Al-Qadisiyah JournalFor Engineering Sciences 18 (2025) 083– 091

Contents lists available at: http://qu.edu.iq

Al-Qadisiyah Journal for Engineering Sciences

Journal homepage: https://qjes.qu.edu.iq

Research Paper

CFD analysis of vertical axis wind turbine with modified blades for deployment in Ilorin, Kwara state, Nigeria

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ARTICLE INFO

Article history:
Received 30 June 2024
Received in revised form 15 September 2024
Accepted 16 December 2024

Keywords:
CFD
Wind turbines
Tubercle
Energy source
Ansys
NACA0015

ABSTRACT

Researchers and the energy industry are currently focusing their efforts on optimizing the effectiveness of vertical-axis wind turbines (VAWT) to cut down on the reliance on energy supply from fossil fuels which releases gases that are toxic to the environment. As such, several methods have been applied, including increasing the velocity and modification of both the trailing and leading edges of the aerofoil. In the present investigation, numerical studies of the flow on the wind turbine blades with a NACA0015 airfoil section equipped with and without tubercles on the trailing edge were conducted using ANSYS Fluent. A computational domain of 2000 *mm* by 35000 *mm* was employed with the K-W SST turbulence model. This two-dimensional computational fluid dynamics (CFD) analysis was performed with Ilorin, Kwara State, Nigeria wind data that was received from the Nigeria Meteorological Agency (NIMET). The modified blade with a wavelength of 90 *mm* and an amplitude of 4 *mm* is seen to have a better thrust than the unmodified blade. It produced a thrust of 118 *N* for a tip-speed ratio (TSR) of 4.0 compared to 109 *N* of the unmodified blade at the same TSR and that of the modified blade (1) which attains 107 *N*. Also, its coefficient of performance is 5% and 6% higher than that of the straight and modified blades (1) respectively, These results suggest that an increase in the tubercle's wavelength and amplitude increased the maximum thrust.

1. Introduction

The global demand for energy is enormous and constantly increasing. Conventional energy sources, particularly fossil fuels, are being rapidly depleted. Moreover, fossil fuels significantly contribute to the greenhouse effect [1,2]. They are responsible for 75% of worldwide greenhouse gases and nearly 90% of carbon dioxide emissions. As a result, fossil fuels are a major cause of climate change [3]. Climate change highlights the urgent need to reduce carbon emissions. This requires decreasing our reliance on fossil fuels, harnessing energy from other natural resources, and exploring alternative energy sources. According to the Paris Agreement, the rise in average global temperature must be limited to 1.5to mitigate climate change and its impacts [2]. To achieve this, we must focus on renewable energy sources such as wind, solar, geothermal, and tidal energy [1]. Among these alternatives, wind energy stands out. It is abundant, has no harmful emissions, and requires minimal space [1]. Wind energy is also freely accessible and environmentally friendly, making it an effective means of reducing fossil fuel use and greenhouse gas emissions. Due to its potential as a viable alternative for power generation, wind energy is a key focus of current research and industrial interest [4]. Wind energy production primarily relies on turbines, which convert kinetic energy from the wind into electrical energy [1]. Wind turbines are classified based on the orientation of their rotational axis, either as vertical-axis wind turbines (VAWTs) or horizontal-axis wind turbines (HAWTs) [4]. HAWTs are widely used for large-scale energy production and come in various sizes. Large-scale HAWTs can generate up to 10 MW of power. On the other hand, VAWTs, which are currently available for offshore applications, can generate up to 10 kW. The VAWTs are easier to install because they have only one moving part, the rotor. VAWTs are useful for domestic applications, whether as a single system or a freestanding installation in areas with adequate wind. As a result, VAWTs are expected to play a vital role in future wind energy generation. Although VAWTs have been in use for a long time, they have not received as much attention as HAWTs. However, VAWTs are becoming increasingly popular because designers are starting to leverage their inherent advantages. These advantages include independence from wind direction, system simplicity, ease of design and construction, better electricity production in turbulent flow, and the potential to achieve a power coefficient (Cp) comparable to HAWTs. These benefits make VAWTs an affordable and practical choice for power generation in rural, suburban, and urban settings, as well as in isolated off-grid locations. Extensive research has been conducted to address the challenges that limit the use of wind turbines as the primary energy-generating source. Kumar and Shah [1], highlight aerodynamic losses as a significant disadvantage of wind turbines. These aerodynamic losses account for about 60% of overall energy losses in wind turbines. These losses occur due to stall, which is caused by boundary layer separation at the airfoil's suction side. To mitigate stall challenges, stall control mechanisms are necessary. There are two types of stall control: active and passive.

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https://doi.org/10.30772/qjes.2024.151245.1293

Nomenclature:

List of variables:

A	Wavelength
B	Amplitude
C	Blade chord length
c_d	Drag coefficient
c_l	Lift coefficient
c_m	Coefficient of moment
c_p	Power coefficient
c_{rc}	Optimal Model Parameter
c_t	Thrust coefficient
d_θ	Azimuthal increment
d_t	Distance from turbine center to domain inlet
H/D	Height to diameter ratio
A	Tip speed ratio
P	Turbine power
R	Radius of Turbine
T	Thrust coefficient
Z	Spanwise coordinate

Greek Symbols:

ω	Rotational speed

Both work by reenergizing the fluid particles in the boundary layer region. Passive stall control modifies the airfoil or blade geometry using steps or protuberances, while active stall control adds momentum to the boundary layer directly through jet flow procedures. A popular passive stall control mechanism is tubercles. The term ”tubercle technologyöriginates from biomimetics and is inspired by the humpback whale. Tubercles can sustain lift at high angles of attack [1]. When tubercles are correctly positioned on the leading edge of a wing, stall delay, and mitigation can be achieved. Lohry et al. [5] suggest that the physical process behind stall mitigation involves the creation of streamwise vortices that energize the viscous layer. Since the publication of Miklosovic, Murray, Howle, and Fish's 2004 work, more empirical data has emerged, indicating the potential advantages of tubercular leading-edge wings. Jingna, Carlos, and Alexander [6] investigated the efficiency of a hybrid vertical axis wind turbine (VAWT) that combines Darrieus and Savonius rotors to understand the power performance of this hybrid configuration under different force distributions. They modeled the hybrid VAWT using an idealized approach to break down the complex dynamics between Savonius and Darrieus components. A simulation using actuator surfaces with evenly distributed forces was employed to determine the optimum force distribution for each turbine component. This method provided a cost-effective way to analyze the turbine's efficiency. The numerical model was validated against momentum theory, showing similar estimates in low-thrust scenarios but diverging in high-thrust scenarios. The study found that the maximum power coefficient of the hybrid VAWT is lower compared to an optimal single actuator Darrieus rotor. This is mainly due to nonoptimal loading on the actuator. As a result, the hybrid configuration did not significantly increase power compared to a standalone Darrieus rotor. However, the hybrid setup may offer advantages in start-up performance, which was not covered in the study.

To improve the performance of VAWTs, Nagare and Kale [7] addressed key challenges such as self-starting capabilities and efficiency improvements. They analyzed different blade configurations and their aerodynamic properties using simulation tools. The studies focused on enhancing performance under various environmental conditions, making VAWTs more viable for urban and remote applications. Zhang [8] used the CFD ellipsyd tool to build a pressure field around a 2D flow field, concluding that the results aligned with experimental data. This approach provides a simplified method for wind turbine analysis. Schubel and Crossley [9] explored modern wind turbine blade design, incorporating aspects such as propulsion, practical and theoretical maximum efficiencies, HAWT blade design, and blade loads. Elgendi et al. [10] researched the flow across wind turbines in diverse landscapes, considering challenging scenarios like atmospheric boundary layer (ABL) wind profiles and turbine wake recovery over rocky and wooded areas. Uchida et al. [11] proposed a new porous disc (PD) wake model for CFD to accurately calculate the downstream wind turbine wake zone's time-averaged wind speed deficiencies. This model was targeted at large-scale offshore wind farms with multiple turbines. The optimal model parameter CRC was validated, and the effect of spatial grid resolution was explored.

Saravanan and Muthurajan [12] explored the feasibility of installing rooftop-attached Savonius-type VAWTs to maximize efficiency. They used Glass Fibre Reinforced Polymer (GFRP) to construct four wind blades for the Savonius turbine, each measuring one metre in height and 0.25 m in diameter. The blade was designed in SolidWorks, followed by modal, static structural, and CFD analyses. The use of GFRP material was found to enhance the turbine's efficiency. A Savonius VAWT designed for household use in remote areas with limited access to energy was also studied [13]. Hameed and Afaq [14] used a combination of analytical and numerical methods, considering design factors like aspect ratio (AR), solidity, and power coefficient, to investigate VAWT performance. Rezaeiha et al. [15] identified pitch angle as a potential factor to increase the efficiency of VAWTs. They employed the URANS transition SST turbulence model in their studies, which resulted in a 6.6% performance increase. Joo et al. [16] conducted a 3D unsteady numerical analysis on H Darrieus VAWT and DMST (double multi-stream tube) to assess aerodynamic performance. They discovered that increasing solidity led to higher blockage and interaction, concluding that solidity alone cannot improve the output of H-Darrieus VAWT. Rahimp et al. [17] used a stream tube modeling analytical approach to validate experimental results on a VAWT, confirming that the experimental results matched the analytical predictions. Mahmood et al. [18] assessed several designs and methods used in designing VAWT systems, concluding that CFD is a cost-effective approach. Feng et al. [19] reported that straight-bladed (SB) VAWTs are ideal for improving performance due to their simple structure and unique shape. Similarly, Gosselin et al. [20] conducted a parametric study of SB-VAWT using the K-W SST turbulence model. Their study identified key performance parameters, including blade number, solidity, airfoil choice, fixed and variable blade-pitch angles, and Reynolds number.

Lastly, Howell et al. [21] experimentally and computationally investigated small-scale VAWTs, emphasizing the impact of tip vortices on the accuracy of predicting turbine performance. Nguyen and Metzger [22] investigated the effects of various design conditions on the operation of straight-bladed vertical-axis wind turbines (SB-VAWTs) in unsteady wind conditions, specifically in suburban and urban areas. They focused on four design parameters: blade airfoil shape, height-to-diameter (H/D) ratio, moment of inertia, and turbine solidity. Their findings suggest that optimal design parameters include an H/D ratio of 1.2, a solidity range of 5–12%, and the use of a NACA0015 airfoil. Sathish [23] conducted a numerical investigation on the operation of composite wind turbine blades, considering performance variables such as temperature, pressure, and velocity variations. Hameed and Afaq [14] also highlighted the significance of the blade as a critical component in enhancing wind turbine performance. Blackwell et al. [24] examined SB-VAWT blade configurations, focusing on parameters like solidity and freestream velocity. Their study concluded that a 3-bladed configuration offers slightly better aerodynamic performance than a 2-bladed counterpart. Similarly, Durrani and Mian [25] confirmed the superiority of the 3-bladed wind turbine configuration in terms of optimal performance when compared to other blade configurations.

Dominy et al.[26] supported the findings of both Blackwell et al. [24] and Sathish[23]. Castelli et al. [27] also investigated various blade configurations, concluding that the 3-blade configuration delivers optimal performance. Zhao et al. [28] employed a variable pitch technique to improve the efficiency of SB-VAWTs by aligning the blade's azimuthal angle with the peak aerodynamic torque, leading to enhanced turbine output. In a related study, Brusca et al. [29] utilized various stream tube models to evaluate the performance of SB-VAWTs across different airfoil models, including NACA0012, NACA0015, NACA0018, NACA0021, and NACA0025. They found that each airfoil has specific optimal parameter values that result in the best performance. Kaviti et al. [30] explored modifications to SB-VAWTs using four different airfoil configurations (NACA0021, NACA0018, NACA0015, and NACA0012). They also examined the addition of Gurney flaps and dimples, concluding that the modifications are most effective for NACA0012 and NACA0015. Wafula et al. [31] conducted a CFD investigation of the aerodynamic performance of NACA0012 and NACA0022 airfoils. The results indicated that NACA0022 generates higher power coefficient (Cp) values under unsteady wind conditions compared to NACA 0012, but its Cp is lower under steady wind conditions. Biadgo et al. [32] performed numerical and analytical studies on the NACA0012 SB-VAWT, using ANSYS and the double multi-stream tube (DMST) model. However, the results showed that the model could not self-start.

Aziz et al. [33] utilized the Q-blade software to address some of the drawbacks associated with VAWTs, comparing the performance of NACA0015 and NACA0012 airfoils. They found that NACA0015 outperformed NACA0012 at high wind speeds, offering higher power output. Zhu et al. [34] identified SB-VAWT as a promising turbine design for harnessing wind energy but noted that it is susceptible to dynamic stall, which causes aerodynamic losses and fluctuations. They suggested passive flow control (PFC) techniques as a cost-effective solution to improve SB-VAWT performance, as PFC consumes no

energy for its operation. Sun and Zhou [35] reviewed current quantitative and experimental research on the effectiveness of PFC techniques in enhancing the flow field around SB-VAWTs, ultimately improving their efficiency. Their review highlighted existing gaps in the research and offered suggestions for future studies. The use of tubercles on wind turbine blades has become increasingly prevalent in the literature, as they have shown potential for improving aerodynamic performance. Prakash et al. [36] modified the leading edge of NACA 0018 blades in H-Darrieus VAWT models by incorporating tubercles under transient conditions. They conducted a numerical analysis using the ANSYS CFX turbulence model, which revealed that the modified blades exhibited better performance than the original models. Similarly, Mishra et al. [37] introduced leading-edge tubercles on H-Darrieus VAWT blades and employed both CFD (using the SST turbulence model) and experimental approaches to assess their impact. The study demonstrated that the modified blades outperformed the unmodified, or clean, blades, especially at high wind speeds. Sridhar et al. [38] applied four different tubercle configurations to the leading edge of VAWT blades and utilized CFD to analyze the turbine's flow characteristics. Their results indicated that the presence of tubercles effectively mitigated flow separation and controlled dynamic stall, leading to a 28% increase in the power coefficient (Cp) and a reduction in acoustic noise. Additionally, Bai et al. [39] explored the benefits of using tubercles on a straight-bladed VAWT with a NACA 0015 blade profile. The study varied the angle of attack from 0°to 40°and used the K-Omega SST turbulence model to solve the relevant transport equations. It was found that the turbine with tubercles produced lower thrust compared to the clean blade, with thrust values decreasing as the amplitude increased and wavelength decreased. The reduction in thrust, ranging from 5% to 55%, was attributed to vortices formed at the leading edge between azimuth angles of 60° to 140°, creating low pressure at the trailing edge.
The current study uses wind data from the Nigerian Meteorological Agency to examine the effects of trailing-edge tubercles on a VAWT with a NACA0015 blade profile. This investigation focuses on a 3-bladed configuration, which is considered optimal based on existing research. By evaluating the impact of these modifications, the study aims to enhance the turbine's operational performance, making it suitable for deployment in Ilorin, Nigeria. The dual goals are to reduce the carbon footprint and improve the stability of the local power supply. This research builds on previous studies by specifically addressing the performance of tubercle-modified blades under local wind conditions, thereby providing valuable insights into the practical application of VAWTs in diverse environments.

2. Methodology

2.1 Physical model

An earlier investigation by [40] demonstrated that modifications to the trailing edge of VAWT blades significantly influence the thrust generated by the turbine. In the current study, the impact of a modified trailing edge on the aerodynamic performance of a wind turbine, potentially deployable in Ilorin, Kwara State, Nigeria, is analyzed. The study focuses on an H-type wind turbine, as illustrated in Fig. 1. This turbine comprises three blades featuring NACA 0015 symmetrical airfoil sections. The turbine's radius is approximately 2 *m*, with a blade diameter of 2.5 *m* and a chord length of 0.4 *m*.

Figure 1. H-type vertical axis wind turbine [41].

The straight and modified blades can be seen in Fig. 2 through Fig. 4 respectively. Figure 5 displays the computational domain, and the mesh is displayed in Fig. 6. The operating conditions of the reference turbine are captured in Table 1. These foregoing characteristics were obtained from Lin et al [40].

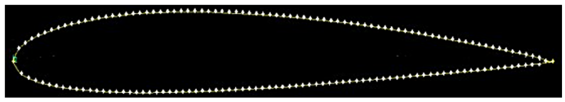


Figure 2. Baseline blade of the wind turbine.

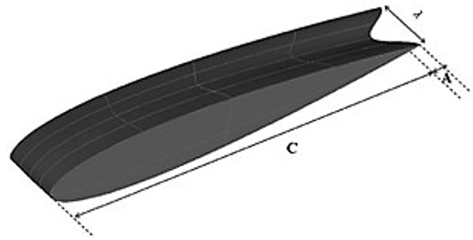


Figure 3. Modified blade-1 ($\lambda = 0.06$).

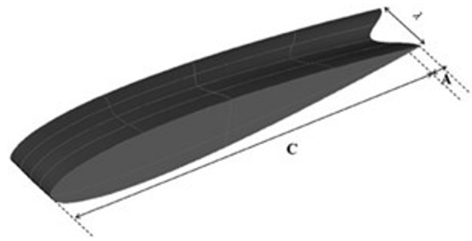


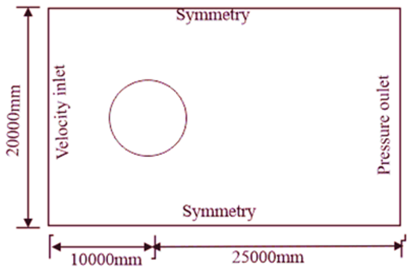
Figure 4. Modified blade-2 ($\lambda = 0.09$).

2.2 Parameter for computation

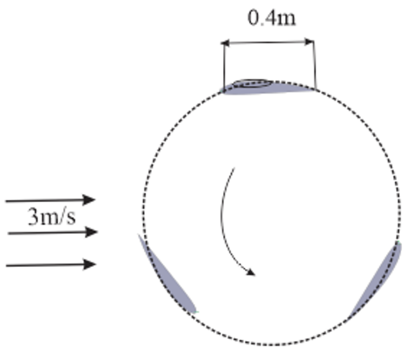
The objective of this study is to quantitatively predict the performance of a VAWT blade with a NACA0015 airfoil using a CFD model. Simulations were carried out in ANSYS Fluent, comparing the performance of straight blades against those modified with tubercles. The CFD model was validated using data from the literature [40]. Table 1 outlines the computational components used in the simulations. The $K-\omega$ SST turbulence model, a two-equation eddy-viscosity model that combines the $K-\omega$ formulation near the wall with $K-\varepsilon$ behavior in the free stream, was employed to close the transport equations. The SST model was selected for its favorable balance between accuracy and computational cost, as well as its reduced sensitivity to free stream conditions. The SIMPLE (Semi-Implicit Method for Pressure-Linked Equations) algorithm was used in conjunction with pressure correction, chosen for its computational efficiency, robust iteration processes for coupling conditions, and high-order differencing schemes. The Green-Gauss Node method was used to compute gradients. To minimize interpolation errors and ensure accurate numerical diffusion, the second-order upwind interpolation method was applied to all equations. The relative motion between the rotating blade zone and the stationary far-field zone in the 2D model was managed using a sliding mesh approach.

2.3 Blade design

The wave-like shape incorporated into the trailing edge of the modified blade (NACA 0015) was generated with Eq. 1.

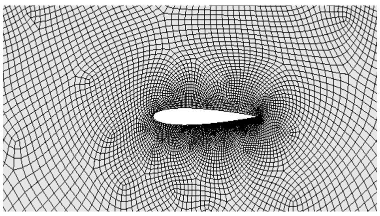


(a) Computational domain.

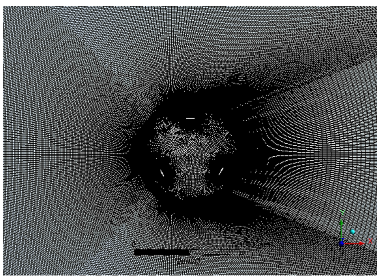


(b) Rotating domain.

Figure 5. (a) Computational domain dimensions; (b) Rotating domain configuration.



(a) Mesh near the aerofoil.



(b) Mesh near the rotating core.

Figure 6. (a)Mesh near the airfoil details, and (b) Mesh near the rotating core concentrated.

$$L(z) = B\ cos(z\pi \frac{z}{\lambda}) \tag{1}$$

Two modified blades were evaluated in this study: Modified Blade (1) and Modified Blade (2). Modified Blade (1) features a wavelength of 60 *mm* and an amplitude of 4 *mm*, while modified blade (2) has a wavelength of 90 *mm* and an amplitude of 4 *mm*. The tip-speed ratio (TSR) was calculated using Eq. 2. The relevant equations are defined as follows:

$$\lambda = \frac{R\omega}{u} \tag{2}$$

Using Eqs. 3 and 4, the time step size (TSS) as well as the number of time steps (NTS) are calculated as:

$$TSS = \frac{N}{0.15915 \times \sigma \times Number\ of\ time\ step} \tag{3}$$

$$NTS = \frac{360N}{\theta} \tag{4}$$

Table 1. Design parameters.

Parameters	Value
Airfoil profile	NACA0015
Rotational speed (rad/s)	2.4 – 9.6
Airfoil chord length (m)	0.4
Tip speed ratio	1.0 -– 4.0
Turbine diameter (m)	2.5
Numbers of blade	3.0
Free stream velocity (m/s)	3.0

2.4 Verification of results

The forces generated on the blades were analyzed across five distinct mesh configurations, with a $y^x \leq 1.0$, as shown in Table 2. Case (ii), with 131,209 elements, was selected for the simulation because the forces in case (ii) were nearly identical to those in case (i). Consequently, the meshing condition of case (ii) was utilized in the computational analysis.

Table 2. Mesh sensitivity test.

Case	Number of Element	Drag Coefficient	Lift Coefficient
Case-i	152406	0.0125786	0.0164359
Case-ii	131209	0.0125760	0.0164352
Case-iii	127618	0.0124530	0.0163570
Case-iv	118216	0.0119730	0.0157210
Case-v	056319	0.0101432	0.0146317

3. Validation of results

As shown in Fig. 7, the coefficients of drag and lift arrived at in the simulation were verified with the aid of data from studies in [32]. This comparison was performed using angle of attacks (AOAs) ranging from 0°to 40°and a Reynolds number (Re) of 360,000. The plots in Fig. 6 show that an excellent fit exists between the predicted lift and drag coefficients and those in the literature.

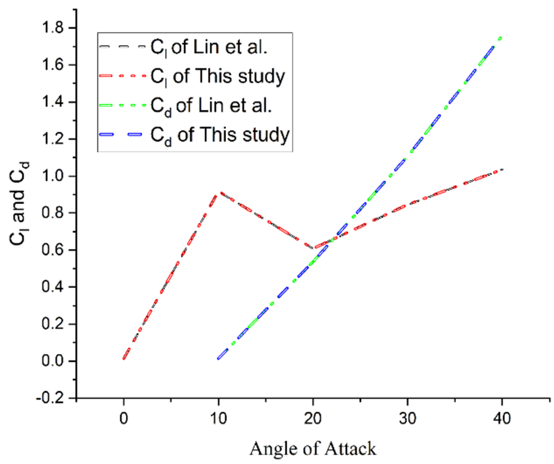


Figure 7. Comparison of lift and drag coefficients obtained from the present research with those of Lin et al.[32]

4. Results and discussions

Figure 8 up to Fig. 13 illustrate the thrust generated by VAWT blades with both straight (NACA0015 profile) and wave-like (modified) configurations during a complete rotation cycle. These simulations were conducted for TSR values ranging from 1.0 to 4.0, with a Reynolds number of 360,000, amplitude of 0.004, and wavelengths of 0.09 *m* and 0.06 *m*, respectively. As seen in Fig. 8, the modified blade (2) displays the highest thrust of 100 *N* at an azimuth angle of 90°. This is slightly higher than those of the modified blade (1) and straight blade. Figure 9 depicts the modified blade (2) with the highest thrust of 102 *N* at an azimuth angle of 90°. Slightly greater than that of TSR 1.0 initially shown above. The TSR of 2.2 in Fig. 10 shows the modified blade (2) exhibiting a higher thrust when compared to the TSR values of 1.6 and 1.0 of similar blades. Also noticeable is the Modified blade (1) with the lowest thrust.

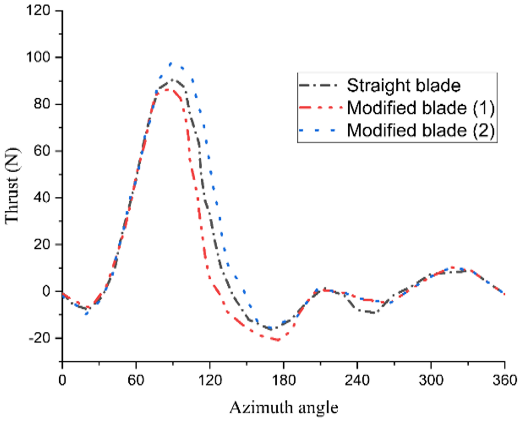


Figure 8. TSR of 1.0

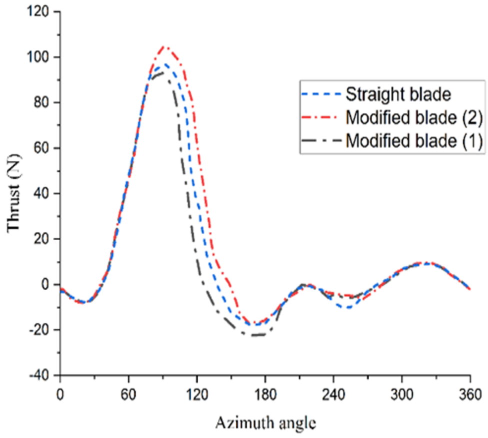


Figure 9. TSR of 1.6

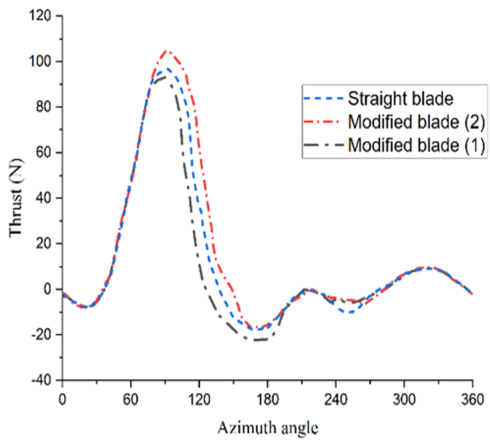


Figure 10. TSR of 2.2

A trend observable in TSR's 1.6 and 1.0. Figure 11 shows the 3 blade models at TSR of 2.8 where in a similar manner, modified blade (2) exhibits the highest thrust at 91°. Figure 12 shows that at TSR of 3.4, though the modified blade (2) exhibits the highest thrust at 93°, the straight and modified blade (1) are visibly similar in from the Azimuth angle of 0° to 130°. Furthermore, Fig. 13 depicts a similar trend initially shown in Fig. 12. In Fig. 8 through Fig. 14, the results are compared with similar findings from [39]. The trailing edge tubercle modification demonstrates a noticeable improvement in blade aerodynamics. This enhancement is attributed to the realignment of vortex distribution, which mitigates the losses identified in the design referenced in [39]. Consistent with [40], the study confirms that trailing edge modifications significantly enhance the performance of modified VAWTs, particularly in the 60°–140°azimuth region where losses typically accrue. The introduction of trailing edge tubercles generates vortices on the leading edge, creating low-pressure zones that increase thrust. Generally, it was observed that Modified Blade 1 underperformed compared to the straight blade in terms of thrust generation, due to the choice of the wavelength-to-amplitude (A/W) ratio.

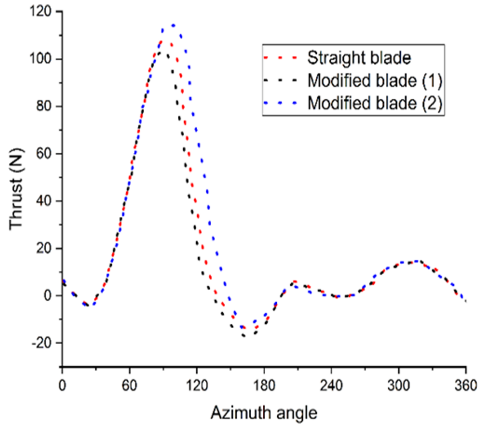


Figure 11. TSR of 2.8

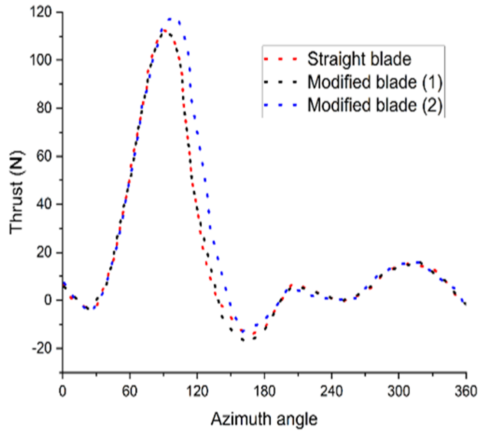


Figure 12. TSR of 3.4

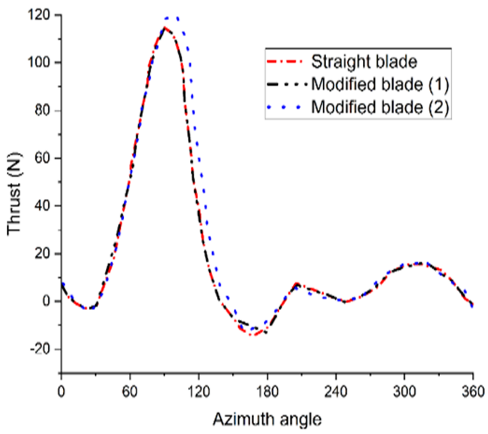


Figure 13. TSR of 4.0

Nevertheless, Modified Blade 1 still performed effectively relative to the results reported in [39], aligning with findings from [40]. The results indicate that for a constant amplitude with varying wavelengths, a decrease in the A/W ratio leads to increased thrust. Comparatively, high A/W ratios appear to be less effective at enhancing leading-edge-induced vortices, a pattern that is also reflected in [40]. While the results in [40] were reported for $TSR = 1.6$, the current study expands the analysis to cover TSR values between 1.0 and 4.0.

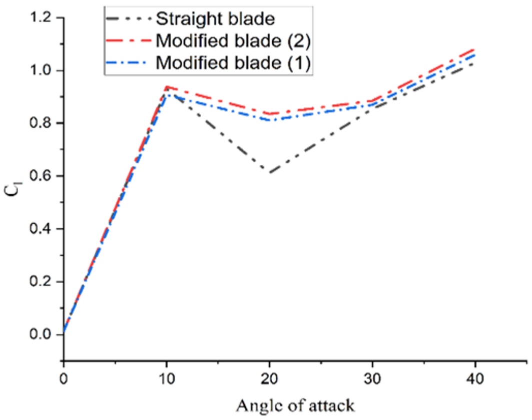


Figure 14**.** The coefficient of lift versus angle of attack for TSR of 1.0

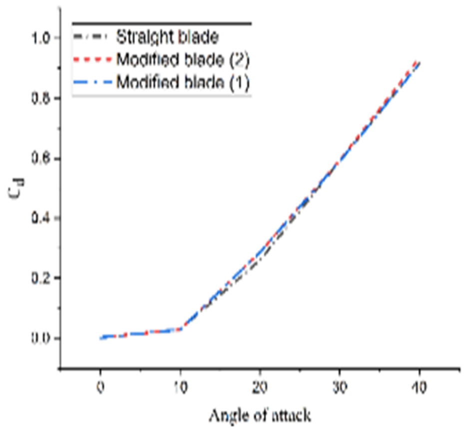


Figure 15**.** The coefficient of drag versus angle of attack for TSR of 1.0

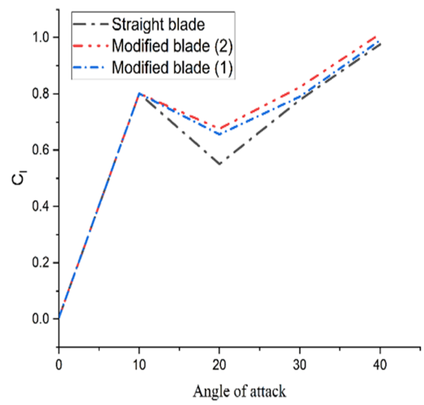


Figure 16**.** Coefficient of lift vs angle of attack for TSR 3.4

This broader range captures the influence of TSR on strengthening induced vortices due to a high A/W ratio, thereby improving thrust generation at low A/W ratios. This phenomenon is evident in the performance of both modified blades 1 and 2, particularly as modified blade 1 eventually matches and slightly surpasses the straight blade. Moreover, the study indicates that thrust is directly proportional to wavelength but inversely proportional to the amplitude of the tubercle or serration in turbine design. Given that the amplitude remained constant in this research, thrust primarily depended on the wavelength. Consequently, modified blade 2, which has a longer wavelength compared to modified blade 1, generated the highest thrust. Furthermore, the effect of the tubercle becomes clear in the modified blade (1) as the TSR increases and its performance improves and closely matches up with the straight blade. Similarly, the performance of modified blade (2) dominates all through, showing that the presence of tubercles (with the appropriate amplitude to wavelength ratio) resulted in performance improvement over the straight blade for all the TSR values considered. Generally, the combined effects of the wavelength and the amplitude in tubercle design play a pivotal role in flow modification around turbines with tubercles.

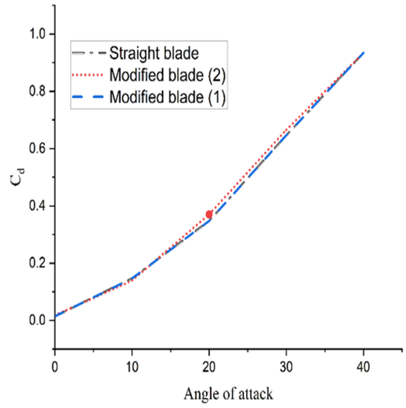


Figure 17**.** Drag Coefficient against the angle of attack for TSR of 3.4

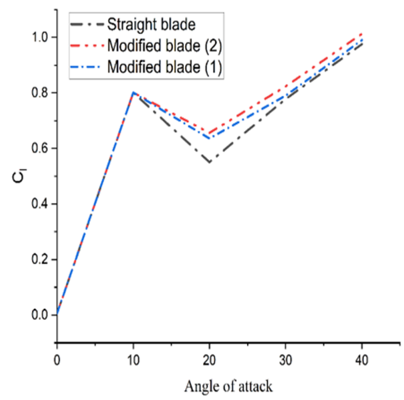


Figure 18**.** Coefficient of lift against angle of attack for TSR of 4.0

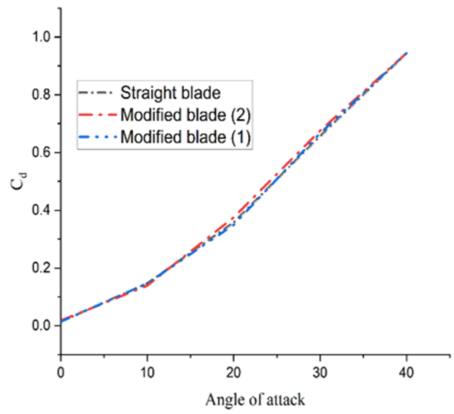


Figure 19**.** Coefficient of drag against the angle of attack for TSR of 4.0

A surge in wavelength will lead to an increase in the induced flow, which will strengthen the force acting on the vortices around the leading edge. This points out the benefits of the trailing-edge tubercle, unlike the leading-edge tubercle in which the vortex moves from the leading edge to the trailing edge thus creating a low-pressure zone on the trailing edge and consequently leading to thrust reductions. For the various TSR values considered, the effect of the presence of tubercles was captured in the Cl values as shown in Figs. 14, 16, and 18, where blades with tubercles have higher post-stall Cl values. Thus, modified blades, with an appropriate amplitude-to-wavelength ratio can vary the flow characteristics, delay flow separation, and hence improve the overall aerodynamic performance of the wind turbine. Furthermore, Figs. 15, 17, and 19 demonstrate further, the positive impacts of tubercles as the modified blades are seen to have Cd values that almost match up with the clean blade.

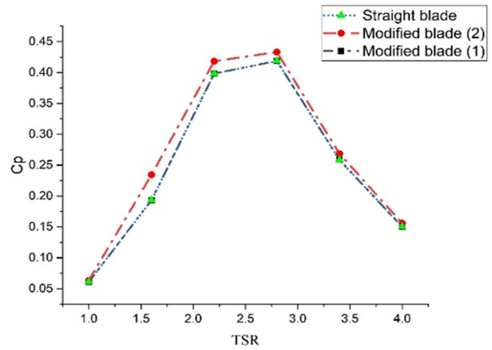


Figure 20**.** Coefficient of performance against TSR at 0°Angle of attack.

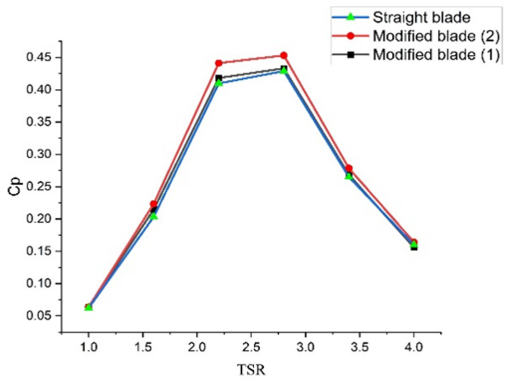


Figure 21**.** Coefficient of performance versus TSR at 10°Angle of attack.

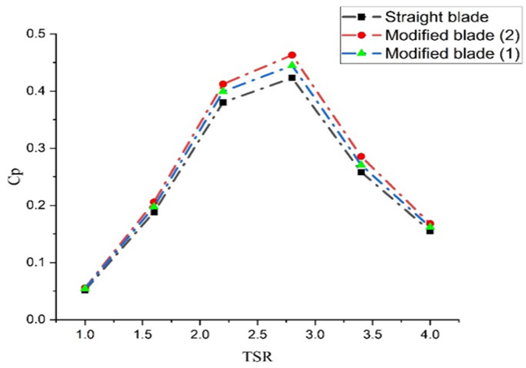


Figure 22**.** Coefficient of performance versus TSR at 10°Angle of attack.

4.1 Coefficient of performance

Three angles of attack 0°, 10°, and 20°, were chosen to evaluate the performances of the turbine for the different blade configurations. The evaluation is based on the turbine's coefficient of performance, and the results are displayed in Figs. 20, 21, and 22. For the three angles of attacks considered, the modified blade (2) has the best coefficient of performance in comparison with the other two blades. At an angle of attack 0°, the modified blade (2) is observed to have its best performance at a TSR of 2.8 with a value of 0.40311. This is about 4% more than that of the straight blade. Furthermore, the optimized blade (1) and the straight blade yielded similar performances. As the angles of attack increased, the maximum performance of blade (1) became better than the straight blade, but blade (2) gave the best performance benefit. At an angle of attack of 20°, the optimized blade (1) has its maximum Cp value at TSR 2.8, with a value of 0.45311. This is approximately 6% better in comparison to the straight blade. The optimized blade (1) Cp is 1% higher when compared to the straight blade. The improvement in the Cp values for the modified blades over the clean blade is due to the modifications in the flow around the turbine blade.

5. Conclusion

The following conclusions have been drawn from the investigation of the VAWT with trailing-edge tubercles: (a) Momentum Transfer and Stall Delay: Tubercles effectively enhance momentum transfer around the wind turbine blades, which helps delay the onset of stall on the blades. (b) Post-Stall Performance: The modified blades demonstrate superior performance (Cp) compared to the baseline blade in the post-stall regime. Specifically, modified blades (2) and (1) exhibit Cp values that are 6% and 1% higher, respectively, than the Cp value of the baseline blade. (c) Thrust Performance: Across the range of TSR values considered, modified blade (2) generates higher thrust than the other blades, particularly at azimuthal angles between 90°and 180°. (d) Impact of Wavelength and Amplitude: The combination of wavelength and amplitude in the tubercle design is crucial in determining its overall effectiveness in delaying flow separation and improving aerodynamic performance.

Authors' contribution

All authors contributed equally to the preparation of this article.

Declaration of competing interest

The authors declare no conflicts of interest.

Funding source

This study didn't receive any specific funds.

Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Acknowledgements

The authors would like to acknowledge the Nigerian Meteorological Centre, Ilorin, Nigeria for providing the wind data that was used for this work.

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How to cite this article:
Olalekan A. Olayemi, Tomisin F. Ajide, Abdulbaqi Jinadu, Leke T. Oladimeji, David O. Olayemi, Taofiq O. Amoloye, and Jumoke M. Bambe (2025). 'CFD analysis of vertical axis wind turbine with modified blades for deployment in Ilorin, Kwara state, Nigeria', Al-Qadisiyah Journal for Engineering Sciences, 18(1), pp. 083-091. https://doi.org/10.30772/qjes.2024.151245.1293