3D CFD simulation and parametric study of a flat plate deflector for vertical axis wind turbine

Kok Hoe Wong a, Wen Tong Chong a,⁎, Sin Chew Poh a, Yui-Chuin Shiah b, Nazatul Liana Sukiman c, Chin-Tsan Wang c

a Department of Mechanical Engineering, Faculty of Engineering, University of Malaya, 50603 Kuala Lumpur, Malaysia
b Department of Aeronautics and Astronautics, National Cheng Kung University, Tainan City 701, Taiwan
c Department of Mechanical and Electro-Mechanical Engineering, National Ilan University, Ilan 260, Taiwan

A R T I C L E   I N F O
Article history:
Received 18 November 2017
Received in revised form 15 April 2018
Accepted 24 May 2018
Available online 26 May 2018

Keywords:
Computational fluid dynamics (CFD)
Flat plate deflector
Power augmentation
Vertical axis wind turbine
Coefficient of power
Velocity vector

A B S T R A C T

Three-dimensional numerical simulations have been performed to analyze the aerodynamic characteristics of a straight-bladed NACA0021 vertical axis wind turbine (VAWT). The unsteady flow CFD simulation was validated with the wind tunnel experiment data available in the literature. Sliding mesh method with the SST k-ω turbulence model was employed to simulate the rotational motion of the VAWT using ANSYS Fluent. The study showed a good agreement between the simulation and the wind tunnel testing. Further simulations were carried out to study the effects of a flat plate deflector being placed at the upwind of the VAWT by varying a few parameters including the position, the inclination angle and the length of the flat plate deflector. The simulations showed that the augmented flow occurred at the near wake region where the flow was accelerated and deflected by the deflector before impinging with the turbine; hence the coefficient of power (Cp) of the VAWT improved significantly. However, the performance of the VAWT was highly dependent on the position of the deflector. From the simulation results, with the optimum parameters, the cycle-averaged coefficient of torque was increased about 47.10% higher compared to the VAWT without the deflector.

© 2018 Elsevier Ltd. All rights reserved.

1. Introduction

The use of fossil fuels for electricity generation has led to serious environmental problems. As an alternative solution, renewable energy is attracting a lot of attention. Among these renewable energies, wind energy is popular in that it is abundant, clean, inexhaustible and environmental-friendly.

Wind turbines have been ingeniously engineered to harness wind energy in agriculture for irrigation and crop grinding for centuries. The vertical axis wind turbines (VAWTs) which are the oldest wind turbine design are able to capture wind energy from omni-direction with the rotational axis aligned vertically. Basically, VAWTs are categorized into two types, which are the drag-type and the lift-type. Savonius rotor is a common drag-type VAWT with cup-shaped or concave-shaped blades. It utilizes the aerodynamic forces to push on the advancing blade to induce the rotational motion. As for the lift-type VAWT such as the Darrieus rotor and H-rotor with airfoil-shaped blades, the rotors are driven by the lift component generated by the pressure difference on both sides of the airfoil blades. Generally, the lift-type VAWTs have higher efficiency; however, poor self-start capability is always the main drawback compared to the drag-type VAWT.

In the research on wind turbine design, there are several approaches to analyze the flow field around the wind turbine. The basic approaches are divided into three main methods, including the computational aerodynamics methods, computational fluid dynamics (CFD), and experimental measurements [1]. For the computational aerodynamics method, the multiple streamtube model, double-multiple streamtube model, and vortex model are the three most common methods used by researchers. CFD simulation is an affordable yet practical approach to simulate the flow field around a VAWT compared to the experiments that incur higher costs especially in the process of design optimization.

2D CFD simulation is simpler compared to the 3D CFD simulation, but at the same time it is less accurate for complex flow and is limited to the single plane case. On the other hand, 3D CFD...
simulation provides accurate flow field prediction, but it requires long computational time and large data storage. In comparison between the simulation and wind tunnel test data, quite consistent 3D CFD simulations were obtained by Howell et al. [2] for a small H-rotor but obvious deviation was observed for 2D simulation due to the presence of rotor tip vortices. Similarly, Rossetti & Pavesi [3] conducted 3D CFD simulations on the H-rotor start-up behavior, where the 3D effects such as secondary flow and tip effects were captured in the simulation that contributed positive torque on the start-up. Over predictions were reported on the VAWTs performance on 2D simulation [4,5].

In addition to the 3D works mentioned above, Bedon et al. [6] conducted 3D Unsteady Reynolds Averaged Navier Stokes (URANS) CFD simulations on the tilted Darrieus VAWT. The result showed a subpar performance as the tilt angle of the VAWT increased. However, a different trend was observed at a different tip speed ratio (TSR), where at high TSR, the coefficient of power (\(C_P\)) decreased significantly, whereas a slight increase of \(C_P\) was observed at low TSR which was caused by the stall operative conditions of the VAWT. By performing the similar simulation on a tilted angle of a H-rotor VAWT, Chowdhury et al. [7] observed an interesting phenomenon that the torque produced at downwind was greater than that of the upright VAWT. This was because the bottom of the tilted VAWT received more fresh wind flow than the upward exhaust air of the upright VAWT that was transferred entirely to the downwind side.

Among the techniques to improve the efficiency of VAWTs, power augmentation features have been proven to be very effective. The augmentation features can be as simple as a flat plate positioned at the upwind of the VAWT. Mohamed et al. [8] conducted 2D simulations on the Savonius rotor with a flat obstacle shielding plate. It showed that a better flow was guided to the advancing blade of the Savonius rotor while the opposing flow to the returning blade was reduced. The resulting \(C_P\) was improved as much as 27%. Similar research was carried out to study the orientation effects of the flat blade on a multi-stage Savonius rotor. The study indicated that the flow was highly dependent on the orientation of the deflector, where a wrong orientation can worsen the result compared to the case without the deflector [9]. A pair of flat curtain plates was placed in front of the Savonius rotor to increase the impinging wind speed. As the length of the curtain plates increased, the rotor performance became better due to larger plate area to deflect more wind flow [10]. Kim and Gharib [11] investigated the effect of a flat upstream deflector on the counter-rotating straight-bladed VAWTs. From their experiment, it was observed that the power output increased significantly when the local wind velocity at the near-wake region was greater than that of the free stream. However, some parameters of the plate such as the aspect ratio and position highly affected the results. Same observations of the effects of an upstream deflector were also reported by Jin et al. [12] that when the turbine was positioned outside the near wake region, the performance improved significantly.

From the literature review, it was found that very scarce research was conducted on the effects of flat plates on the performance of the lift-type VAWT. Moreover, most of the augmentation devices are placed side by side with the VAWT. The main purpose of this paper is to investigate the effects and the flow characteristics of a flat plate deflector system which is placed at the lower side of the upwind of a two straight-bladed VAWT via 3D simulation, the content of the paper covering the following issues:

a) Detail simulation setup including blockage ratio, mesh refinement test, time step study, and turbulence model to obtain a reasonably accurate simulation result;
b) Validation of 3D simulation with wind tunnel testing in the literature by comparing the coefficient of power generated on a blade of the VAWT;
c) Flow characteristics investigation and the parametric study on the flat plate deflector including the position, inclination angle, and length.

2. Flow field setup

2.1. Aerodynamics of the H-rotor VAWT

For a wind turbine, the tip speed ratio (TSR), denoted by \(\lambda\), is a non-unit parameter; it is defined as the ratio of the velocity at the blade tip to the free stream wind velocity as [13]:

\[
\text{TSR}, \lambda = \frac{R \omega}{U_\infty} \quad (1)
\]

where \(U_\infty\) is the free stream velocity, \(R\) is the rotor radius, and \(\omega\) is the angular velocity.

As depicted in Fig. 1(a), unlike the horizontal axis wind turbine, the forces acting on each VAWT rotor blade are continuously varying with the azimuthal angle (\(\theta\)). The difference of lift and drag forces generated by the airfoil is due to the continuously varying angle of attack (\(\alpha\)) on the blade by the resultant wind velocity (\(w\)). The angle of attack is the angle between the chord line and the resultant wind direction (\(w\)) towards the airfoil, mathematically
defined as [13]:

\[
\alpha = \tan^{-1}\left(\frac{\sin \theta}{\lambda + \cos \theta}\right) - \beta,
\]

(2)

where \( \beta \) is the pitch angle.

There are two important parameters to characterize wind turbine performance, namely the coefficient of torque \( (C_T) \) and the coefficient of power \( (C_p) \), being defined as follows [14–20]:

\[
C_T = \frac{T}{0.5 \cdot \rho \cdot A_R \cdot (U_\infty)^2},
\]

(3)

\[
C_p = \frac{p}{0.5 \cdot \rho \cdot A_R \cdot (U_\infty)^3} = \frac{T \cdot \omega}{0.5 \cdot \rho \cdot A_R \cdot (U_\infty)^3} = \lambda \cdot C_T,
\]

(4)

\[
P = 0.5 \cdot C_p \cdot \rho \cdot A_R \cdot (U_\infty)^3.
\]

(5)

2.2. Geometry and numerical model

The straight-bladed VAWT used in these CFD studies are modeled according to the rotor specifications from the wind tunnel experiments conducted by Li et al. [13] as shown in Fig. 1 (b). In the experiment, a two straight-bladed H-rotor VAWT with NACA 0021 airfoil was employed. The height \((H)\) and the diameter \((D)\) of the VAWT were 1200 mm and 2000 mm respectively, whereas the chord length \((c)\) of the blade was 265 mm with a pitch angle \((\beta)\) equal to 6°. As depicted in Fig. 1 (a), the pitch angle is the angle between the chord line and the tangential line. In the wind tunnel test, the turbulence intensity of the wind tunnel was 0.5%. As reported in the experiment by Li et al., a torque meter and Laser Doppler Velocimeter (LDV) were used to evaluate the torque and aerodynamic performance, while the pressure distribution was measured by 32 wireless pressure taps attached to one of the rotor blades.

2.3. CFD spatial domain discretization & boundary condition

For the simulation, two sub-domains were modeled: a cuboid for the tunnel stator and a cylinder for the VAWT rotor. Shown in Fig. 2 are the top view and the side view of the domain with the boundary condition applied. The tunnel stator domain was modeled in the size of 10D (width) \( \times \) 10D (height) \( \times \) 25D (length) while the VAWT rotor domain was characterized by a rotational diameter 15D and 0.2 m gaps for the top and bottom. The VAWT rotor domain was located at 10D from the inlet and 15D from the outlet to allow full development of wakes. The domain size was considered appropriate, as reported in Lam and Peng [5] study on the wake characteristics of a VAWT with a smaller domain size of 10D (width) \( \times \) 8D (height) \( \times \) 16D (length) with the rotor domain 5D from the inlet.

As shown in Fig. 2, the two bladed H-rotor VAWT was modeled in the rotor domain, while the flat plate deflector was located at the stator tunnel domain. The flat plate deflector was placed at a horizontal distance, \( X \) from the rotational axis and a vertical distance, \( Y \) from the bottom edge of the VAWT. The length of the flat plate deflector was denoted by \( L \) and the inclination angle of the flat plate deflector from the vertical plane was denoted by \( \Phi \). The blockage factor is the ratio of the frontal projection area of the VAWT and the deflector system to the tunnel stator cross-sectional area. This value is suggested to be less than 6%–7.5% for numerical simulation and 10% for experiment [5]. In this simulation, the blockage factor for the VAWT was only 0.6% and 4.2% for the case with the largest size of the deflector system; both fell within the acceptable range.

Since the simulation aimed to reproduce the results of the wind tunnel test, a uniform wind inlet velocity \((U_\infty)\) of 8 m/s was employed with the turbulence intensity of 0.5% and the length scale of 18.55 mm. The TSR of the benchmark experiment is 2.58, corresponding to \( Re = 3.27 \times 10^5 \). The outlet gauge pressure was set to be 0 Pa, while all the side surfaces were defined as symmetric flow. Like in most cases with low wind speeds, the non-slip condition was assumed for all surfaces of blades and the deflector. In order to allow the cell zones to be connected easily and to ensure the fluxes can pass from one mesh to another for using the sliding mesh method, all three boundaries between the cylinder rotor domain and the tunnel stator domain were treated as interfaces. The two straight-bladed VAWT in the rotor domain rotates clockwise with \( \omega = 20.64 \) rad/s.

2.4. Solver settings

The commercial software ANSYS Fluent which is based on the finite volume method was used to perform the 3D simulation for
Fig. 2. Boundary condition and the domain size of the VAWT used in numerical simulation (a) top view (b) side view (c) meshes.
solving the time-dependent Unsteady Reynolds-Averaged Navier Stokes (URANS) equation with the pressure based formulation. The pressure-velocity coupling solution scheme employed the SIMPLE (Semi-Implicit Method for Pressure Linked Equation) algorithm to solve the Navier-Stokes equation. In the simulation, the air was used as the fluid with the default properties settings, $1.225 \text{ (kg/m}^3{\text{)} for density and } 1.7894 \times 10^{-5} \text{ (kg/m} \cdot \text{sec) for viscosity. The convergence criteria for all the parameters were chosen to be } 1 \times 10^{-5}.

The coefficients of torque were simulated and observed on a single blade of the VAWT in all cases using ANSYS Fluent. The coefficients of torque were repeatedly calculated until convergent results were achieved for two consecutive revolutions with discrepancy percentages less than 1% as follows:

$$\text{Convergence} = \frac{\bar{C}_T(n+1)(\theta) - \bar{C}_T(n)(\theta)}{\bar{C}_T(n)(\theta)} < 1\%$$

For each iteration, the solution gets converged before proceeding to the next time step. The number of revolution to meet the convergence criterion differs for each case. For most of the cases, the calculation of $C_T$ satisfied the criterion in Equation (6) after 7 revolutions. The gradient of the solution variable was set as least square cell based with the standard pressure. It is quite often for the second-order upwind scheme to encounter convergence difficulties from the instability and oscillations of solutions in the iteration process. This can be solved by using first order upwind scheme as the initial guess for the first revolution before switching to the second-order scheme. For this reason, the first order upwind scheme was applied to the momentum, turbulent kinetic energy, and the specific dissipation and also first order implicit for transient formulation; after a complete revolution, these parameters were set to second order upwind [2,4,5]. Fig. 3 illustrates the coefficient of torque for nine revolutions for the VAWT. Instability was observed in the initial stage and after several revolutions, a periodic solution was obtained. The calculation was stopped as the discrepancy of the cycle-averaged $C_T$ for two consecutive revolutions was less than 1%.

### 2.5. Mesh independency test

The ICEM CFD software packaged with ANSYS Fluent was used to generate mesh files for the simulations. Two mesh domain files (VAWT rotor & tunnel stator) were generated separately to simplify the meshing steps. By using the appended function in the software, meshes were then re-attached in the solver stage and the VAWT rotor domain was embedded within the tunnel stator domain.

<table>
<thead>
<tr>
<th>Mesh</th>
<th>Total no. of cells</th>
<th>Computational time (hrs)</th>
<th>$C_T, \text{ave}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1</td>
<td>3,370,398</td>
<td>45</td>
<td>0.05571</td>
</tr>
<tr>
<td>M2</td>
<td>1,849,999</td>
<td>14</td>
<td>0.05576</td>
</tr>
<tr>
<td>M3</td>
<td>1,437,135</td>
<td>10</td>
<td>0.05506</td>
</tr>
<tr>
<td>M4</td>
<td>1,114,779</td>
<td>8</td>
<td>0.05437</td>
</tr>
<tr>
<td>M5</td>
<td>908,015</td>
<td>6</td>
<td>0.05189</td>
</tr>
</tbody>
</table>

**Fig. 3.** Periodic coefficient of torque over nine cycles of the turbine.

**Fig. 4.** The cells arrangement (a) leading edge (b) trailing edge.
Since the mesh intensity gives significant impact on the accuracy of the result, a fine mesh is desired. However for 3D simulation, mesh refinement is costly in terms of computational time and requires huge data storage, therefore it is crucial to
conduct mesh independency test to select an appropriate mesh size to minimize the computational cost and provide a quality analysis. As the main focus is on the tangential torque created by the blades which is the most critical output of the wind turbine simulation, hence, the VAWT rotor mesh consists more than 80% of the total cells in all the cases. The unstructured mesh generated consists of a majority of tetrahedral cells in combination with some pyramid and prism cells. The prism cells with high aspect ratios were required to minimize the computational cost and provide a quality analysis. 

In order to expedite the simulations with acceptable computational time for a complete revolution of the rotor, the computational time for M1 and M2 was much shorter than M3. Hence, the mesh scheme M2 was used for the rest of the simulations.

2.6. Time step study

The Courant number (Co) or the Courant-Friedrichs-Lewy (CFL) criterion is a widely used criterion for the numerical stability of different schemes. It is the ratio between the temporal time step (Δt) and the time required for a fluid particle to convect through a cell of dimension Δx with velocity (V), i.e [22,24]:

\[ Co = \frac{V(Δt)}{Δx} < 1. \]

Equation (8) shows a relation between the time and space discretization and therefore these parameters vary dependently. From aforementioned mesh independency test, a fine mesh is required for yielding a reliable simulation result. However, the reduction of cell size while the time step remains unchanged will cause unstable and convergence difficulties as the Co number increases [24]. For large rotational step, the momentum equation which considers the strongly coupled effect caused by swirling flows is difficult to solve. This is due to the large pressure gradients in the radial direction, causing numerical inaccuracies and discourages computational convergence [22]. Consequently, the time step of the azimuthal increment has to be chosen appropriately in order to obtain a reliable result and shorten the computational time. In this simulation, four different time-steps were tested, being 4.228 × 10^{-4} s, 8.456 × 10^{-4} s, 1.691 × 10^{-3} s and 2.537 × 10^{-3} s that respectively corresponded to 0.5°, 1°, 2° and 3° rotation of the rotor domain per time step, wherein 30 iterations per time step were applied. For time step larger than 3°, convergence difficulty occurred.

Fig. 6 depicts the effects of the time step on the cycle-averaged coefficient of torque. The results obtained for the first three time marching steps are very close, while 2.537 × 10^{-3} s (equivalent to 3° per time step) showed a relatively larger error compared to other cases. In order to expedite the simulations with acceptable computational accuracy, the marching scheme of 1° per time step, equivalent to 8.456 × 10^{-4} s was selected as the final setting for
Fig. 9. Velocity measurements around the flat plate deflector.

Fig. 10. Velocity measurement points around the flat plate deflector.

Fig. 11. Experiment and simulation results for the velocity measurement.
Fig. 12. Coefficient of pressure on the blade surface when $\theta = 0^\circ$ and $90^\circ$ at TSR $= 2.58$.

Fig. 13. Coefficient of pressure on the blade surface when $\theta = 180^\circ$ and $270^\circ$ at TSR $= 2.58$.

Fig. 14. Coefficient of torque for various $X$ distances with $Y = 1/3H$, $\varphi = 0^\circ$ and $L = 1.0H$. 

Fig. 15. Velocity contour for various X distances (a) bare turbine (b) $X = 0$ (c) $X = R$ (d) $X = 2R$ (e) $X = 3R$ with the blades at azimuthal angle (i) $0^\circ$ and $180^\circ$ (ii) $90^\circ$ and $270^\circ$ on the XZ plane.
2.7. Turbulence model

The selection of a proper turbulence model plays a crucial role in producing reliable results with satisfactory computational stability. From the comparison of three different turbulence models which are the Standard \(k-\varepsilon\), the RNG \(k-\varepsilon\), and the \(k-\omega\) SST (Shear Stress Transport) for simulating flows on VAWT, Balduzzi et al. have shown that results obtained by the \(k-\omega\) SST agreed well with experiments while numerical stability, reliability, and flexibility were maintained in the near wall treatment [25]. Similar findings were also reported by Chowdhury et al., indicating that the \(k-\omega\) SST showed results closest to the experimental data as compared with those obtained by the other two turbulence models [7]. For the turbulence model selection in this simulation, comparison between the \(k-\omega\) SST, Standard \(k-\varepsilon\), the RNG \(k-\varepsilon\), and the Realizable \(k-\varepsilon\) was conducted. Fig. 7 shows as the \(C_p\) against the azimuthal angle for a complete revolution, it was observed that all \(k-\varepsilon\) cases under predict the result. Comparisons between the Standard \(k-\varepsilon\) with the RNG \(k-\varepsilon\), and the Realizable \(k-\varepsilon\) turbulence model, the improved version of \(k-\varepsilon\) showed a better estimation than the Standard \(k-\varepsilon\) on the flow features where the rotation, vortices and the streamline curve are considered [26]. Both the RNG \(k-\varepsilon\), and the Realizable \(k-\varepsilon\) were quite close to each another. However, the SST \(k-\omega\) turbulence still outperforms in the prediction where it effectively blends the robust \(k-\omega\) model in the near wall region and switches to the standard \(k-\varepsilon\) model at the far stream to handle a complex flow with the adverse gradient [5–7]. Hence, Menter’s \(k-\omega\) SST turbulence model was adopted for the simulation. The details on the SST \(k-\omega\) equation can be found in the literature [27].

2.8. Deflector system & parameters

For the study of the flow characteristics and the effect of the flat plate deflector on the VAWT, a few parameters of the flat plate deflector were examined, including:

a) X distance (horizontal distance from the rotational axis)
b) Y distance (vertical distance between the lower edge of VAWT and the top edge of the flat plate deflector)

c) Inclination angle, $\phi$

d) Length, $L$ of the flat plate deflector

As illustrated in Fig. 8, the flat plate deflector was positioned at the upwind of the VAWT. In order to examine the effects of the position of the flat plate deflector, four $X$ distances were simulated which were $X = 0$ (at the rotor axis), $R$, $2R$ and $3R$.

At the same time, other parameters were set as $Y = 1/3H$, $\phi = 0^\circ$ and $L = H$. The $X$ distance which showed the highest $C_{Tave}$ was used to test the effect of the vertical $Y$ distance which varied from $Y = 0, 1/3H, 2/3H$ and $H$, as shown in Fig. 8. Also, the best position of the deflector was used to investigate the effects of the inclination angle where four different angles of $\phi = 0^\circ, 30^\circ, 45^\circ$ and $60^\circ$ were tested. Lastly, the simulation followed by the effects of the flat plate deflector length as a factor which was varied from $L = 0.5H, 1H, 1.5H$ and $2H$. For all the cases, the width and the thickness of the flat plate deflector plate were fixed as $3D$ and $10\,\text{mm}$ respectively which cover the diameter of the VAWT.

### 2.9. Lab test

A simple lab test was conducted to verify the flow field around the flat plate deflector. In the lab test, a piece of acrylic sheet with the dimensions of $0.15\,\text{m} \times 0.45\,\text{m} \times 0.005\,\text{m}$ was employed as the flat plate deflector. It was placed at a distance of $3\,\text{m}$ in front of the wind source created by a blower array with an oncoming wind velocity of $6.0 \pm 0.5\,\text{m/s}$ as shown in Fig. 9. The details of the experimental setup are reported in Refs. [28,29]. A hot wire anemometer was used to measure the wind velocity around the flat plate deflector and a total of 12 measuring points were taken as shown in Fig. 10.

The simulation with the same setting was repeated on the flat plate deflector alone with the oncoming wind speed of $6\,\text{m/s}$ in order to compare with the lab test result. Fig. 11 illustrates the lab test and the simulation result. It shows that a good agreement was obtained where the wind velocity at all the measuring points were consistent between both lab test and simulation with an error of $\pm 0.5\,\text{m/s}$. The highest wind velocity was measured from the lab test at point, $P_2$, which was $7.13\,\text{m/s}$, while from the simulation it was $7.083\,\text{m/s}$ at the near wake region which was about $18\%$ higher than the oncoming wind velocity. In addition, low velocities close to $0\,\text{m/s}$ measured in front and behind the deflector shows that the wind flow was decelerated when approaching the deflector, while the wake was generated behind the deflector.

### 3. Results and discussions

#### 3.1. Simulation validation

The CFD simulation was validated by the wind tunnel test data published by Li et al. [13] The coefficient of power ($C_p$) data from the test was obtained at every $5^\circ$ azimuth angle, hence a total of $72$ data to display the curve of a complete revolution of the VAWT at TSR $2.58$. Fig. 7 illustrates the $C_p$ against azimuth angle ($\theta$) on a blade of the H-rotor VAWT.

The simulation result shows a good agreement with the wind tunnel test results. From Fig. 7, it is observed that for a complete revolution, there are two crests occurring at $\theta$ roughly equal to $90^\circ$ and $225^\circ$ and two troughs at about $0^\circ$ and $180^\circ$. The trend of the curve is influenced by the varying angle of attack and the resultant wind flow. The first sharp crest achieves a high magnitude of $C_p$ when the blade travels at the upwind where the angle of attack is optimum [4]. The other crest at $\theta = 225^\circ$ which was broader and much lower than the first one, arises from the blade interacting with the wake generated by the blade itself at the upwind transferring to the downwind. As a result, the torque created at the upwind turns out to be much greater than the downwind. The troughs of the curve appear when the rotor blade is parallel to the free stream and the angle of attack is zero.

It is also observed that there are some discrepancies especially at $\theta$ between $220^\circ$ and $35^\circ$. According to the simulation performed by Li et al., the same discrepancies occurred. This was due to the effect of the induced velocity which was generated from the tip vortex. The lower and negative value obtained from the simulation was due to the relative angle of attack is lower than the stall angle.

### Table 2

Summary of cycle-averaged coefficient of torque for $X$ distance.

<table>
<thead>
<tr>
<th>Distance $X$ (m)</th>
<th>Bare turbine</th>
<th>0</th>
<th>R</th>
<th>2R</th>
<th>3R</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_{Tave}$</td>
<td>0.0558</td>
<td>0.0486</td>
<td>0.0559</td>
<td>0.0661</td>
<td>0.0620</td>
</tr>
<tr>
<td>$%$</td>
<td>–</td>
<td>-12.83</td>
<td>0.18</td>
<td>18.63</td>
<td>11.12</td>
</tr>
</tbody>
</table>

Fig. 16. Coefficient of torque for various $Y$ distances with $X = 2R$, $\phi = 0^\circ$ and $L = 1.0\,H$. 

because of the effect of the blade tip vortex in the wind tunnel experiment. The flow at the downwind region was very complex from the effect of the blade passing through the upwind region. Li et al. claimed that it is hard to evaluate the effect of pressure distribution exactly by using CFD analysis due to the analysis accuracy is lowered in dynamics stall [20]. At the upwind regions, the CFD calculation was larger which was caused by the fluid force in the rotation direction component being reduced, due to induction resistance. Also, the frictional drag of the blade surface was not able to be captured by the pressure measurement in the wind tunnel experiment [20]. In addition, the simplification of the geometry in the modeling also contributed to the discrepancies [4,30]. As reported in the literature which conducted simulation on NACA airfoil series, similar trends were obtained at $\theta$ between 230° and 45°.

Fig. 17. Velocity contour for various X distances (a) $Y = 0$ (b) $Y = 1/3H$ (c) $Y = 2/3H$ (d) $Y = H$ with the blades at azimuthal angle (i) 0° and 180° (ii) 90° and 270° on the XZ plane.
In addition to the validation with coefficient of power, the pressure distribution on the blade surface was examined by comparing the coefficient of pressure, $C_{\text{pressure}}$ with Li et al. wind tunnel data. Figs. 12 and 13 illustrate the pressure distribution at azimuthal angle of 0°, 90°, 180° and 270°. It can be observed that the pressure distribution of the rotor blade from the simulation follows the trend from the experiment well.

3.2. Effects of the deflector system

3.2.1. Effects of the X distance

With the verification of the simulation setup, the effect of a flat plate deflector was investigated. From the simulation results, it showed that the existence of the flat plate deflector was able to improve the performance of the VAWT significantly; however, it was highly dependent on the position of the deflector.

Fig. 17. (continued).
As shown in Figs. 10 and 15, the velocity vector diagrams show that when the wind flow approaching the flat plate deflector which was placed at the upwind, in front of the flat plate deflector, the wind velocity was retarded and created a low velocity region, hence forming the blockage effects. The wind flow was then separated and deflected to the top and the bottom. It was accelerated approximately about 20% higher than the oncoming wind velocity at the near wake region. Also, a high vorticity wake region was formed behind the deflector [11,12]. Fig. 15 (a) illustrates the velocity contour for a bare turbine. After the wind energy was harnessed, a low wind velocity region was formed behind the VAWT.

Fig. 14 indicates the effects of the X distance of the flat plate deflector. It can be clearly seen that the deflector was able to increase the $C_T$ significantly, especially for the case where $X = 2R$ and $3R$. At azimuthal angle $90^\circ$, the $C_T$ was about 20% higher compared to the bare turbine. This was due to the accelerated wind flow being deflected toward the VAWT as shown in Fig. 15(c–e). According to Equation (5), the wind power is directly proportional to the cube of the wind velocity, therefore the performance of the VAWT improve markedly with the augmented wind flow. Table 2 shows the $C_T$ for various X distances. When $X = R$, the $C_T$ trend was almost the same with the bare turbine as shown in Fig. 14 where the $C_T$ was 0.0559, a value slightly higher than the bare turbine of about 0.18%. As can be seen from Fig. 15(c)(i), at the upwind region, although the wind was deflected towards the lower spanwise of the VAWT rotor blade, however, the upper spanwise of the rotor blade suffered from the low wind region which was caused by the blockage effect of the flat plate deflector especially when the rotor blade at $\theta = 90^\circ$ in Fig. 15 (c)(ii).

Moreover, when comparing the velocity vector for Fig. 15(c–f), it was observed that the wind flow deflected is more concentrated when $X = 2R$ and $3R$. The highest improvement occurred when $X = 2R$, the $C_T$ was increased about 18.63% compared to the bare turbine. As $X$ increased to $3R$, the augmentation percentage slightly drops to 11.12%, which was mainly due to a greater wake at the downwind region where $\theta$ was about $270^\circ$ with lower wind velocity as shown in Fig. 11 (e).

However, there was a $C_T$ reducing trend when the deflector was getting closer or underneath the VAWT. For the case where $X = 0$ (the deflector right below the rotor axis), the performance of the VAWT dropped especially at the upwind region, which the $C_T$ was about 12.83% lower than the bare turbine. From Fig. 15(b), it shows that the low velocity region in front of the deflector extended to the VAWT causing the blockage effect on the VAWT, where the upwind wind velocity reduced tremendously. Also, an increase of $C_T$ was observed for $\theta$ between $200^\circ$ and $270^\circ$ (Fig. 14), in this case, due to some fresh wind being deflected upward at the downwind region. As shown in Fig. 15 (b)(ii), the deflected wind flow with high velocity approaching the rotor blade at $\theta = 270^\circ$ causing an increase of torque created. A similar observation was reported by Chowdhury et al. for a tilted H-rotor. In their research, the downwind region achieved a better performance due to obtaining more fresh wind flow rather than the turbulence flow and wake transferred entirely from the upwind [7].

Table 3

<table>
<thead>
<tr>
<th>Distance Y (m)</th>
<th>Bare turbine</th>
<th>0</th>
<th>1/3H</th>
<th>2/3H</th>
<th>H</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_T$, ave</td>
<td>0.0558</td>
<td>0.0135</td>
<td>0.0661</td>
<td>0.0739</td>
<td>0.0704</td>
</tr>
<tr>
<td>%</td>
<td>–</td>
<td>–75.74</td>
<td>18.63</td>
<td>32.61</td>
<td>26.19</td>
</tr>
</tbody>
</table>

Table 4

<table>
<thead>
<tr>
<th>Inclination angle, $\phi$</th>
<th>Bare turbine</th>
<th>0°</th>
<th>30°</th>
<th>45°</th>
<th>60°</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_T$, ave</td>
<td>0.0558</td>
<td>0.0739</td>
<td>0.0612</td>
<td>0.0581</td>
<td>0.0541</td>
</tr>
<tr>
<td>%</td>
<td>–</td>
<td>32.61</td>
<td>9.75</td>
<td>4.12</td>
<td>–2.95</td>
</tr>
</tbody>
</table>

3.2.2. Effects of the Y distance

Since when $X = 2R$ showed the best results, therefore it was fixed to investigate the Y distance effects. The Y distance is the distance between the lower edge of the VAWT and the upper edge of the flat plate deflector and it was varied from $Y = 0$, 1/3H, 2/3H and H. As shown in Fig. 16, a similar trend with the X distance was observed where the deflector amplified the wind flow velocity reaching the VAWT significantly. Also, when the deflector was placed too near to the VAWT, a subpar performance was obtained. For the case $Y = 0$, the $C_T$ value for all $\theta$ reduced drastically.

As the deflector was placed further from the VAWT, at $Y = 1/3H$, 2/3H and H, good augmentation effects were observed. At $\theta = 90^\circ$ and $200^\circ$, an improved $C_T$ was obtained compared to the bare turbine as shown in Fig. 17. This was mainly due to the high velocity wind which was deflected towards the VAWT especially at the upwind region. Moreover, the wake effects were shifted down and

![Fig. 18. Coefficient of torque for various angles of inclination, $\phi$, with $X = 2R$, $Y = 2/3H$ and $L = 1.0H$.](image-url)
away from the VAWT when the Y distance increased as shown in Fig. 17(b–d).

When Y distance was increased from 1/3H to 2/3H, the $C_T,\text{ave}$ value was increased from 0.0661 to 0.0739 which was about 18.63% and 32.61% compared with the bare turbine. This is because a more concentrated deflected wind flow was created when $Y = 2/3H$ compared to $Y = 1/3H$ as shown in the velocity vector figures (Fig. 17(b–c)). Comparing the case where the deflector at $Y = 2/3H$ and $H$, a similar $C_T$ trend is observed from Fig. 16. However, the $C_T,\text{ave}$ value was slightly reduced to 0.074 when $Y = H$. This is mainly due to a lower $C_T$ trend caused by a small reduction of the wind velocity at $\theta = 90^\circ$ as shown in velocity contour Fig. 17(d) compared to Fig. 17(c), yet it was still about 26.19% higher than the bare turbine.

Fig. 19. Velocity contour for various inclination angles (a) $\varphi = 0^\circ$ (b) $\varphi = 30^\circ$ (c) $\varphi = 45^\circ$ (d) $\varphi = 60^\circ$ with the blades at azimuthal angle (i) 0° and 180° (ii) 90° and 270° on the XZ plane.
On the other hand, as shown in Fig. 17(a), no wind occurred at the central region of the VAWT for the case $Y = 0$, while almost half of the swept area in spanwise suffered from low wind velocity which was caused by the wake effects. The $C_{T,ave}$ only achieved 0.0135 compared to the bare turbine of 0.0558 which was about 75.74% reduction (see Table 3).

3.2.3. Effects of the flat plate deflector inclination angle, $\varphi$

The simulation was continued in order to study the effects of the inclination angle, $\varphi$ with the position $X = 2R$ and $Y = 2/3H$. From Fig. 18, as the inclination angle increases, the augmentation effects become less significant, especially at the upwind region. The $C_{T,ave}$ values for different inclination angles of the deflector are tabulated in Table 4, indicating that the maximum $C_{T,ave}$ was obtained when

---

Fig. 19. (continued).
the deflector has no inclination ($\phi = 0^\circ$) which was 32.61% higher than the bare turbine. The reason for this phenomenon is because of the resultant velocity vector. At no inclination angle (Fig. 19(a)), the wind flow was forced to deflect upward with a higher magnitude of y-direction velocity vector; hence the resultant wind flow was deflected heading towards the VAWT. As the inclination angle increased, the y-direction vector became less which leads to a decrement of $C_T, ave$. Moreover, the reduction of the deflector projection area also contributes to less augmentation effects where less wind flow was captured and deflected. When the inclination angle increased up to $60^\circ$, the graph is almost the same with the case without the deflector plate as depicted in Fig. 18. This also can be observed from Fig. 19(d), where the augmented wind flow was parallel with the oncoming flow.

3.2.4. Effects of the flat plate deflector length, $L$

For the last parameter of the simulation, the length of the deflector plate was varied from $L = 0.5H, 1.0H, 1.5H, 2.0H$ with other parameters fixed as $X = 2R$, $Y = 2/3H$ and $\phi = 0^\circ$. From Table 5, all cases gave a better result compared to the bare turbine. As the length $L$ increases, the $C_T, ave$ increases until the optimum length where $L = 1.5H$. The $C_T, ave$ achieved was 0.0820 compared to the bare turbine, 0.0588; it was approximately about 47.10% increment. Further increasing the length to $L = 2.0H$, the $C_T, ave$ slightly reduced to 0.0800, yet still about 43.40% higher than the bare turbine. Referring to Fig. 20, a longer deflector in fact induced a higher $C_T$ at the upwind region due to more wind flow being captured and deflected towards the VAWT as shown in Fig. 21. The same observation was reported in the research by Altan [10]. At the downwind region, except for $L = 0.5H$, all other cases showed an increase of $C_T$ at $\theta$ between $200^\circ$ and $270^\circ$ where the augmented wind flow extended to the downwind region in Fig. 21(b–d).

Although a longer length deflector generates a higher $C_T, ave$, the cost incurred will also be higher. This is due to the supporting structure of the deflector has to be stronger as greater drag force is exerted on the deflector. In addition, the application of a large deflector is not suitable for the wind turbine farm as too much wake generated will affect one another. Fig. 22 depicts the top view of the velocity contour for different flat plate deflector length, $L$. From the figures, it can be observed that when the length, $L$, increases from 0.5 $H$ to 2.0 $H$, the wake is extended longer.

From the simulation results, the parameters which yield the best results occurred when $X = 2R$, $Y = 2/3H$, $\phi = 0^\circ$ and $L = 1.5H$. However, these parameters were limited for a specific type of wind turbine. Other factors including the solidity and the aspect ratio are good to consider in the future study. As aforementioned, the $C_T$ values obtained from the simulations are merely for the single rotor blade. In order to calculate the overall performance of the 2-straight bladed VAWT, the $C_T$ graph is offset by an azimuth angle of $180^\circ$ for the second blade [4,15]. Fig. 23 shows the simulated $C_T$ values for blade 1, blade 2, and the total sum of the $C_T$ values at each azimuth angle for the best case. Under this condition, the total $C_T, ave$ value was 0.1640, corresponding to the $C_T, ave$ of 0.4231.

3.3. Vortex shedding visualization

Comparison on the vortex shedding by the VAWT rotor blades and the flat plate deflector were performed for the optimal case where $X = 2R$, $Y = 2/3H$, $\phi = 0^\circ$ and $L = 1.5H$ and the case with lowest $C_T, ave$ value which is $X = 2R$, $Y = 0H$, $\phi = 0^\circ$, and $L = 1.0H$. Fig. 24 shows the 3D view of vorticity coloured by velocity for a better visualization of the effect of the flat plate deflector.

From Fig. 24, it can be observed that the wake generated by the VAWT is not axisymmetric like the HAWT, where at a different azimuthal angle, the strength of the vortex generated is different. For the case with the optimal parameters of the flat plate deflector, when the blade travels at the upwind, it interacts with the augmented wind flow, and a high turbulence region is generated at the trailing edge and the blade tips. As shown in Figs. 24 and 21(e), the VAWT is away from the wake generated by the flat plate deflector, and the rotor blade only interacts with some wake region near to the lower blade tip at the downwind region.

On the other hand, for the case $Y = 0$, where the lowest $C_T, ave$ value was obtained. It can be seen from Fig. 24(b), the wake stream

<table>
<thead>
<tr>
<th>Table 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Summary of cycle-averaged coefficient of torque for each parameter.</td>
</tr>
<tr>
<td>Length, $L$</td>
</tr>
<tr>
<td>$C_T, ave$</td>
</tr>
<tr>
<td>%</td>
</tr>
</tbody>
</table>

Fig. 20. Coefficient of torque for various flat plate deflector lengths, $L$, with $X = 2R$, $Y = 2/3H$ and $\phi = 0^\circ$. |
generated by the flat plate deflector with low velocity is propagated to almost half of the rotor swept area. As aforementioned, the upwind region is crucial for the rotor to create lift force for the rotor overall torque; however, in this case, the blockage effects of the deflector are significant and causing a low $C_{T_{ave}}$ value was obtained. Only the upper spanwise of the rotor blade in the upwind region has interacted with the augmented wind flow.

3.4. Potential application

From the abovementioned study, it shows that a proper location of the flat plate deflector at the upwind of a VAWT is able to enhance the power output of the VAWT significantly by speeding up the oncoming wind flow. This deflector is suitable for retrofitting on the stand-alone VAWT to increase the power generation with

Fig. 21. Velocity contour for various lengths (a) $L = 0.5H$ (b) $L = 1.0H$ (c) $L = 1.5H$ (d) $L = 2.0H$ with the blades at azimuthal angle (i) 0° and 180° (ii) 90° and 270° on the XZ plane.
the same oncoming wind flow. As illustrated in Fig. 25, the potential application of the deflector on the VAWT where the deflector is arrayed around the VAWT pole with a simple supporting structure to capture omni-direction wind. The wind flow will be deflected toward the VAWT to increase the rotational speed, hence increase the power output. This on-site electric power generated is suitable for the island and isolated places which are far away from the national grid line system. The power generated can be used for many applications especially for lighting during night time. In addition, the deflector can be utilized for other applications, for instance, as advertisement board, map, directory or decorative light reflector during night time. Also, it can reduce the visual impact of the flickering for the rotation of the VAWT.

Fig. 21. (continued)
4. Conclusions

The aerodynamic performance of an NACA0021 straight-bladed vertical axis wind turbine with a flat plate deflector was investigated using CFD simulations. The CFD simulation was first validated by the wind tunnel testing data from the literature. Details of the simulation setup, meshing methodology, and time step selection are described in the paper. The simulation results showed a good agreement with the wind tunnel experiment. Also, the effects of a flat plate deflector placed at the upwind of the VAWT were investigated. From the study, the flat plate deflector serves as a power augmentation feature to improve the performance of the VAWT by deflecting and accelerating the wind flow towards the VAWT. The wind at the near wake region was about 20% higher than the oncoming wind flow. However, it was highly dependent on the position. A few parameters of the flat plate deflector were investigated for their effects on the overall performance of the VAWT including the X and Y position at upwind, the inclination angle and the length of the deflector. From the simulations, it can be concluded that the best cycle-averaged $C_T$ with a gain of about

Fig. 22. Wake generated for various flat plate deflector length, L (Top view-XY plane).
47.10% happens when the deflector was placed at an upwind distance 2R from the rotor shaft, 2/3H from the bottom edge of the rotor blades, no inclination angle and with a deflector length of 1.5H. This flat plate deflector is suitable and easy to be retrofitted on the existing VAWT system to further increase the power output. This study was carried out under the condition where the deflector...
operated in a single wind flow direction. For future study, an omni-direction feature can be ingeniously designed and analyzed to boost the capability of a VAWT in capturing more wind energy from multiple directions. Also, the present analysis was carried out on a specific type of VAWT which aspect ratio about 1. It is necessary to study the effects of the aspect ratio for the deflector and the VAWT in future.

Acknowledgment

The authors would like to thank the University of Malaya for the UMRC grant (RP043A-17AET) and the RU Grant (ST013-2017). Special appreciation is also credited to the Malaysian Ministry of Higher Education, MOHE for the Fundamental Research Grant Scheme (FP053-2017A).

References

[29] A. Rezaeiha, I. Kalkman, B. Blocken, CFD simulation of a vertical axis wind turbine operating at a moderate tip speed ratio: guidelines for minimum


