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Numerical analysis of the aerodynamic and geometric relationship of a vertical axis wind turbine

Wei Kee Go[1], **Nurfarina Batrisyia Muhammad Hairi**[1], **Ahmad Fazlizan**[2], **Kok Hoe Wong**[3], **Wan Khairul Muzammil**[4#]
1 Faculty of Engineering, Universiti Malaysia Sabah, Jalan UMS, 88400, Kota Kinabalu, Sabah, MALAYSIA.
2 Solar Energy Research Institute, Universiti Kebangsaan Malaysia, 43600, Bangi, Selangor, MALAYSIA.
3 Carbon Neutrality Research Group, University of Southampton Malaysia, 79100, Iskandar Puteri, Johor, MALAYSIA.
4 Centre of Research in Energy and Advanced Materials, Faculty of Engineering, Universiti Malaysia Sabah, Jalan UMS, 88400, Kota Kinabalu, Sabah, MALAYSIA.
#Corresponding author. E-Mail: khairulm@ums.edu.my; Tel: +6016-8494000; Fax: +6088-320348.

ABSTRACT The demand for wind energy has a high potential as an alternative energy source. Vertical axis wind turbine (VAWT) has good developmental potential for unfavourable wind conditions, especially in urban areas, such as low wind speed. This paper aims to conduct a comprehensive numerical analysis of the two-dimensional H-Darrieus VAWT to understand the VAWT's performance with different solidities. The VAWTs were subjected to low and ultra-low Reynolds number conditions with various tip speed ratio (TSR) values. The numerical investigation was conducted using ANSYS Fluent software using high-fidelity Computational Fluid Dynamics (CFD) technology. Based on previous studies' experiences and data, different computational settings in CFD simulation were employed. The geometric parameters of the study were validated against published simulation and experimental data to ensure the accuracy of the simulation results obtained in this study. The CFD simulation results demonstrated that only a high solidity turbine (σ = 1.20) at a low TSR of 2.0 and a low solidity turbine (σ = 0.60) at a moderately high TSR of 2.5 could generate the optimal quantity of energy since instantaneous moment coefficient lies in the positive region while operating under low Re 75000. In contrast, some turbine configurations produced negative C_m at specific operational TSR ranges when the rotor was subjected to low Re (15000) and ultra-low Re (5000 and 9000). According to the results, the negative instantaneous moment and power coefficients meant that the wind turbine could not be optimally configured due to insufficient power converted from the wind's kinetic energy.

KEYWORDS: H-Darrieus VAWT; wind energy; computational fluid dynamics; wind turbine; on-site energy generation.
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INTRODUCTION

Wind energy is one of the most promising renewable energy resources for power generation, and rapid growth has been seen in its acceptance since 2000. In the modern era, wind turbines extract kinetic energy from the wind to generate electricity. Over the years, the demand for small-scale wind turbines in built environments has increased to reduce urban areas' carbon emissions. Vertical axis wind turbine (VAWT) has good developmental potential because VAWT is suitable for unfavourable wind conditions, such as low wind speed, high turbulence, and wind direction variations. They are favourable on top of buildings as they can receive wind from any direction and have a design that can be integrated simply with building architecture. However, these wind rotors generally have lower efficiency. They respond better in turbulent wind flow, which is common in urban areas. In general, analysing the aerodynamic performance of VAWTs is a difficult task as the flow in such systems is complicated, caused by phenomena such as dynamic stall, blade-wake interaction, and flow curvature effects. In the study of De Marco *et al.* (2014), due to the complexity of the phenomena, the investigation of VAWT aerodynamics is often impossible through analytical models, such as blade-element momentum theory. Hence, computational fluid dynamics (CFD) is an adequate study tool for investigating and analysing the aerodynamic performance of VAWTs under the influence of various geometrical and operational parameters. As for the geometrical aspect of a

VAWT, Rezaeiha *et al.* (2018) studied the impact of different solidities from 0.09 to 0.36 on the 2-bladed VAWTs' performances. They found that a low solidity turbine obtained the highest power coefficient at a moderately high tip speed ratio (TSR). In contrast, a high solidity turbine could improve the performance of the power coefficient at low TSR. Mohamed (2012) also found that a low solidity turbine is preferred for straight-bladed Darrieus VAWT to gain a more comprehensive operating range. Castelli *et al.* (2011) and Hassan *et al.* (2016) have proved that CFD simulation can provide accurate results against the results obtained by experimental setup if computational settings are set up correctly and thoroughly. Both researchers found that the CFD method can deal with the numerical analysis of complex wind flow, such as unsteady flow through the blade's surface. The aerodynamic characteristics of different geometric ratios, such as aspect ratio and solidity, may affect the characteristics of the entire wind turbine. However, rigorous studies on the performance of these parameters are still being explored.

RESEARCH METHODOLOGY

In general, this study was conducted to investigate the aerodynamic performance of the VAWT by using the numerical methodology of computational fluid dynamics. This was done to evaluate the effects of the rotor's solidity (i.e., different rotor radius) on straight-bladed VAWTs in low and ultra-low Reynolds number wind conditions. A two-dimensional H-Darrieus VAWT consisting of three blades with varying geometry configurations was created using computer-aided design (CAD) software. The computational settings and parameters of the H-Darrieus VAWT are based on the recommendations of Rezaeiha *et al.* (2018) to obtain accurate CFD simulations of VAWT at different tip speed ratios and solidities. A regime of CFD simulations was then performed using various configurations in ANSYS Fluent. A validation study also confirmed that the computational settings and parameters were adequate for further simulation analysis.

Geometry Parameters and Turbine Operating Parameters

A two-dimensional CFD model was developed to implement the H-Darrieus VAWT in a virtual environment. In the current study, the turbine blades of the VAWT are equipped with NACA0021 series symmetrical profiles due to the lift and drag data availability for an extensive range of Reynold numbers. The chord length of each turbine blade is equivalent to 0.1 m. The turbine model will be tested in the tip speed ratio, TSR (2.0, 2.5, and 3.0). TSR is given by

$$\text{TSR}, \lambda = \frac{\omega R}{V} \tag{1}$$

where ω is the turbine's rotational speed in rad/s, R is the turbine radius, and V is the incoming wind speed. In the case of a wind turbine's solidity, it is altered by changing the rotor radius as given by

$$\text{Solidity}, \sigma = \frac{Nc}{R} \tag{2}$$

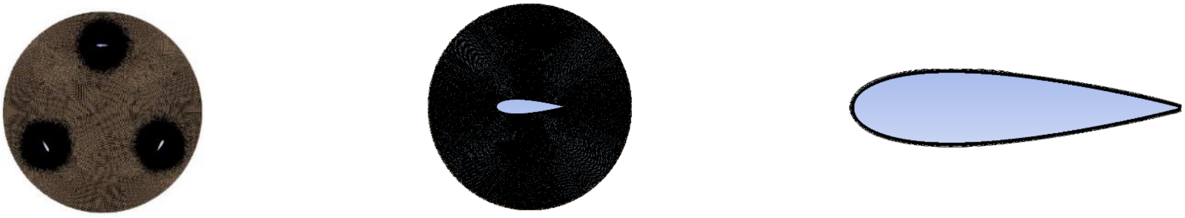
where σ is the solidity, N is the number of blades (3 blades in the current study), c is the airfoil chord length (i.e., 0.1 m), and R is the rotor's radius. The Reynolds number is related to the characteristic length of the case study, which is the rotor diameter, D, and incoming wind flow, V, i.e., $\text{Re} = \rho VD/\mu$. Table 1 shows the wind speeds used in the current CFD study. The selected rotor radius (i.e., R = 0.25 m, 0.50 m, 2.50 m, corresponding to solidities of 1.20, 0.60 and 0.12, respectively), inlet wind velocities and corresponding TSR values (i.e., 2.0, 2.5, 3.0) were used to determine the wind turbine's rotational speed.

Table 1. Incoming wind speeds in low and ultra-low Reynolds numbers.

Reynolds number, Re		**Rotor diameter, *D* (m)**		
		0.50	**1.00**	**5.00**
		Incoming wind speeds, *V* (m/s)		
Low Re	15000	0.44	0.22	0.04
	45000	1.31	0.66	0.13
	75000	2.19	1.10	0.22
Ultra-low Re	5000	0.15	0.073	0.015
	9000	0.26	0.131	0.026

Computational Settings and Parameters

The computing domain was divided into three sub-domains: the whole rectangular domain, the rotating domain, and the control domain containing only the blade, as per the recommendations by Rezaeiha *et al.* (2018). A structured grid was used in all domains, and the grid growth rate at each domain boundary was set at 1.1. The blade surface's inflation layer contains 20 layers with a growth rate of 1.15, and the first layer height was set at 1.3 x 10^{-5} m. The sample of the mesh configuration is shown in Figure 1.



(a) **(b)** **(c)**

Figure 1. Mesh configuration on **(a)** Rotating domain, **(b)** Control domain, and **(c)** Boundary layer near the blade's wall.

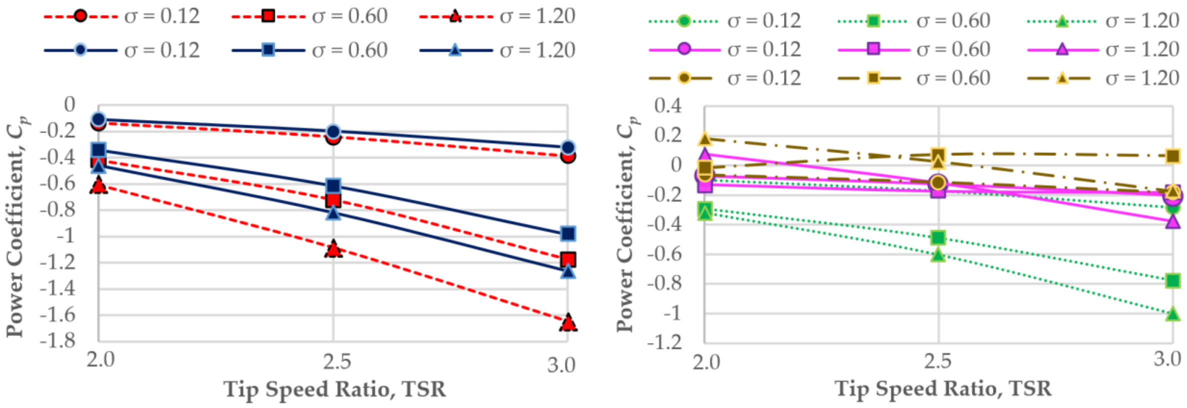
The four-equation Transition Shear-Stress Transport model (TSST) was selected for performing all CFD simulations in this study. To develop the computing domain's boundary condition, the whole rectangular domain's top and bottom walls are symmetrical with no-slip condition. The inlet velocity and outlet pressure are applied to the inlet and outlet domains. In the Fluent solver, the time-step and number of time-steps must be applied for transient analysis. Based on a time-step sensitivity analysis, it was found that an azimuthal increment of 0.5° was sufficient. Therefore, the number of rotations used in the study was 16, and the number of time-steps was 11520 (i.e., number of time-step = number of rotations x 360/0.5). Also, in the CFD study, the Semi-Implicit Method for Pressure-Linked Equations (SIMPLE) algorithm was used as the numerical procedure to solve the Navier-Stokes equations. Furthermore, the instantaneous moment coefficient (C_m) was recorded and collected at the 16th turbine rotation. The maximum number of iterations was set to 50. Additionally, the convergence criteria were set to a maximum of 1 x 10^{-5} for all parameters in this analysis. The averaged C_m over the last rotation was used to calculate the turbine's power coefficient (i.e., C_p = TSR x C_m).

RESULTS AND DISCUSSION

Power Coefficient Analysis of the Wind Rotor With Different Solidities

The results obtained from the simulations in ultra-low and low Reynolds number wind conditions are evaluated, along with three alternative turbine configurations with varying solidities

(σ = 0.12, 0.60, and 1.20). Figure 2 summarises the power coefficient performance. The data showed that the Reynolds numbers substantially impacted the turbine's power performance. Based on a fixed solidity VAWT, these results align with Danao *et al.* (2013), which showed that when wind speed increases, C_p increases, and the C_p-TSR curves converge at higher wind speeds, demonstrating the influence of Reynolds numbers. Li & Li (2010) discovered that turbine solidity is one of the most prevalent factors that degrades the VAWT's performance and reduces power output. As shown in Figure 2(a), the solidity of the rotor under the ultra-low Re environment seems to affect the turbine's performance, as the C_p values become more negative as the solidity increases. The downward trend in the negative power coefficient region may have occurred due to the parametric reduction of radius in the higher solidity rotor, which would increase blockage for the wind flow to travel through the rotor compared to the lower solidity rotor. According to the numerical results in Figure 2(b), C_p values of all turbine configurations under low Reynolds number wind conditions of 15000, 45000, and 75000 became more negative with increasing TSR. For example, using the numerical results of rotor solidity σ = 0.60 at a low Reynolds number of 15000, the negative C_p value grows from -0.293 to -0.776 from TSR 2.0 to 3.0. At a higher Reynolds number of 75000, it can be observed that the same rotor has an increasing trend of power coefficient that rises to the positive region, which means that the turbine begins to generate an effectual power output at a higher wind speed.



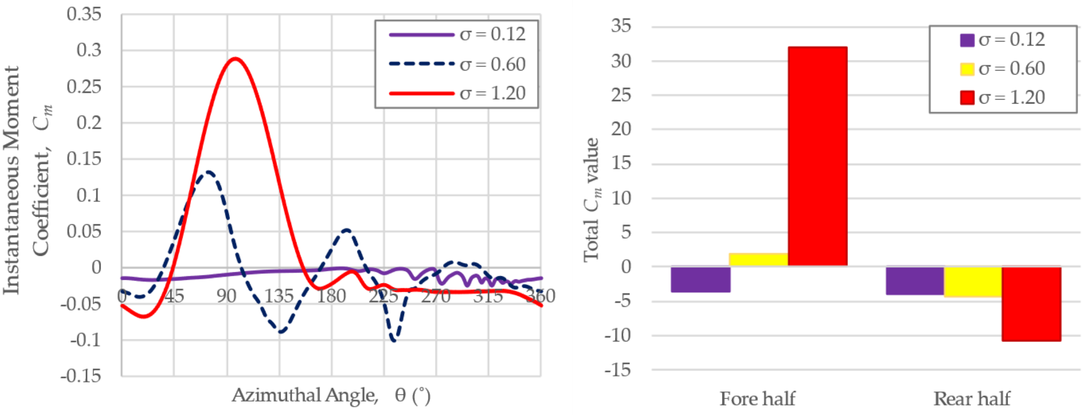
(a) **(b)**

Figure 2. Power coefficient for different TSR using various solidities under **(a)** Ultra-low Reynolds number wind conditions (Red: Ultra-Low Re 5000; Blue: Ultra-Low Re 9000), and **(b)** Low Reynolds number wind conditions (Green: Low Re 15000; Purple: Low Re 45000; Gold: Low Re 75000).

It is also worth noting that most of the C_p values in Figure 2 are negative. In the current study, the rotational speeds of all turbine configurations are fixed, which is determined by (Equation 1). Additionally, the incoming wind speeds are controlled by the Reynolds numbers. As a result, the negative power coefficient is necessary to maintain the rotational speeds. In other words, additional power is required for the rotor to keep the rotational speed constant during the computations. The graph shows a situation where the turbine's performance is degraded owing to low wind speeds under low and ultra-low Re wind conditions. Generally, good turbine performance can be obtained by combining low solidity turbines with high TSR. This indicates that for constant wind speed, when the turbine rotates at a moderately high rotational speed (i.e., high TSR), optimal performance can be achieved with a larger turbine diameter (i.e., low σ). In contrast, if the turbine rotates at a low rotational speed (i.e., low TSR), an optimum performance can be achieved with a smaller turbine diameter (i.e., high σ). It is also known that good low Reynolds number performance is desired to minimise the dead band (i.e., negative C_p values). However, Kirke (1998) found that lowering the Reynolds number in general could induce a lower overall performance of the VAWT. This is because, fundamentally, the wind does not have more kinetic energy at low Reynolds numbers. Therefore, a high Reynolds number is required to induce more significant blade lifts.

Analysis of Turbine's Performance Based on Rotor Geometrical Region

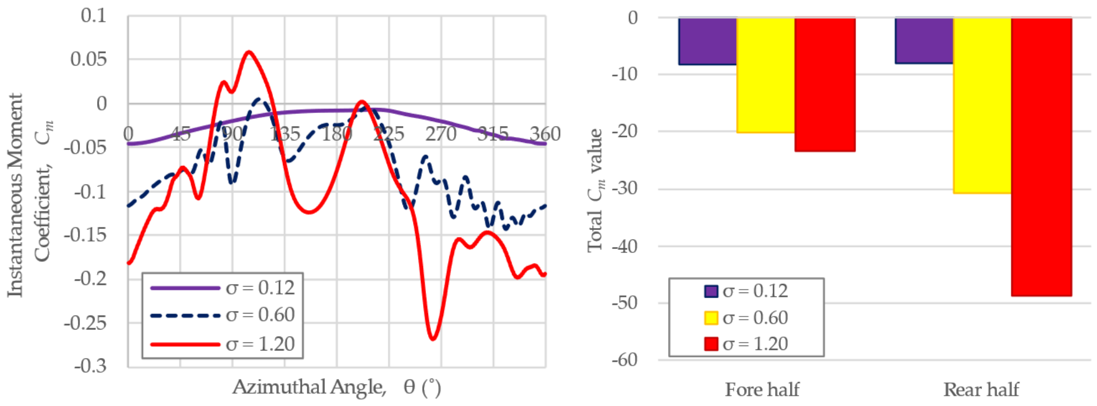
Figures 3 and 4 show the moment coefficient, C_m, produced by a single turbine's blade. Figures 3a and 4a show the instantaneous moment coefficient for all azimuth angles in the 16th rotation. At the same time, Figures 3b and 4b illustrate the total C_m generated by the rotor fore half ($0^\circ \leq \theta \leq 179.5^\circ$) and the rotor rear half ($180^\circ \leq \theta \leq 359.5^\circ$), where turbines run at TSR of 2.0 with a low Re 75000 and ultra-low Re 5000. Based on the data from the rotors in low Re 75000 wind conditions, increasing the solidity from 0.12 to 1.20 at a TSR of 2.0 (Figure 3) appears to enhance the overall C_m output, notably in the fore half. This is demonstrated by the fact that the fore half of a high solidity turbine produces the highest total C_m compared to the medium and low solidity turbines. Moreover, no turbines were seen to be able to generate positive C_m values on the rear half, and this indicates that the complex wind flow crossing from the fore half towards the back half interacts with the blades in the downstream region with a poor angle of attack, resulting in more considerable drag forces, with reduced lift forces.



(a) **(b)**

Figure 3. (a) Instantaneous moment coefficient, C_m of the rotor with different solidities, and **(b)** Total contribution of C_m separated by different regions at TSR of 2.0 (low Re 75000).

Meanwhile, based on data analysis from turbines that ran in ultra-low Re 5000 wind conditions, all turbine configurations with solidities of $\sigma = 0.12$, 0.60, and 1.20 have a total negative C_m output on both the fore and rear half at TSR 2.0 (Figure 4). The turbine with $\sigma = 0.12$ has the lowest negative total C_m value, implying that it requires less torque due to geometry effects. In contrast, the turbine with $\sigma = 1.20$ gets the most negative total Cm value, suggesting that it requires a large amount of torque to maintain its rotation.



(a) **(b)**

Figure 4. (a) Instantaneous moment coefficient, C_m of the rotor with different solidities, and **(b)** Total contribution of C_m separated by different regions at TSR of 2.0 (ultra-low Re 5000).

CONCLUSION

The study showed that the VAWT simulated in the low Re 75000 had shown a positive interaction when the turbine diameter was varied under different TSR operating conditions. High solidity turbines operate well at low TSRs, whereas low solidity turbines operate well at high TSRs. Due to the geometry effect and operating conditions, the negative C_p values represent additional power to keep the rotational speed constant during the computation. The negative C_p region is also called a "dead band" since power is absorbed in this region. The current study also shows that the VAWT generated a negative C_m in specific Reynolds number wind conditions. This indicates that the turbine does not generate adequate power and provides minimum power. In other words, the airflow over the airfoil blade does not generate enough lift force to produce a positive C_m. The analysis based on the different geometrical regions of the turbine points to an essential fact about VAWT power generation. Turbine solidity significantly impacts the fore half's performance at low Re 75000 and TSR. In ultra-low Re 5000 wind conditions, regardless of whether the turbines are in the fore or rear half, all turbine configurations appear to negatively influence the total C_m output at low and high TSR. To conclude, a two-dimensional model of VAWT was successfully developed for numerical analysis of turbine geometry performance. As a result, the turbine solidity, which varies with turbine diameter and Reynolds number, directly impacts the turbine's wind flow and power performance.

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