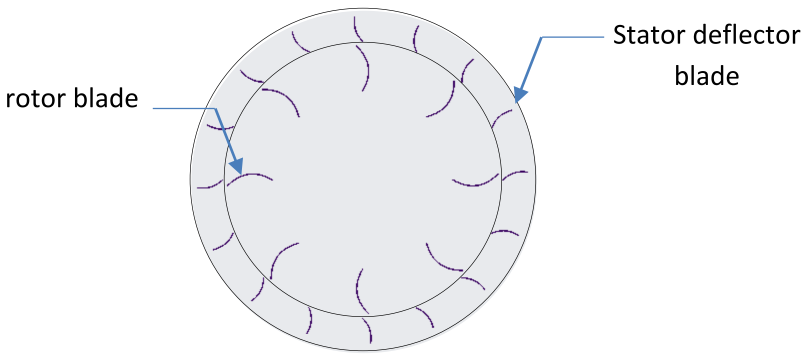


Fig. 15. Schematic showing the stator deflector blades added to VAWT rotor

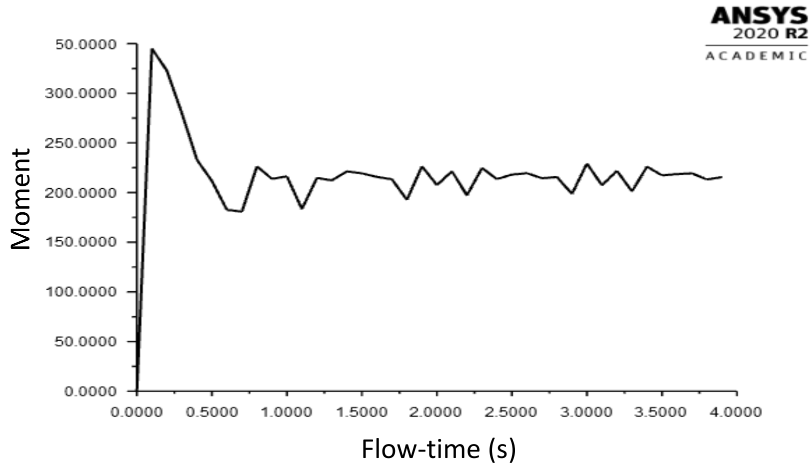


Fig. 16. Variation of torque of eight rotor blades version B with stator blades deflector

9. Conclusion

Small-scale VAWT's have recently gained popularity as a viable renewable energy source, particularly in rural areas. A numerical investigation has been performed to study the influence of profile and blade numbers of Savonius VAWT. ANSYS Fluent 15.0 was used to simulate the flow characteristics around the turbine blades. k-ϵ turbulent model and h sliding mesh technique were adopted to solve the governing equation within the wind turbine rotor region. Several factors were considered in this study, including the number of blades, blade's shape, and the presence of a stator blade deflector. The results revealed that utilizing eight VAWT blades rather than four blades to the same profile improved VAWT performance by 64%.

Furthermore, expanding the concave profile of the blade can improve the torque generated by around 8%, but a more considerable increase in concave form causes a 5.6% decrease in torque. Likewise, adding a stator deflector to the VAWT design can potentially promote the torque produced by 70%. The outcome of this study demonstrated that adjusting the limited parameter will aid in determining the best configuration for a small vertical wind turbine to test this concept in the future.

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