Experimental and simulation investigation into the effects of a flat plate deflector on vertical axis wind turbine

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A B S T R A C T

Power augmentation features have been proven as one of the wind turbine performance enhancement methods particularly for vertical axis wind turbines (VAWTs). Researches showed that with the aid of a deflector, shroud or a single plate, the power output of a VAWT can be increased remarkably. In this paper, lab tests and simulations were performed to investigate the aerodynamic effects and the flow field around a flat plate deflector as a power augmentation device which is placed at the lower upstream of a micro H-rotor VAWT. From the study, the deflector is able to induce a high velocity wind at the near-wake region which was about 25% higher compared to the oncoming wind velocity. The deflected wind flows improve the performance significantly as well as reduce the self-start velocity of the turbine. Nonetheless, it is highly dependent on the positioning of the flat plate deflector. Both experiment and simulation showed a notable observation on the position effect of the flat plate deflector. From the lab test, with the deflector at the optimal position, the maximum coefficient of power \( C_p \) achieved was 7.4% increment compared to the bare turbine. Also, from the simulation, the optimal position showed an improvement of averaged \( C_p \) up to 33% compared to the bare turbine. The flat plate deflector is simple, low cost, and can be easily retrofitted to existing stand-alone VAWT systems to improve the efficiency making them suitable for on-site power generation in urban and isolated places.

1. Introduction

Recently, vertical axis wind turbines (VAWTs) have gained attention for wind energy harvesting due to their unique omni-direction characteristic, compactness, and the ability to operate in harsh turbulence conditions. Various innovative ideas have been proposed and adopted by researchers to achieve higher efficiency for the VAWT including the modification of the VAWT configuration and the blade section.

A new patented Darrieus VAWT design was introduced by Batista et al. [1] in which the end of the blades can be bent into any angle inside, outside or parallel to the main blade body. When the blade’s end is bent inward, it allows the wind turbine to extract wind energy from both the vertical and horizontal directions. Moreover, the augmented blade profile height improves the self-starting behavior of the turbine. The articulating H-rotor is another idea that allows the blades to oscillate freely and tilt around the rotor shaft by an articulating joint [2]. This design allows a low self-start, and the blades are Swift to adapt to the wind flow. Harra et al. [3] suggested a double blade VAWT which can be transformed into a butterfly-shaped wind turbine that improves the self-starting behavior at low TSR, especially when the ratio of the inner blade to the outer blade is increased. Modification on the rotor blade is another approach to improve the performance of the VAWT. As reported in [4], winglets and endplates were added to the rotor blades to produce extra lift forces while lowering the drag forces and eliminate the blade tip losses, resulting in significant efficiency improvement where the airfoil behaved like a 2-D blade. Beri and Yao [5] claimed that a modified airfoil divided into two sections with a trailing edge was able to improve the self-start of a VAWT. Adding semi-circular dimple cavity [6,7] and Gurney flap [7] on the blade profile improved the turbine efficiency by about 25% due to the generated flow recirculation that increased the lift force at a positive angle of attack and hence the tangential force was increased.

Power augmentation device is another popular method that can improve the performance of the VAWT output significantly. Some researches have shown that with the power augmentation feature, the wind turbine can exceed the Betz limit [8,9]. However, the addition of

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components will incur extra cost. Among the power augmentation features reported in [8], a flat plate deflector is the simplest power augmentation device. Mohamed et al. [8,10] employed an obstacle shielding plate in front of a Savonius rotor returning blade which reduced the counter moment of the turbine, hence improving the total moment of the turbine. The measured power output coefficient was increased by about 38.9% compared to the conventional Savonius rotor. For the conventional Savonius rotor, the negative static torque coefficient that prevents it to self-start was fully eliminated by the optimal obstacle plate, and it further increased the static torque coefficient significantly, hence the self-start capability was always obtained as the major advantage of the obstacle shielding plate. A similar finding was reported by Golecha et al. [8,11], where the position of the deflector plate was investigated. The research revealed that an optimal position of a deflector plate at upstream would maximize the Savonius rotor power output, where the coefficient of power was increased by about 50% in the experiment. The deflector plate acted as an obstacle for the flow towards the returning blade that generated negative torque. However, the positioning of the deflector was crucial; for an inappropriate orientation, the plate did not cover the returning blade, but the accelerated flow created higher reverse flow. Atlun and Atilgan [12,13] conducted experiments and simulations of a curtain plate on the performance of a Savonius rotor. The curtain plate comprises two flat plates with the same function as the aforementioned research. With the curtain plate, the rotor performed better.

Most of the research on the flat plate deflector employs a drag-type VAWT. In Kim and Gharib [14] research, an upstream deflector was introduced to improve the efficiency of two counter-rotating straight bladed VAWTs. A proper positioning of the VAWT behind the deflector was able to increase the tailoring free stream. As the power output is proportional to the cube of the oncoming wind velocity, thus the VAWT power output increased significantly. However, the power output was reduced in the situation when the turbine was placed inside the streamline or too close to the deflector due to small flow inside the wake region. A similar investigation of the upstream deflector on a pair of counter-rotating H-rotor VAWTs was performed by Jin et al. [15] by experiment and simulation. The study revealed that the upstream deflector is able to enhance the power output significantly; however, it is highly dependent on the size and the position. As the deflector width was increased, the near wake region became larger which reduced the power output of the VAWT, also, the further the distance of the deflector from the VAWTs, the augmentation effects became less. Other than using a flat deflector, Takao et al. [16,17] employed the guide vane row which comprises of three arc plates that are positioned at the upstream of a three-bladed H-rotor VAWT. The design can be yawed by the tail vanes to orientate the direction to align to the wind flow. The guide vane row deflects the wind flow to increase the positive torque where the maximum \( C_P \) was increased by 1.5 times with the design. Also, Santoli et al. [18] investigated a convergent duct on a H-rotor VAWT. From his research, by using the concept of the Venturi effect, the wind velocity was increased with the reduction of the cross-sectional area of the convergent duct, hence the power generated was increased by about 125% and 30% at wind velocity 8 m/s and 15 m/s respectively. Another curve-shaped upstream deflector design was investigated by Stout et al. on a three-bladed H-rotor [19]. This deflector redirects the wind flow from the returning turbine blade, hence reducing the negative torque generated on the VAWT.

For most of the augmentation devices, they are based on the principle of obtaining higher mass flow rate for the wind stream by converging the flow before it interacts with the turbine, thus, creating a higher positive torque on the VAWT. In comparison between the drag type and lift type VAWT, the drag type VAWT mainly reduces the negative torque created on the returning blade by diverting the flow towards the advancing blade. While for most of the lift type VAWT, the function of the augmentation device is to change the wind path to a better angle of attack on the airfoil blade to create higher lift forces for the rotation [8].

From the literature review, scarce research has been conducted on the effects of a flat plate deflector as a power augmentation device on lift-type VAWTs. Also, most of the research have been conducted with the deflector being placed side by side with the VAWT using 2D simulation. The 3D flow effects are still unclear. The key objective of this work is to investigate the effect of the flat plate deflector on a VAWT by varying the position at the lower upwind via experiment and 3D simulation. The present paper is organized as follows: in Section 2, the basic formulation of a VAWT, the lab tests setup and methodology are explained. The CFD simulation modeling and numerical settings are reported in Section 3. Section 4 presents the results of the experiment and simulation, with discussions on the findings. Finally concluding remarks on the study are reported in Section 5.

2. Lab test

2.1. VAWT performance parameters

The flow characteristics for a straight bladed VAWT is complicated compared to the HAWT, where the lift and drag forces created on each HAWT blade are the same. For the VAWT, because the resultant wind velocity impinges on the blade at a different angle of attack, the lift and drag forces generated on each blade at various azimuthal angles periodically changes [20]. Fig. 1 illustrates the forces and velocities on a VAWT, \( F_L \) and \( F_D \), representing the lift force and the drag force created by the rotor blades. For the wind turbine, the tip speed ratio (TSR), \( \lambda \) is defined as the ratio between the blade’s tip speed and the on-coming wind speed [6,21–23].

\[
\text{TSR} = \frac{R \omega}{U_{\infty}},
\]

where \( \omega \) denotes the rotational speed of the VAWT, \( R \) is the rotor radius and \( U_{\infty} \) is the oncoming wind speed. The relation between the angle of attack, \( \alpha \), the pitch angle, \( \beta \), the azimuthal angle, \( \theta \) and the TSR, \( \lambda \), is expressed as [20,24]:

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

In order to evaluate the wind turbine efficiency, there are two important parameters which are the coefficient of torque, \( C_T \) and the
controlled by using the adjustable power supply. The magnitude of the hysteresis braking force applied on the rotor shaft was measured using a torque transducer display (Model: Magtrol 3410) to show the measured balancing of the system. The torque transducer was connected to the bearing section of the test rig, the distance, $Y$, was measured by a hot wire anemometer (model: Extech HD350). In order to check the wind velocity data at the test section were measured by a heavy duty pitot tube anemometer (model: Extech HD350). In order to check the uniformity of the wind velocity, a total of 25 points ($5 \times 5$ equi-spaced) for the wind velocity were measured in a plane at a distance of 3 m from the blower fan set. The distance 3 m from the blower fan array was selected to ensure less wind velocity fluctuation. The oncoming wind speed was calculated by averaging the 25 measured wind velocity, which was $U_\infty = 6.0 \pm 0.5$ m/s. The length and the width of the test area were $12 \, \text{m} \times 3 \, \text{m}$ respectively.

The flat plate deflector used in the testing was a 10 mm thickness acrylic sheet of 0.3 m length $\times 0.9$ m width which was corresponded to $D \times 3D$ of the rotor diameter as shown in Fig. 2. The dimensions of the flat plate deflector were chosen in such a way so that the length was the same as the turbine height, while the width of the deflector fully covered the diameter of the VAWT so that the result is not affected by the wind flow from the side.

### 2.3. Experiment methodology

Before the testing was performed on the VAWT, the velocities of the wind flow around the flat plate deflector were measured by a hot wire anemometer with the on-coming wind velocity of 6 m/s. As shown in Fig. 3, the locations of the measuring point from $V_1$ to $V_{12}$ were 10 cm from the flat plate deflector.

The lab test was then conducted for the VAWT without the flat plate deflector to examine the performance of a bare VAWT. The center of the VAWT was placed at 3 m from the center of the blower fans array as depicted in Fig. 2. For every test, the VAWT was started with free running (without load) by disconnecting the brake with the torque transducer for 5 min to examine the self-start behavior and the maximum rotational speed. Later on, a different magnitude of load was applied by the hysteresis brake while the data were recorded by the computer for every interval of 0.1 s over a period of 5 min. The data provided by the torque transducer are rotational speed, torque and power; hence, 3000 data for every parameter were recorded and averaged for different loads applied. The load was increased for a few stages until maximum where the VAWT was not able to rotate further. Lastly the coefficient of power, $C_p$, and the tip speed ratio, $TSR$ were calculated according to Eqs. (1) and (4).

In order to investigate the effects of the flat plate deflector positioned at the center upstream of the VAWT, two parameters were investigated which were the horizontal distance, $X$, and the vertical distance, $Y$ as shown in Fig. 3. The horizontal distance, $X$, was the distance between the deflector and the VAWT radius; whereas, the vertical distance, $Y$, was the gap between the lower edge of the VAWT to the upper edge of the deflector. The deflector was placed perpendicular to the oncoming wind flow. The distance $X$ was varied from 0 m, 0.15 m and 0.30 m (corresponding to $X/R = 0, 1/2$ & 1) with distance $Y$ was fixed as 0.1 m ($Y/H = 1/3$). Due to the space constraint caused by the bearing section of the test rig, the deflector placed underneath the VAWT rotor axis ($X/R = -1$) was not performed. For distance $Y$, three different cases were tested which were 0 m, 0.1 m, and 0.2 m (corresponding to $Y/H = 0, 1/3$ and 2/3) with distance $X/R = 1$. Lastly, the test was conducted for the optimal position to investigate the self-start behavior of the VAWT with and without the flat plate deflector.

### Table 1

Lab test VAWT’s parameter.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type of airfoil</td>
<td>FX 63.157</td>
</tr>
<tr>
<td>Number of blade</td>
<td>5</td>
</tr>
<tr>
<td>Rotor radius (m)</td>
<td>0.15</td>
</tr>
<tr>
<td>Rotor height (m)</td>
<td>0.3</td>
</tr>
<tr>
<td>Chord length (m)</td>
<td>0.045</td>
</tr>
<tr>
<td>Pitch angle (°)</td>
<td>10</td>
</tr>
<tr>
<td>Blade material</td>
<td>Aluminium extrusion</td>
</tr>
</tbody>
</table>
3. Numerical simulation

3.1. Geometry modeling & numerical settings

The flow characteristics for the VAWT are complex due to the interaction of the oncoming flow and the blades at upwind generates wakes that transfer to the downwind region and impinge with other blades. It becomes more complicated with the addition of an augmentation device employed in the system. Computational fluid dynamics (CFD) simulation is a popular tool to analyze such complex cases. Researches show that 2D CFD simulation over predicts the performance of VAWT compared to 3D CFD simulation [21,25,27,30,31]. 3D CFD simulation can provide better approximate results to the experiment where it can simulate the 3D effects such as secondary flows and the tip effect [21,31]. However, long computation time and large storage space are always the drawbacks for 3D CFD simulation. In this paper, 3D CFD simulations were performed to analyze and explain the flow characteristics of the flat plate deflector on the VAWT performance.
The simulation was carried out by re-simulating and validating the results from the wind tunnel experiments conducted by Li et al. [20,32] by using the commercial CFD software Ansys Fluent. These simulations were mainly to show and explain the flow characteristic on the VAWT after the deflector. The wind tunnel test data by Li et al. was selected for the validation case due to the availability of the $C_T$ data of every azimuthal angle that can be compared with the data generated by the CFD software. In the wind tunnel test, a two-bladed NACA 0021 airfoil H-rotor with 1.2 m height ($H$) and 2 m diameter ($D$) was employed in the circular open test section in the wind tunnel testing. The oncoming wind speed was 8 m/s with the wind tunnel turbulence intensity of 0.5%. The chord length of the blade was 0.265 m with 6° pitch angle. By wind speed was 8 m/s with the wind tunnel turbulence intensity of 0.5%. The chord length of the blade was 0.265 m with 6° pitch angle. By using pressure taps attached to a rotor blade, the pressure distribution on the blade was captured and hence the fluctuations of the $C_T$ and $C_p$ values at every azimuthal angle over a cycle were generated.

For the 3D simulation, two domains were modeled: the VAWT rotor domain in a cylindrical shape and the tunnel stator domain in a cuboid shape by using the Design Modeler software packaged with Ansys software. Fig. 4 illustrates the dimension of the domains and the boundary conditions applied in the simulations. The size of the tunnel stator was modeled in 10 $D$ width $\times$ 10 $D$ height $\times$ 25 $D$ length. The rotor domain was embedded in the center of the cross-section of the stator domain with distance 10 $D$ from the inlet and 15 $D$ from the outlet. This distance was to allow for the full development of the wake. The domain size was considered suitable as reported in Lam and Peng’s [31] study on the wake characteristics of a VAWT with the domain size of 10 $D \times$ 10 $D \times$ 16 $D$. The rotor domain was modeled in a cylinder with diameter 1.5 $D$ and a gap of 0.2 m at both top and bottom away from the VAWT. According to [33], the blockage ratio is the projection frontal area of the VAWT to the tunnel cross-sectional area, whereby it should be less than 3% for numerical simulation of the urban flows and 5–5.7% for aeronautical and vehicle aerodynamics analysis [31]. In this case, the blockage ratio was 0.6% for bare VAWT and 3.6% with the flat plate deflector which fell in the acceptable range. The VAWT and the deflector were modeled in the rotor and stator domain respectively. The VAWT was modeled according to Li et al. wind tunnel test. However, the rotor strut and shaft were neglected due to the limited information provided. The deflector was modeled in 3 $D$ width $\times$ 1 $H$ length $\times$ 10 mm thickness as in the lab test. A few simulations were conducted by varying the position of the flat plate deflector with the $X$ and $Y$ distances where $X/R = -1, 0, 1 & 2$ and $Y/H = 0, 1/3, 2/3 & 1$.

The frontal area of the tunnel was set as velocity inlet, $U_\infty$, with the oncoming wind velocity equal to 8 m/s at TSR of 2.58 as benchmark for the wind tunnel testing [20]; whereas, the rear area of the tunnel was set as pressure outlet with the outlet gauge pressure of 0 Pa. The turbulence intensity was employed as 0.5% according to the testing. All side surfaces were defined as symmetry [21,34] to allow the solver to consider the side boundary as a free shear slip wall to avoid the real wall effects [35], while the flat plate deflector and the VAWT rotor blades were defined as the non-slip wall. The shared boundaries of the cylinder domain and the tunnel domain were set as the interface to ensure the fluxes can pass from one mesh to another. In order to perform the rotational motion of the VAWT, sliding mesh method was used with the rotor domain rotated in the clockwise direction with rotational speed, $\omega = 20.64$ rad/s, where the TSR equals to 2.58.

For the convergence criteria, all parameters were set to 1E-5. The coefficient of torque, $C_T$ for one of the VAWT’s blade generated by the software was observed. The azimuthal angle 0° was the start point of the VAWT rotor. The $C_T$ data for each time step was recorded and after a complete revolution, all $C_T$ data were averaged and the averaged $C_T$ value was calculated according to Eq. (5). The simulation was stopped when the convergence criteria was achieved which was the discrepancy percentage of the average coefficient of torque for two consecutive cycles was less than 1%, as denoted in Eq. (6).

$$\text{Convergence} = \frac{C_{T(i)}(\theta) - C_{T(i-1)}(\theta)}{C_{T(i-1)}(\theta)} < 1\%,$$

For this unsteady simulation, the Ansys Fluent software which is based on the finite volume method was used to solve the Unsteady Reynolds-Averaged Navier Stokes (URANS) equation with the SIMPLE (semi-implicit method for pressure linked equation) algorithm. Air with the default property settings was used as the fluid. Least square cell based was set as the gradient of the solution variable, and for the momentum, turbulent kinetic energy, specific dissipation rate as well as the transient formula, second-order upwind was set.

3.2. Mesh method and mesh dependency test

Ansys ICEM CFD software was used to generate the meshes. In order to simplify the meshing step, both of the VAWT rotor and tunnel stator domains were generated separately and by using the append function to merge them in the solver stage. Selection of a suitable mesh size is crucial especially for the 3D CFD simulation which involves a huge number of cells. A finer mesh can ensure a more promising and reliable simulation result; however, it is costly in computational time and data storage space, hence mesh dependency test was performed to select an appropriate mesh size. In this simulation, the rotor blades were the most critical part as the VAWT $C_T$ is generated by the surface pressure of the blades; therefore attention was focused on the mesh sizing method at this region. The VAWT rotor domain consists of almost 80% of the total number of the unstructured mesh cells which was constructed in a majority of tetrahedral cells with some pyramidal and prism cells. The high aspect ratio prism cells were defined at the

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**Fig. 4.** Domains dimensions and boundary conditions.
inflation layer near the blade to capture the boundary layer gradient. Eq. (7) shows the dimensionless \( y^+ \) value, where \( u \) is the friction velocity at the nearest wall, \( y \) is the distance to the nearest wall, and \( v \) is the local kinematic viscosity of the fluid.

\[
y^+ = \frac{\mu y}{v}
\]  \hspace{1cm} (7)

According to theoretical derivations and experimental explorations, classification of the boundary layers are viscous sub-layer \( (y^+ \leq 5) \), buffer layer \( (5 < y^+ \leq 30) \), log-law region \( (30 < y^+ \leq 500) \), and outer layer \([31,36]\). For the mesh near the blade’s wall, the inflation layer method was applied with the first layer cell thickness of 0.05 mm, growth rate of 1.2 and a total of 30 layers in order to obtain the \( y^+ \) value less than 5 \([27,36]\). As shown in Fig. 5, the inflation layer at the leading edge and the trailing edge with the cell thickness coarsens gradually from the blade wall surface. The meshing scheme of the interface boundaries were set to be the same for both the domains, this is to ensure small tolerance gap and the meshes closely follow the shape of the cylindrical feature \([37]\).

In order to ensure the mesh-independent solution, refinement of mesh was conducted. Similar mesh dependency method was reported in \([38]\). A total of seven different mesh sizes were examined; the details of each mesh are tabulated in Table 2. M1 was the finest cells, about 3.3 million cells gradually coarsened the cell size to M7 which is about 0.9 million cells. The time required for a complete revolution by an Intel quad core i7-960 processor 3.2 GHz with 16 GB RAM computer were summarized in the table also.

From the grid refinement study, when the total number of mesh was higher than M3 which was about 1.85 E+06 cells, the averaged coefficient of power converged. Fig. 6 shows the average coefficient of power, \( C_p \) for a complete revolution versus the number of cells. The differences between M3, M2 and M1 were less than 1%. Referring to Table 2, the computational time for M1, M2 and M3 were 45, 15 and 14 hours per revolution respectively, hence, in order to save computational time while maintaining promising simulation results, the following simulations were carried out with mesh size M3.

### 3.3. Time-step sensitivity study

According to the Courant-Friedrichs–Lewy (CFL) criterion, there is a relation between the time step and the space discretization \([37,39,40]\).

As a finer mesh size will give a higher accurate result, however, maintaining time steps while reducing the mesh size will cause instability and convergence difficulties as the Courant number increases \([40]\). Hence, the azimuthal increment has to be selected properly in order to obtain a reliable result. In addition, a small azimuthal increment will require a longer time for a complete revolution. In this paper, four different time steps were simulated which were \(4.228 \times 10^{-4} \) s, \( 8.456 \times 10^{-4} \) s, \( 1.691 \times 10^{-3} \) s and \( 2.537 \times 10^{-3} \) s which is equivalent to \(0.5°, 1.0°, 2.0°\) and \(3.0°\) azimuthal angle increment per time step. For each time step, 20 iterations were applied. Fig. 7 depicts the
The turbulence model is crucial in producing a trustworthy simulation result. Balduzzi et al. [41] compared three different turbulence models which were the SST $k$-$\omega$ (Shear Stress Transport), standard $k$-$\varepsilon$ and the RNG $k$-$\varepsilon$. From the study, it was found that the SST $k$-$\omega$ agreed well with the experiment. The same finding was obtained in [27,41,42] where the SST $k$-$\omega$ turbulence model obtained the nearest result to the experiment compared to the other two models. These three turbulence models were investigated in the simulation to select the highest accuracy to the experiment. The same time steps were used in the literature [15,26,27].

3.4. Turbulence model

The turbulence model is crucial in producing a trustworthy simulation result. Balduzzi et al. [41] compared three different turbulence models which were the SST $k$-$\omega$ (Shear Stress Transport), standard $k$-$\varepsilon$ and the RNG $k$-$\varepsilon$. From the study, it was found that the SST $k$-$\omega$ agreed well with the experiment. The same finding was obtained in [27,41,42] where the SST $k$-$\omega$ turbulence model obtained the nearest result to the experiment compared to the other two models. These three turbulence models were investigated in the simulation to select the highest accuracy to the experiment. Fig. 8 illustrates the prediction of the averaged coefficient of power for a complete revolution of a single blade for the VAWT. It was observed that the SST $k$-$\omega$ turbulence model shows a better prediction especially at the downwind region, where the RNG $k$-$\varepsilon$ and standard $k$-$\varepsilon$ underestimate the results.

Better prediction of the SST $k$-$\omega$ turbulence model is due to the ability to capture the wake vortices better than the $k$-$\varepsilon$ model, thus, at the downwind region, it is closer to the experimental data [42]. The standard $k$-$\varepsilon$ model is a high--Re number model which is valid for fully turbulent flows, however, the flow regime of the system is laminar ($Re = 3.27 \times 10^5$), hence the prediction is less accurate. For the RNG $k$-$\varepsilon$ model, although the formulation accounts for the low-Re number effect, however, it depends on the near wall treatment [43]. The SST $k$-$\omega$ model is suitable to be used in low-Re turbulence model without any extra damping function [15,44]. This model shows a good prediction of the turbulence in adverse pressure gradients and separating flow situations [44]. The SST $k$-$\omega$ model is an improved version of the standard $k$-$\omega$ model which blends the $k$-$\omega$ and $k$-$\varepsilon$ model together where at the near wall region of the boundary layer, the $k$-$\omega$ model is activated and transformed to the $k$-$\varepsilon$ model at the far field [37,42,43,45]. The adjustment of the eddy viscosity formulation enables this model to accurately deal with the transport effects of the turbulent shear stress which can avoid the common problem associated with the $k$-$\varepsilon$ model [42].

3.5. Validation of simulation

3D CFD simulations were performed to explicate the aerodynamic flow field of the experiment. Before further investigation of the effect of the flat plate deflector, the simulation was first validated with the wind tunnel experiment data published by Li et al. [20]. As shown in Fig. 8, the coefficient of power at various azimuthal angles for a complete cycle at TSR 2.58 is plotted. The simulation data have a good agreement with the experimental data, even though there are some variations especially at the downwind side. The maximum $C_P$ achieved was 0.65 and 0.61 for the simulation and experiment respectively, which the variation of 0.04 (about 6.5%) at azimuthal angle about 90°. On the other hand, the largest variation happened at azimuthal angle 0° where a difference of approximately 0.18 on the $C_P$ value. The CFD approach predicted well the trends.

According to the simulation performed by Li et al. [28], a similar discrepancy was observed at the angles between 245° and 30°. In their simulation, the $C_P$ value at azimuthal angle 315° shows the largest discrepancy happened with the $C_P$ value of −0.15 and 0 were obtained from the simulation and experiment respectively, the differences on the $C_P$ value was about 0.15. This discrepancy was mainly due to the effect of the induced velocity that was generated from the tip vortex. The relative angle of attack is lower than the stall angle because of the effect of the blade tip vortex in the wind tunnel experiment. In addition, the flow field is very complex at the downwind region which is caused by the wake effect of the blade from the upwind region. The power

Fig. 7. Time step sensitivity test.

Fig. 8. Turbulence model.
coefficient obtained from the blade surface pressure measurement does not contain the frictional drag of the blade surface. Also, these discrepancies are due to the geometrical simplification between the physical model and the simulation [26,33]. As reported in [21,22,24,26,33,46,47] which uses similar NACA airfoil series H-rotor, the same trends were observed for the azimuthal angles between 330 and 30°. The discrepancy was accepted in this simulation, as the simulations were mainly to visualize and explain the flow characteristics on the effect of the existence of the flat plate deflector.

4. Results and discussions

4.1. Lab test results

4.1.1. Velocities around the flat plate deflector
The measurement of the velocities around the flat plate deflector was conducted for twelve locations as shown in Fig. 3. Table 3 reports the velocities measured. It was observed that when the wind flow was approaching the flat plate deflector, a low wind velocity was measured, and behind the flat plate deflector there was almost no wind flow. However, at points V7 and V11 (Fig. 3), a high velocity which was about 25% higher than the oncoming wind flow was created at the near wake region. These high velocity regions were due to the wind flow being deflected at the edge of the deflector.

4.1.2. Effects of X position
From the lab tests, the comparison between the bare turbine and the effects of the flat plate deflector were examined. As shown in Fig. 9, the rotational speed of the VAWT at free running accelerated from stationary and achieved stable maximum rpm after a time of about 100 s. It was observed that the flat plate deflector affected the performance of the VAWT significantly; nevertheless, it was highly dependent on the position of the deflector. When the flat plate deflector was placed at 0.15 m (X/R = 1), the rotor rotational speed of about 410 rpm was increased by 7.3% compared to the bare turbine of 382 rpm. As the X distance increased to 0.3 m (X/R = 2), the rotational speed was not further increased, but slightly reduced to 363 rpm (−5%) about the same with the bare turbine. This was due to the augmentation effects getting less as the deflector was too far away from the VAWT. However, not all the cases the deflector showed higher rpm compared to the bare turbine. Conversely, it was observed that at 0 m (X/R = 0) where the deflector was right below the VAWT rotor blade, maximum rotational speed decreased drastically and just achieved 269 rpm (−29.6%). This was due to the deflector being too close to the VAWT, where the oncoming flow was slowed down when approaching the deflector. It is noticeable that the initial gradient of the curve for X/R = 1 and 2 were higher than the bare turbine, where a proper position of the flat plate deflector will increase the angular acceleration of the rotor that can achieve the same rpm in a shorter time.

The performance of the VAWT can be represented by the coefficient of power, Cp value. From the lab test, the power of the VAWT was measured by the torque transducer and by using Eq. (4), the Cp values were calculated. Fig. 10 shows the coefficient of power, Cp against TSR. The polynomial lines with the order of three were added in the graph for a better visualization of the Cp trend. When the flat plate deflector was placed at X distance of 0.15 m (X/R = 1), the maximum Cp was 0.0523 at TSR between 0.9 and 1 compared to the bare turbine value of 0.0487 at TSR 0.9, which was about 7.4% increment. The wind was accelerated and deflected towards the VAWT; hence it improved the Cp value. However for the case where the X distance = 0 m (X/R = 0) and 0.30 m (X/R = 2) both the performance were subpar compared to the bare turbine case, where the performance of the VAWT decreased markedly especially for the case where the deflector was placed right below the VAWT radius (X/R = 0), the maximum Cp only achieved 0.0294 at TSR between 0.6 and 0.7, which was reduced by about 39.6% compared to the bare turbine. This phenomenon is due to the deflector induced blockage effect rather than the augmentation effect when the deflector was right below the rotor radius. The oncoming wind was slowed down when approaching the deflector and the VAWT. As the power of the wind turbine is directly proportional to the cube of the oncoming wind velocity, hence the performance dropped drastically. More detail reason will be explained by the flow field characteristic with the CFD below. The Cp and TSR values obtained were relatively small which was due to the fact that a micro wind turbine was used in the lab tests, and similar results were reported in [14,48,49].

4.1.3. Effects of Y position
Since at X distance of 0.15 m (X/R = 1) was the best distance for X, therefore this distance was fixed for the investigation of the Y distance effects. Fig. 11 shows the rotational speed of the VAWT for various Y distances. It was observed that for Y/H = 1/3 and 2/3, the initial gradient of the curve was higher than the bare turbine, where the VAWT accelerated faster with the deflector. When the Y distance was 0.1 m (Y/H = 1/3), it showed the best result where the maximum rpm was 410 compared to the bare turbine at 382 rpm which was about 7.3% increment. The maximum Cp value achieved was 0.0523, approximately 7.4% higher compared to the bare turbine maximum Cp value of 0.0487.

Further increasing the Y distance to 0.2 m (Y/H = 2/3), the VAWT performance slightly drops, but the rotational speed which was 398 rpm was still higher than the bare turbine case. From Fig. 12, it shows that the trend of the flat plate deflector at Y/H = 2/3 was very close to the bare turbine case, which was due to the gap between the flat plate deflector and the VAWT was too large, where the augmentation effect was no longer significant. An obvious performance decrement was the case with no gap between the VAWT and the flat plate defector (Y/ H = 0), both the maximum rotational speed and the Cp reduced significantly where the rotational speed was just 204 rpm with a maximum Cp of 0.0212. Compared to the bare turbine, it was about −46.6% and −56.5% decrement in rotor speed and Cp value respectively. This decrement was due to large flow blockage and wake effects by the deflector which was placed too close to the VAWT, where the VAWT swept area partially fell into the wake region behind the deflector and experienced low velocity and turbulent flow. Further explanation is reported in the simulation result.

From the lab tests, it can be concluded that the position of the flat plate deflector is crucial to ensure positive increment of power effects to enhance the performance of the VAWT. In order to have a significant augmentation effect, the deflector has to be placed at the horizontal distance X/R = 1 with the vertical distance of Y/H = 1/3 from the bottom edge of the VAWT. More discussion on the flow field around the deflector will be presented in the simulation result.

Table 3 summarizes all the results of the lab tests.

4.1.4. Self-start behavior
The self-start capability of the VAWT was investigated for the

<table>
<thead>
<tr>
<th>Mesh</th>
<th>Velocity (m/s)</th>
<th>Difference with the oncoming velocity (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>V1</td>
<td>5.55</td>
<td>−7.50</td>
</tr>
<tr>
<td>V2</td>
<td>3.62</td>
<td>−39.67</td>
</tr>
<tr>
<td>V3</td>
<td>3.45</td>
<td>−42.50</td>
</tr>
<tr>
<td>V4</td>
<td>4.25</td>
<td>−29.17</td>
</tr>
<tr>
<td>V5</td>
<td>5.74</td>
<td>−4.33</td>
</tr>
<tr>
<td>V6</td>
<td>6.91</td>
<td>15.17</td>
</tr>
<tr>
<td>V7</td>
<td>7.48</td>
<td>24.67</td>
</tr>
<tr>
<td>V8</td>
<td>1.39</td>
<td>−76.83</td>
</tr>
<tr>
<td>V9</td>
<td>1.34</td>
<td>−77.67</td>
</tr>
<tr>
<td>V10</td>
<td>1.24</td>
<td>−79.33</td>
</tr>
<tr>
<td>V11</td>
<td>7.5</td>
<td>25.00</td>
</tr>
<tr>
<td>V12</td>
<td>5.55</td>
<td>−7.50</td>
</tr>
</tbody>
</table>
presence of the flat plate deflector. At free loading condition, without the flat plate deflector, the turbine self-starts at a velocity of 3.55 m/s. For the case with the deflector placed at the optimal position in the experiment which was $X/R = 1$ and $Y/H = 1/3$, the turbine was able to self-start at a lower wind velocity of 2.83 m/s. Although the observation is not significant, however, a better self-start ability was achieved. The reason for this observation is that the approaching wind flows was sped up by the deflector and possess a higher velocity of about 3.51 m/s, which was about 24% higher than the oncoming wind speed before it interacts with the VAWT.

4.2. Simulation results

4.2.1. Effects of the deflector at various $X$ distances

As aforementioned in the lab tests, the location of the flat plate deflector significantly affects the performance of the VAWT. The simulation result shows a notable trend of the flat plate deflector with the lab test. Fig. 13 depicts the $C_p$ values for a single blade at various azimuthal angles generated by the simulation. For a complete revolution, there are two peaks that occur at the azimuthal angle of about 90° and 230° which is due to the angle of attack being optimum. As shown in Figs. 13 and 14, the first peak with a higher magnitude happens as the blade travels at the upwind interacts with the undisturbed oncoming wind flow. When the blade travels to the downwind, due to the wake generated by the trailing edge initially transfers to the downwind region, this complex and turbulent flow causes the energy harnessed to be much lower as shown in Fig. 14.

Fig. 15(a–e) illustrates the side view of the velocity vector and the velocity contour with the blades at 0° and 180° azimuthal angle; whereas Fig. 15(b–e) indicates the flow field around the flat plate deflector. It can be clearly seen that a low speed region occurs in front of the deflector. When the on-coming wind flow approaches the flat plate deflector, it was retarded and this created inevitable blockage effects. A large amount of the oncoming wind flow was then deflected and accelerated upward and downward after passing through the flat plate deflector, and heading towards the VAWT. These observations agreed

Fig. 9. Starting behavior and maximum rpm for bare turbine and with deflector at various $X$ distances.

Fig. 10. Performance of the VAWT with and without deflector at various $X$ distances.
with those in the literature [14,50]. Also, a low velocity and low pressure wake region was generated behind the flat plate deflector. On the other hand, at the near wake region which is the region near the top and bottom edges of the flat plate deflector, a high velocity flow which was about 10–30% higher than the free stream flow was formed that created the augmented effects to the VAWT. As shown in Fig. 15(a), for a bare turbine, after the blades interact with the wind flow, a low speed region was created behind the turbine.

For the case where \(X/R = -1\), the deflector was placed right below the rotational axis of the rotor. As shown in Fig. 13, there was a peak between azimuthal angles 200–270°; this was mainly due to the wind flows being deflected upward to the second half cycle as shown in Fig. 15(b). Compared to other circumstances, the wake generated at the upwind was transferred to the downwind side which causes a turbulent and lower wind velocity. However, the deflector at this location accelerated and deviated up fresh wind to the downwind side; hence a higher \(C_p\) was achieved. A similar observation was reported in [27,42], where a tilted VAWT showed a power gain due to less downwind wake interference and obtaining fresh wind. Although advantage was achieved at the downwind region, the overall efficiency for this case dropped drastically. This performance attenuation was mainly due to the blockage effects of the deflector, where a low velocity region created at the upwind. As the positive torque for a lift- type turbine is mainly generated at the upwind region, this low velocity region causes low positive torque obtained. As shown in Fig. 13, the first peak was much lower compared to the bare turbine. The averaged \(C_p\) value for a complete cycle was 0.1247 which decreased about 13.34% compared to the bare turbine at 0.1439.

For the case where \(X/R = 0\), the deflector was placed below the rotor radius at the upstream. Almost the same peak with the bare turbine was achieved for the upwind; while a better gain at the second cycle at the azimuthal angles of about 200–240° as shown in Fig. 13. As observed from the velocity contour, the deflected wind flow impinges on almost half of the wing span and the augmented wind flow extended

### Table 4

Experimental results of the maximum \(C_p\) for the bare VAWT and with the deflector at various positions.

<table>
<thead>
<tr>
<th>Bare turbine</th>
<th>Distance X</th>
<th>Distance Y</th>
</tr>
</thead>
<tbody>
<tr>
<td>(X/R = 0)</td>
<td>0 m ((X/R = 0))</td>
<td>0 m ((Y/H = 0))</td>
</tr>
<tr>
<td>1.5 m ((X/R = 1))</td>
<td>0.1 m ((Y/H = 1/3))</td>
<td>0.0487</td>
</tr>
<tr>
<td>3.0 m ((X/R = 2))</td>
<td>0.2 m ((Y/H = 2/3))</td>
<td>0.0294</td>
</tr>
</tbody>
</table>

| Maximum \(C_p\) | 0.0487 | 0.0294 | 0.0523 | 0.0448 | 0.0212 | 0.0523 | 0.0477 |
| Change (%) | – | –39.6 | 7.4 | –8.0 | –56.5 | 7.4 | –2.1 |

---

**Fig. 11.** Starting behavior and maximum rotational speed for bare turbine and with deflector at various \(Y\) distances.

**Fig. 12.** Performance of the VAWT without and with deflector at various \(Y\) distance.
to the downwind region compared to the bare turbine case. The averaged $C_p$ value was achieved was about 0.1441 which is approximately a 0.14% decrease.

From the velocity contour in Fig. 15(d–e), the on-coming wind flow was amplified expressively where a high wind velocity region was attained at the upwind region for both the deflector placed in front of the VAWT where $X/R = 1$ and 2. Large amount of wind flows were deflected toward the VAWT upwind region. As shown in Fig. 13, a peak with approximately 30% higher was achieved compared to the bare turbine at the upwind, which improved the overall efficiency of the turbine by about 18.55% and 11.05% for $X/R = 1$ and 2 respectively. However, starting from azimuthal angles of 250–360°, especially for the case $X/R = 2$, the averaged $C_p$ value decreased which is mainly due to the turbulent flow and the wake generated. Lower wind velocity was observed for the downwind region in Fig. 15(e) compared to Fig. 15(d) especially at azimuthal angle of 270°.

### 4.2.2. Effects of the deflector at various Y distances

For the deflector Y distance effects, as shown in Fig. 16, the VAWT performance improved significantly with a proper gap between the deflector and the lower edge of the VAWT. When the top edge of the deflector was placed at the same level as the VAWT’s bottom edge ($Y/H = 0$), the on-coming wind velocity decreased tremendously, where the $C_p$ for all azimuthal angles reduced significantly. The positive $C_p$ was only captured at azimuthal angle between 45° and 140°. The averaged $C_p$ value obtained was 0.0349 equivalent to 75.75% reduction compared to the bare turbine. From the velocity contour (Fig. 17(a)); most of the rotor region suffered from great velocity retardation and turbulence after the flat plate deflector, where no flow happened at the central region of the VAWT. The rotor swept area fell into the flat plate deflector blockage region.

On the other hand, for other Y distances, Fig. 17(b–d) show an obvious flow enhancement particularly at the upwind region. The $C_p$...
value at 90° and 230° azimuthal angle was about 10–30% higher to the bare turbine case.

For the case $Y/H = 1/3$, some wake region still fell on the rotor swept area especially at the downwind side as shown in Fig. 17(b); however the averaged $C_p$ value of 0.1706 still higher than the bare turbine. The averaged $C_p$ increased significantly as the $Y$ distance
increased until $Y/H = 2/3$ with averaged $C_P$ value of 0.1908 as shown in Fig. 16. Further increase in the $Y$ distance after the optimum point to $Y/H = 1$, the augmentation effects became less significant with the $C_P$ value slightly dropped to 0.1815, yet approximately 26.13% increment compared to the bare turbine. Fig. 17(c) and (d) shows that the wake region has low effects on both the $Y/H = 2/3$ and $Y/H = 1$ cases as it was below the rotor swept area.

From the simulation results, as shown in Table 5, the highest VAWT performance occurred at $X/R = 1$ and $Y/H = 2/3$ about approximately 32.59% better than without flat plate deflector. Fig. 18 shows the 3D view for the horizontal plane velocity contour at the mid of the deflector together with the vertical mid plane velocity vector. The simulation results are summarized in Table 5.

As abovementioned, the averaged $C_P$ obtained is only for a single blade of the two-bladed VAWT. As shown in Fig. 19, in order to calculate the overall improvement for the optimal position of the deflector which is $X/R = 1$, $Y/H = 0.66$, the graph was offset 180° for the second blade [21,26,42,47,51]. From the simulation, the overall simulated $C_P$ for the bare turbine was 0.2877 and 0.3815 for the bare turbine and the optimal deflector case respectively. It was increased by approximately 32.6% with the proper position of the flat plate deflector.

From the study, although different H-rotor VAWT was used in the lab experiment and the simulation, however, a similar trend on the effects of the deflector position was observed.

Also, it is noticeable that the augmentation factor by the flat plate deflector was about 7.3% and 33% in the experiment and simulation respectively, where the simulation achieved better result. This discrepancy is probably due to the physical model of the lab tests, with additional blockage effects which were caused by the test rig. From the simulation result, it can be observed that the wind flow was deflected upward and interacted with the rotor blades. In fact in the lab tests, the rotor shaft and the double layers plate-shaped struts contributed the parasitic effect which reduced the wind flow especially for the situation when the skewed wind flow interacted with the rotor struts before reaching the rotor blades [21,26]. The augmentation effect from the experiment was lower and less significant. This was also due to a high solidity VAWT being used, where the supporting strut blockage effect of the deflected wind flow becomes more significant with a higher solidity VAWT.

4.3. Potential applications of the research

From the study, a proper positioning of the flat plate deflector at the lower upwind of the VAWT is able to improve the efficiency of the turbine by accelerating the wind flow before impinging on the turbine. By using this idea, there are some potential applications of the concept...
Fig. 17. Velocity vector and velocity contour with/without deflector at various X distance. (a) $Y/H = 0$ (b) $Y/H = 1/3$ (c) $Y/H = 2/3$ (d) $Y/H = 1$. 
for wind power generation such as the stand-alone VAWT and the rooftop mounted VAWT.

The flat plate deflector is easy to be retrofitted to current stand-alone VAWT systems. As illustrated in Fig. 20(a), the potential application of the deflector on the VAWT is to capture the consistent sea breeze. This concept is very suitable for coastal areas and islands that are far away from the national grid line system. The on-site electric power generated can be used for many applications especially for lighting during the night. With the simple structure and cost involved, the performance of the turbine can be increased significantly. In addition, the deflector can be utilized for other applications such as advertisement board, map, signboard, directory or a light reflector during night time.

Another potential application of the research finding is for rooftop mounted VAWT in urban areas. The wind flow in an urban area is complex and highly turbulent as it is affected by local suburban topography, including the shape of a building, the roof profile and the building’s layout [52]. The VAWTs are suitable for the urban area especially for the rooftop application due to their ability to capture wind from all directions and operate well in turbulent conditions. Some shapes of buildings are able to concentrate and speed up the wind flow, example: the building edges, and the passage between two buildings [53]. The research findings of this study can be used as a guideline for rooftop VAWT installation. Fig. 20(b) shows an artist’s impression of a rooftop mounted VAWT. The building façade acts in a way similar to the flat plate deflector, directing and accelerating the wind flow upward to the VAWT. Hence, in order to benefit from this amplified wind flow, the VAWT is recommended to be installed at a distance where 1 < X/R < 2 from the edge of the building with the 1/3 < Y/H < 1 from the top surface of the roof. However, there are some other factors which affect the flow such as the roof shapes, the skewed angle, and oncoming wind profiles [54].

5. Conclusion and future research

In this paper, the effects of a flat plate deflector on the H-rotor VAWT were investigated by varying its position at the lower upwind via experiment and 3D CFD simulations. The wind flow characteristics around the deflector and the coefficient of power, C_p of the VAWT were examined. Detailed experiment and simulation setup were reported. The simulation was validated with the wind tunnel testing data available in the literature, and a good agreement was obtained.

The study showed that the deflector serves as a power augmentation device which improved the efficiency of the VAWT significantly. The oncoming wind flow was diverted and accelerated to the side edge of the deflector plate. The deflected wind flow at the near wake region possessed a high velocity which was about 25% higher compared to the oncoming wind flow. Due to the power of the wind being directly proportional to the cube of the wind speed, when this augmented wind flow interacts with the VAWT, it increased the rotor rpm and the efficiency of the VAWT.

The performance of the VAWT is highly dependent on the positioning of the flat plate deflector. From the experiment and simulation, a similar trend was observed for the positioning effects of the flat plate deflector on the VAWT. At the optimal position of the deflector at the lower upwind, the augmented wind flow induced a higher positive torque on the rotor blades at the upwind region of the VAWT, hence enhancing the C_p significantly. When the deflector was being placed too near to the VAWT, the wake generated from the deflector reduced the VAWT performance. The maximum C_p was increased about 7.3% from the experiment; whereas from the simulation, the simulated averaged C_p obtained was about 33% increment. Positive augmentation effects were obtained with the horizontal distance 1 < X/R < 2 and vertical distance 1/3 < Y/H < 1. Also, with the proper positioning of the deflector, the VAWT showed a better self-start capability.

From the research finding, the flat plate deflector is suitable to be retrofitted on stand-alone VAWT systems. With the simple design, the

![Fig. 18. Velocity vector and velocity contour for the optimal flat plate deflector position.](image-url)
Fig. 19. Overall $C_p$ against azimuth angle for the optimal deflector position.

Fig. 20. Artist’s impression for (a) Integration of multi-purpose flat plate deflector on stand-alone VAWTs near the beach (b) Rooftop mounted VAWTs.
augmented deflected wind can yield a higher power output. For future work, the effects of some other parameters of the flat plate deflector such as the size, the aspect ratio, the tilt angle, the shape of the deflector are good to explore. Also, on the rotor side, the influence of the solidity of the VAWT and the supporting strut effects will be closely investigated in the near future.

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