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Efficiency Improvement of Vertical Axis Wind Turbines with an Upstream Deflector

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Abstract

The suitability of using an upstream deflector to improve the efficiency of a vertical axis wind turbine is presented in this study. A two-dimensional vertical axis wind turbine (VAWT) was modelled and simulated using ANSYS Fluent 14.0 computational fluid dynamics (CFD) software to solve the k-epsilon (RNG) turbulence model. Firstly, the open rotor design was optimised by varying orientation and pitch angle, prior to analysing the effect increasing wind speed had on the turbine performance. A maximum efficiency of 19.101% was achieved and was used as the open rotor design. A series of curved upstream deflectors were then evaluated in terms of efficiency improvements against the original open rotor design. Installation of the deflector resulted in a redirection of the fluid flow from the returning turbine blade, therefore reducing the negative torque induced on the system. Additionally, deflector width angles of 45° and 36° were found to improve the turbine performance by 1.266%. Finally, a scale model of the wind turbine was constructed and experimentally tested using a wind tunnel. No correlation between the CFD and experimental results was found due to variations in the wind speed tested by both methods. However, the VAWT design operated at a reasonably efficient level during the experimental testing, even under suboptimal conditions.

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Keywords: Vertical Axis Wind Turbine (VAWT), Upstream Deflector, CFD, Wind Tunnel

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1. Introduction

With the negative environmental effects of long-term fossil fuel use, alongside the depletion of previously abundant oil and gas reserves, there is a global demand for a sustainable and clean alternative energy resource [1]. Wind energy has become one of the most viable alternative energy resources, with recent technological advances leading to more efficient turbine designs. The main focus of research has been into horizontal axis wind turbines (HAWTs), which have reached their maximum capability in terms of size and power output. Vertical axis wind turbines (VAWTs) offer many advantages over the conventional HAWT design and are receiving increased interest. VAWT designs can be split into two main categories, lift types (Darrieus) and drag type (Savonius), based on which component of aerodynamic force is used as a means of propulsion [1]. Savonius VAWTs consist cup or bucket shaped blades which catch the wind and rotate the shaft [2]. Whereas Darrieus VAWTs consist of airfoil shaped blades, which are propelled as the wind flows over them by a means of lift, causing the shaft to rotate, driving the generator [2].

One major advantage of the VAWT design is that they are omni-directional, able to extract wind energy in all directions and therefore don't require an expensive yaw and pitch system [1]. However, this also results in a problem of negative torque induced on the returning turbine blades (the blades acting against the direction of flow at the end of their rotation). To reduce this problem, one effective, yet simple method is to install deflectors, also known as guide vanes or stators [3]. Deflectors redirect the airflow away from the returning turbine blades, decreasing the amount of negative torque and therefore deceleration, which subsequently reduces performance.

Kim and Gharib [3] experimentally investigated the effect on the power output of two lift based counter-rotating straight bladed VAWTs with a flat-plate upstream deflector. Their wind tunnel investigation revealed the deflector had a positive effect on the power output of the counter-rotating VAWTs. Additionally, they found that the deflector geometry and position from the turbines had a significant impact on the increase in power output [3]. Takao, et al. [4] undertook a similar wind tunnel investigation into the effect of using a guide vane row (a type of deflector) on the performance of a three-bladed Darrieus VAWT. The guide vane row consisted of three arc plates and for an 8 m/s wind speed, increased the turbine power coefficient approximately 1.8 times the original open rotor [4]. Both Kim and Gharib [3] and Takao et al. [4] have shown through experimental research that the use of flat-plate upstream deflectors and guide-vanes respectively, can have a positive effect on the performance of straight-bladed VAWT designs.

Computational fluid dynamics (CFD) can be used as a more practical testing method, allowing in-depth analysis to be conducted using considerably fewer resources. It is often used during the preliminary design stage as it allows for designs to be altered and optimized numerically, prior to the expensive manufacture and physical testing of a prototype. With regards to evaluating turbine augmentations (deflectors), CFD is widely used as the preferred testing method, then completing experimental testing as a means of validation.

Mohamed, et al [5] used CFD to study the effect of using a stationary deflector to shield the airflow from the returning blade of a three bladed Savonius rotor. The study revealed that the deflector geometric parameters significantly affect turbine performance, with certain deflector angles resulting in a reduction in efficiency. However, under optimal conditions, the deflector plate increased the three-bladed Savonius turbine efficiency by 27.5%. Likewise, Burlando, et al. [6] investigated the effect stators (deflectors) have on turbine performance of a Savonius turbine variant and compared the results obtained through numerical CFD means with experimental wind tunnel testing. The rotor was tested under static conditions and therefore, to simulate rotation, four deflector orientations were analyzed, allowing the turbine performance to be calculated at multiple operational conditions. The experimental results were found to be affected by the wind tunnel domain walls and length, with the numerical results showing overestimation of performance values [6]. There are known discrepancies between results obtained through 2D CFD and experimental tests. Zadeh, Komeili and Paraschivoiu [7] and Rolland, et al. [8] stated that one reason for this is due to 2D CFD failing to accurately capture the effects of tip vortices. Recirculating flow and multiple sources of error associated with experimental testing are other known reasons for differences between CFD results and experimental testing.

The purpose of this study is to investigate the fluid flow around a three-bladed VAWT and analyse the effect an upstream deflector effect has on the turbine efficiency. Initially, numerical analysis is conducted using CFD to validate the chosen airfoil geometry, then design and optimize the VAWT design for both the open-rotor and deflector configurations. A small prototype model was then manufactured and experimentally tested using a wind tunnel to verify the CFD results of the open-rotor configuration only.

2. Numerical Analysis

All of the CFD simulations were performed in two dimensional using ANSYS Fluent 14.0 [9]. The geometry and mesh of the open-rotor models were created using ANSYS Fluent 14.0 Design Modeller. The governing equations are based on the continuity and momentum equations and are solved using the k-epsilon (RNG) turbulence model. However, it should be noted that the power output of a numerically modelled turbine can be overestimated when 2D models are used. The order of the numerical investigation was to optimize the open-rotor first, then the Augmented-rotor (deflector).

2.1. Open-Rotor and Augmented-Rotor Model Design and Setup

Initially, the open-rotor model was used to optimize the turbine configuration in terms of wind speed (U) and azimuth angle (θ). Thereafter, the augmented-rotor (open-rotor including deflector) was used to evaluate and optimize the deflector angle (ϕ).

The Darrieus-turbine design consisted of three NACA 7715 airfoil blades of 1 m chord length. The dimensions of the model domain were chosen in a way that allowed for the fluid to stabilize before entering the rotor domain, as having the rotor too close to the inlet can produce inaccurate results [11, 12]. The rotor was placed over twelve rotor diameters from the inlet and twenty from the outlet, while the domain width was set to eight rotor diameters in size and was made a symmetrical boundary, to prevent flow recirculation occurring. Figure 1 displays the numerical model geometry, with the corresponding sizes stated in Table 1. Three domains were used for the numerical analysis; the outer fluid domain, the rotating rotor domain and the inner fluid domain, as labelled in Figure 1. As there was limited computer resources available, the model was split into 11 separate projected areas to simplify the meshing process. A mesh independent solution was found to occur with a mesh containing 300,379 elements, with approximately 500 elements around each airfoil perimeter. The mesh was refined in the rotor domain to accommodate the large pressure and velocity variations to be measured around the airfoil blades. The rotor domain was defined as a moving reference frame, with the angular velocity input parameter used to vary the tip speed ratio (λ) of the turbine, for a range of simulations. An output parameter of torque (T) was used in many calculations to measure turbine efficiency.

The augmented-rotor was modelled identically to the open-rotor model, with the exception of having a fixed stationary wall, included to act as a deflector plate, as shown in Figure 2. To evaluate the turbine performance for a range of operating conditions, top-quadrant and bottom-quadrant deflectors were simulated. The angle of attack for an airfoil is dependent on the azimuth angle of the blade, the variation of which with respect to the direction of fluid flow (U) is also displayed in Figure 2.

Table 1. Model Parameters used for Rotor Numerical CFD Simulations [10, 11, 12].

Model Parameter	Symbol and Value	Model Parameter	Symbol and Value
Domain Length (m)	L = 100	Deflector Angle/Width	ϕ = variable
Inlet Length (m)	$l_1 = 20$	Deflector Radius (m)	r_d = variable
Outlet Length (m)	$l_2 = 10$	Inlet Velocity (m/s)	U = variable
Domain Width (m)	W = 24	Solver Type	Pressure-Based
Airfoil Type	NACA 7715	Viscous Model	K-epsilon (RNG)
Airfoil Chord Length (m)	c = 1	Inlet: Turbulent Intensity	2%
Number of Airfoils	N = 3	Inlet: Turbulent Length Scale (m)	1
Rotor Radius (m)	R = 1.5	Outlet: Backflow Turbulent Intensity	2.2%
Rotor Solidity	σ = 1	Outlet: Backflow Turbulent Intensity Ratio	0.1
Rotor Height (m)	H = 1		

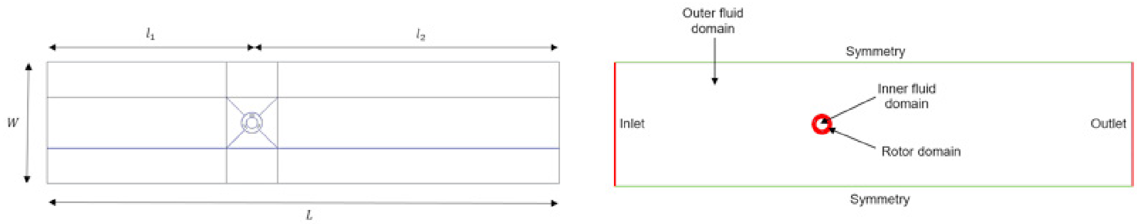

Fig.1. (a) Computational domain; (b) Boundary conditions.

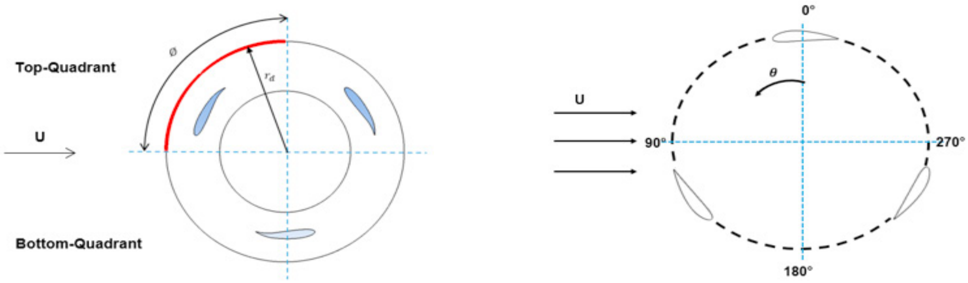

Fig. 2. Deflector Modelling (a) Dimensions (b) Azimuth Angle Measurement Method.

3. CFD Modelling Results and Discussion

3.1. Bottom-Quadrant Deflector Optimization

Four Bottom-Quadrant deflector variations were tested, with deflector angles or widths (ϕ) of 90°, 63°, 45° and 36°, all of which had a deflector radius (r_d) of 2 m. The coefficient of performance values for varying deflector angles are displayed in Table 2. The results show that deflector angles of 90° and 63° decrease the performance of the turbine by 9.006% and 9.034%, respectively. Whereas the smaller, 45° and 36° deflector angles increase the maximum efficiency of the rotor by 1.741% and 2.212%, respectively. The tip speed ratio, at which the maximum coefficient of performance occurs ($\lambda_{CP.MAX}$) is also seen to drop by 0.375 and 0.25 for these deflector angles respectively.

Table 2. Maximum Coefficient of Performance for Varying Deflector Angles (Bottom-Quadrant).

Deflector Angle, ϕ (°)	$C_{P.MAX}$	η (%)	$\lambda_{CP.MAX}$
0 (open rotor)	0.19101	19.101	1.875
90	0.10095	10.095	1.250
63	0.10067	10.067	1.500
45	0.20842	20.842	1.500
36	0.21313	21.313	1.625

The efficiency drops with larger deflector widths of 90° and 63° are due to the way in which they direct the flow. Although they were designed to reduce the effect of negative torque, they are in fact seen to alter the flow to blades 1 and 3, reducing the forces of lift. This relationship is displayed in the pressure contour and velocity streamline plots in Figures 3 to 6. With larger deflector widths (ϕ = 90° and 63°) the pressure distributions on the deflector do achieve the desired result of reducing the pressure distribution, and therefore flow, around the returning blade (blade 2). However, the size of the deflectors leads to the redirection of the flow to blade 1, reducing the induced force of lift on the blade. For the smaller deflector widths (ϕ = 45° and 36°) the flow onto blade 1 is not altered significantly. This allows for the generation of torque as if the turbine was in its 'open-rotor' condition, while reducing the flow to the returning blade (blade 2). This allows for the improvement of the systems efficiency, while reducing the rotational speed of the system required to reach optimal efficiencies.

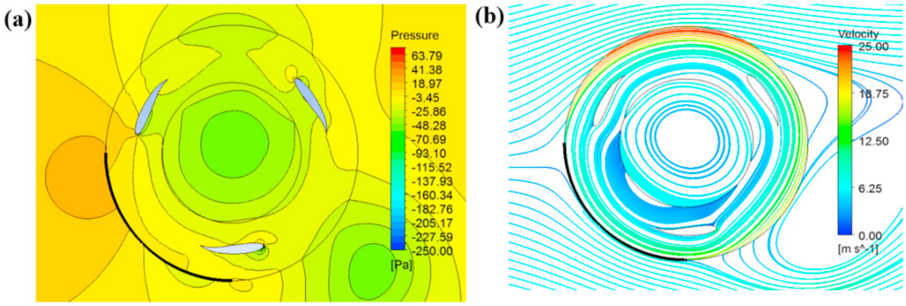

Fig. 3. Setup A (ϕ = 90°): (a) Pressure contours, (b) Velocity streamlines.

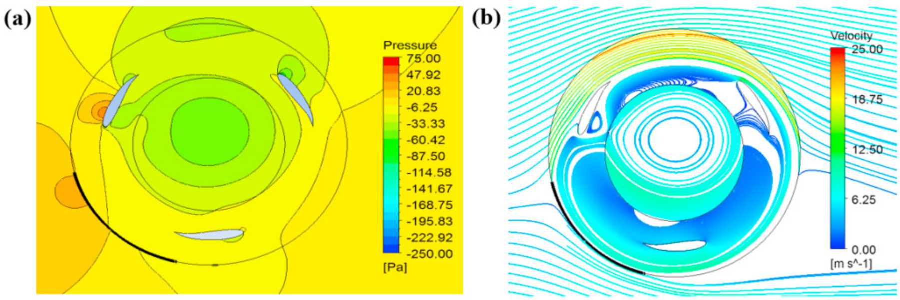

Fig. 4. Setup B (ϕ = 63°): (a) Pressure contours, (b) Velocity streamlines.

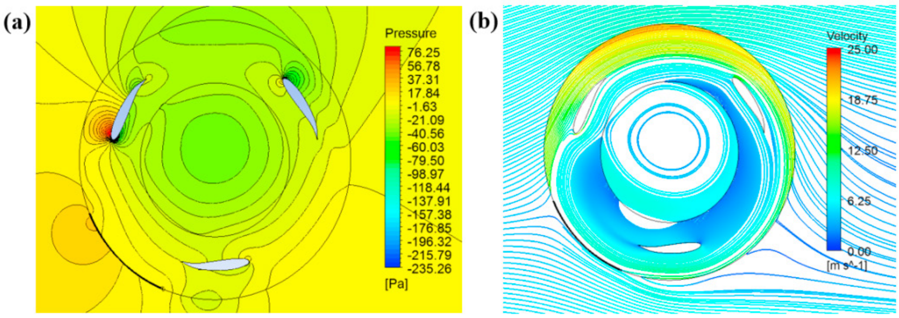

Fig. 5. Setup C (ϕ = 45°): (a) Pressure contours, (b) Velocity streamlines.

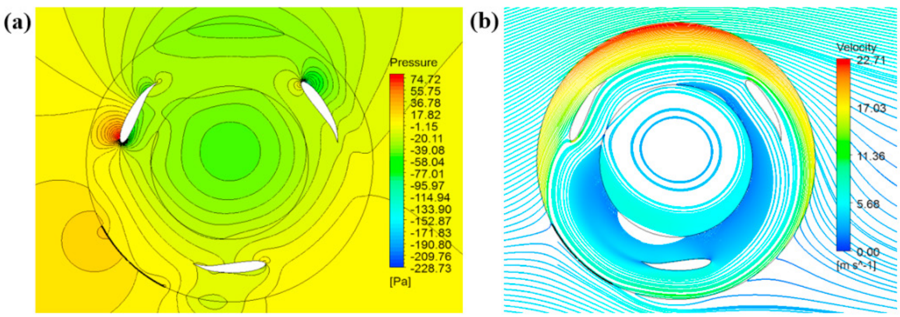

Fig. 6. Setup D (ϕ = 36°): (a) Pressure contours, (b) Velocity streamlines.

3.2. Top-Quadrant Deflector Optimization

For comparison, an identical set of simulations were conducted with the use of a series of top-quadrant deflectors, with widths of 90°, 63°, 45° and 36° implemented. However, significant decreases in the turbine efficiency were obtained when all top-quadrant deflector variations were used, the results for which are displayed in Table 3.

Table 3. Maximum Coefficient of Performance for Varying Deflector Angles (Top-Quadrant).

Deflector Angle, ϕ (º)	$\mathbf{C_{P.MAX}}$	**η (%)**	$\boldsymbol{\lambda_{CP.MAX}}$
0 (open rotor)	0.19101	19.101	1.875
90	0.20367	20.367	1.125
63	0.08023	8.023	1.625
45	0.15365	15.365	1.750
36	0.16845	16.845	2.125

Smaller deflector widths (ϕ = 63°, 45° and 36°) reduced the efficiency of the rotor by 11.078%, 3.736% and 2.256%, respectively. This is due to the flow velocity behind the deflector increasing suddenly, altering the flow to blade 1 in each case. This increased flow velocity over the top surface of blade 1 reduces the pressure difference around the airfoil and the subsequent lift force generated. For a larger deflector width (ϕ = 90°), the maximum efficiency is seen to increase by 1.266% from that of the open-rotor. However, the average efficiency becomes marginally worse than that of the open-rotor. This decrease in the average efficiency could be due to the formation of recirculating airflow behind blade 3.

3.3. Open-Rotor and Augmented-Rotor Comparison

The results of the coefficient of performance of the open-rotor and augmented-rotor variations, for orientation b and d, are displayed in Figure 7. From the results an increase in the average performance of the turbine can be seen from the use of the bottom deflector with parameters of ϕ = 36° and r_d = 2 m. Although the maximum efficiency of the turbine did not increase vastly when compared to that of the open-rotor (only an increase of 1.266%), the performance of the turbine is increased over a range of tip speed ratios. The optimum tip speed ratios are also seen to occur at lower rotational speeds, thus leading to an improved design that can provide similar power output while rotating at a slower rate. Also, the small size of the deflector allows for the axis of rotation of the turbine to be situated outside of the wake of the deflector; a necessity in the performance improvement of a VAWT [3]. However, as mentioned earlier, using the top-quadrant deflector (ϕ = 90º; r_d = 2 m), decreases the performance of the turbine for all orientations, as shown in Table 3. Although maximum performance is seen to increase by 3.705% for orientation (a), the average performance of the turbine decreases significantly for orientations (b), (c) and (d). This is due to the decrease in the pressure distribution over blade 1 and the increase in flow over blade 2, the returning blade.

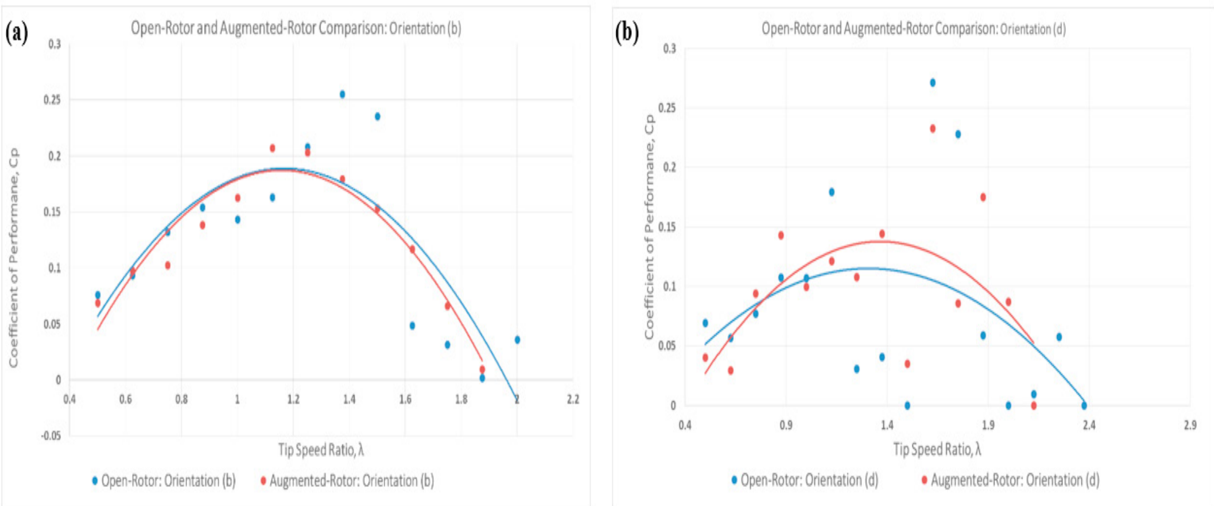

Fig. 7. CP versus TSR (λ): Open-Rotor and Augmented-Rotor (Bottom-Quadrant) – (a) Orientation b, (b) Orientation d.

4. Experimental Prototype Testing

4.1. Experimental Setup and Design

A scale model (prototype) of the original open-rotor VAWT design was constructed to provide an experimental validation to the numerical CFD results, through wind tunnel testing. An image of the constructed scale model is displayed in Figure 8, with dimensions located in Table 4. 3D printing was used to manufacture the three NACA 7715 airfoils. The experimental testing started by varying the wind speed to determine the initial 'cut in wind speed', which was found to be approximately 10 m/s. Therefore, three wind speed conditions were proposed to be analyzed, approximately 10 m/s, 15m/s and 20 m/s. A tachometer was used to measure the rotational velocity (ω), and the wind tunnel sensors provided readings of lift and drag forces. The power output (Po), wind power (Pa) and therefore turbine efficiency (η) were analyzed for the three average wind speeds tested (U_{AVE}).

Table 4. Experimental Scale Model Dimensions and Parameters.

Model Parameter	Symbol and Value	Model Parameter	Symbol and Value
Airfoil Type	NACA 7715	Blade Length (mm)	L = 180
Chord Length (mm)	c = 60	Rotor Diameter (mm)	D = 180
Number of Blades	N = 3	Wind Tunnel Dimensions (mm)	460 x 460 x 1220

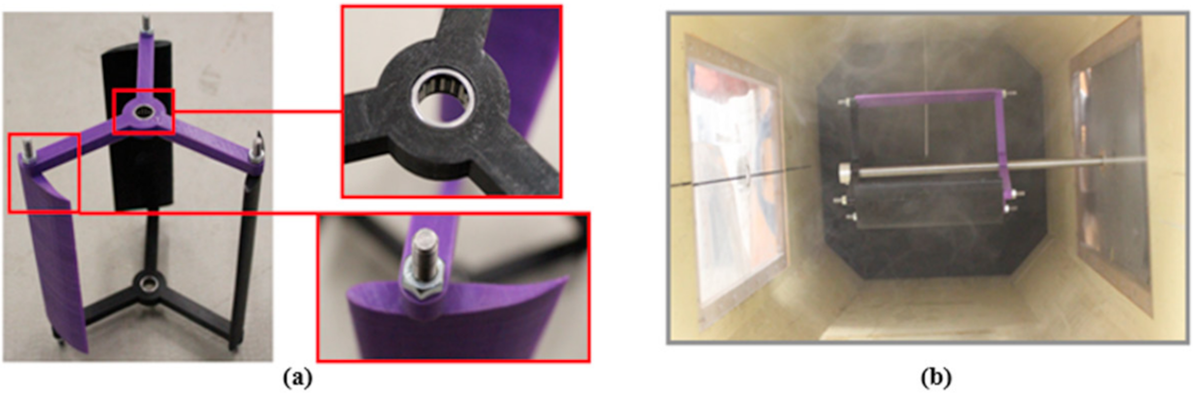

Fig. 8. Experimental Model (a) Fully Constructed (b) Position within Wind Tunnel.

4.2. Experimental Prototype Testing Results and Discussion

As expected, the experimental testing revealed that turbine efficiency increases with increasing wind seed (Table 5). The turbine efficiency increased by 1.951% from the initial 10.914 m/s wind speed to the 15.478 m/s average speed and a further 3.903% from 15.478 m/s to the final 19.318 m/s wind speed. Similar to the numerical analysis, the efficiency of the scale model increased with increasing wind speeds. However, several sources of error were established prior to testing, including:

- Flow recirculation from wind tunnel walls
- Wind tunnel length restriction does not allow for laminar flow to be established

Table 5. Experimental Testing Results.

Setup	U_{AVE} (m/s)	P_a (W)	ω (rad/s)	λ	T (Nm)	P_o (W)	C_P	η (%)
1	10.914	25.799	2.321	0.01914	0.10620	0.24645	0.00955	0.955
2	15.478	73.586	7.016	0.04079	0.30475	2.13819	0.02906	2.906
3	19.318	143.066	18.977	0.08841	0.51334	9.74181	0.06809	6.809

Several modifications to the experimental method adopted could reduce some of the sources of error. These include the use of a 'honeycomb' or 'mesh' structure to subdue the velocity fluctuations in the stream, methods previously adopted by [3, 13]. Additionally, a larger tunnel domain can be used to reduce the occurrence of flow recirculation, as mentioned by Erickson, Wallace and Peraire [14], however this method was unachievable due to the limited resources available. Therefore, the experimental results can only be used as a means of validating the trends, as the actual performance Figures are known to vary significantly due to the sources of error stated previously.

5. Future Work

Further investigation into the use of the NACA 7715 aerofoil and deflector orientations is being conducted by postgraduate students at the Robert Gordon University. The work consists of numerical analysis (both 2D and 3D CFD), as well as, experimental testing on a scale prototype model. The future work aims to further verify the effectiveness of using a deflector on a small VAWT performance. This is complimented with a study on deflector variations that are showing promising results when applied to a small rooftop VAWT design.

6. Conclusion

The high solidity, three-bladed, Darrius VAWT rotor was successfully designed and modelled using ANSYS Fluent 14.0, solving for the unsteady Navier-Stokes equation and the k-epsilon (RNG) turbulence model. The use of small, curved upstream deflectors were found to improve the optimal performance of the turbine marginally (by 1.266%); with the turbine requiring decreased rotational velocity to provide optimal performance values. Thus, the use of the deflector was seen to have a positive effect on the turbines performance. This was deduced to be from the redirection of flow from the returning blade of the turbine, thus reducing the negative torque induced in the system. Finally, a series of experimental tests were carried out on a scale model to validate the behavior of the numerically simulated rotor. The results were however affected by several sources of error and the numerical and experimental results could not be fully correlated due to the variation in the wind speed tested in by both methods.

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