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# A Comparative Study on the Performance of Three-Blade and Four-Blade Archimedes Wind Turbines at Low Wind Speeds Using Ansys Simulation

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**Abstract:** The Archimedes wind turbine is a promising technology for renewable energy applications in low wind speed conditions, yet the optimization of the blade geometry still requires a comprehensive investigation. This study aims to analyze the effect of variations in the number of blades (three and four) and pitch angles (50°, 55°, 60°, and 65°) on the aerodynamic performance of Archimedes wind turbines using the ANSYS 2024 R1 Computational Fluid Dynamics (CFD) simulation. The research methodology applied the SST turbulence model k-ω with a constant Tip Speed Ratio (TSR) at a value of 1 to isolate the influence of geometric parameters on the coefficient of power (Cp). The simulation was carried out with a residual convergence criterion of 0.001 throughout 1000 iterations until a stable solution was reached. The results of the analysis showed that a four-blade configuration with a pitch angle of 65° resulted in an optimal Cp of 0.2027, representing an 85.6% performance improvement over the three-blade configuration of 50° (Cp = 0.1092). Velocity and pressure contour visualization revealed that the four blades demonstrated superior attachment flow, a more even distribution of pressure differential, and an organized wake structure that minimized energy dissipation. The study's conclusions identified a four-blade configuration at a pitch angle range of 60-65° as the optimal design for Archimedes wind turbine applications in low wind speed conditions, making a significant contribution to the development of renewable energy technologies for urban and tropical regions.

**Keywords:** Archimedes, Blade Configuration, CFD Simulation, Pitch Angle, Wind Turbine

## 1. Introduction

Renewable energy has become a key focus in efforts to mitigate climate change and reduce dependence on depleting fossil fuels [1]. Wind turbines are one of the most promising energy conversion technologies due to their abundant potential and are environmentally friendly [2]. However, conventional wind turbines have significant limitations in operating in low wind speed conditions, especially in tropical and urban areas where average wind speeds are generally below 5 m/s [3]. The Archimedes Wind Turbine (AWT) is here as a design innovation that overcomes these limitations through a spiral blade configuration that is able to capture wind energy more efficiently at low speeds [4].

Previous research has shown that the spiral blade geometry in AWT produces higher initial torque than conventional horizontal axis wind turbines [5]. Several studies have explored the effect of blade count on turbine efficiency, but most have focused on conventional turbines with results showing trade-offs between aerodynamic efficiency and starting torque [6].

Pitch angle optimization has also been extensively researched, with the finding that the right pitch angle can increase the coefficient of power by up to 15-20% [7]. However, comprehensive investigations into the optimal combination of blade number and pitch angle in AWT, especially for low wind speed conditions, are still very limited [8].

The research gap identified was the lack of systematic comparative studies that analyzed AWT performance with variations in the number of blades (three and four blades) and pitch angles simultaneously using an accurate Computational Fluid Dynamics (CFD) approach. The novelty of this study lies in a comprehensive analysis of the comparative aerodynamic performance between three-blade and four-blade configurations on AWT with four pitch angle variations (50°, 55°, 60°, and 65°) using ANSYS CFD simulations under fixed Tip Speed Ratio (TSR) conditions, which has not been specifically performed in the previous literature.

The formulation of this research problem is how the effect of variations in the number of blades and pitch angle on the coefficient of power of AWT at low wind speeds. The purpose of the study was to determine the optimal configuration between the number of blades and the pitch angle that resulted in the highest coefficient of power at AWT. The benefits of this research are expected to make a significant contribution to the development of more efficient AWT designs for applications in low-wind speed areas, as well as provide reference data for researchers and practitioners in the field of renewable energy.

# 2. Methods

## *2.1 Model Description*

The Archimedes wind turbine geometry investigated in this study consists of a vertical-axis rotor equipped with spiral-shaped blades wrapped helically around a central shaft. The rotor is characterized by a constant outer diameter 500 mm and a uniform height 370 mm, forming a cylindrical swept volume. Each blade follows an Archimedean spiral profile with a constant blade thickness along the span, designed to promote smooth flow guidance and enhanced momentum exchange at low wind speeds. Two blade configurations were examined, namely three-blade and four-blade arrangements, in which the blades are evenly distributed circumferentially to maintain geometric symmetry and balanced aerodynamic loading. The pitch angle of the spiral blade was systematically varied at 50°, 55°, 60°, and 65°, measured at the mid-span location relative to a fixed horizontal reference plane normal to the incoming wind direction. This geometric framework ensures consistent comparison between configurations while preserving identical rotor dimensions and swept area across all simulations.

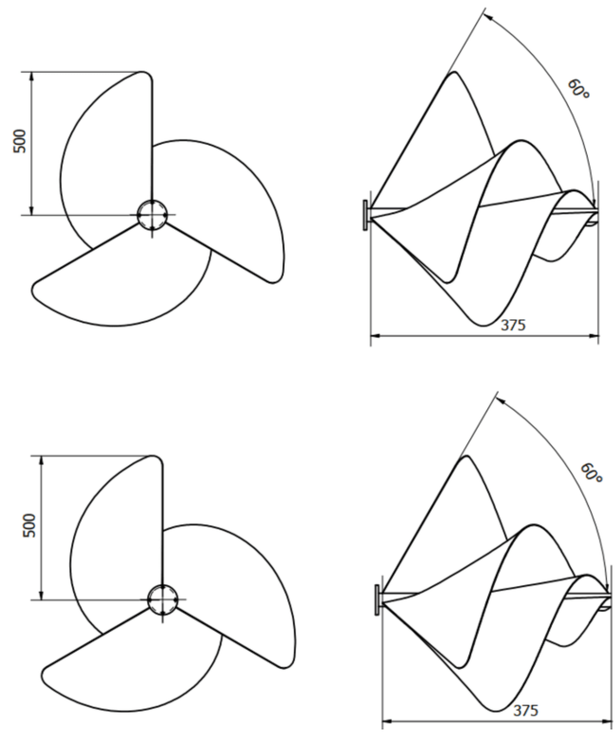



***Figure 1.*** *Scaled engineering drawing of the Archimedes wind turbine showing the rotor diameter (D), rotor height (H), blade pitch angle (β), and blade arrangement for the three-blade and four-blade configurations.*

In this study, the pitch angle (β) is defined as the angle between the tangent line of the spiral blade at the mid-span location and the horizontal plane perpendicular to the incoming wind direction. The pitch angle is measured at the blade mid-span to ensure consistency among configurations and to represent the effective aerodynamic orientation of the spiral blade along the rotor height.

## *2.2 Simulation Parameters*

***Table 1.*** *Simulation Parameters*

| Parameters | Value | Unit |
|---|---|---|
| Wind Speed V) | 3 | m/s |
| Air Density (ρ) | 1,225 | kg/m$^3$ |
| Swept Area (A) | 0,785 | m$^2$ |
| Blade Diameter (D) | 0,5 | m |
| Blade High (H) | 0,375 | m |
| Number of blades | 3 and 4 | pcs |
| Pitch Angle | 50, 55, 60, 65 | ° |
| Temperature | 300 | K |

The coefficient of power (Cp) is calculated using the projected swept area of the blade, defined as $A = 0,785\ m^2$, where D is the rotor diameter and H is the rotor height. This definition is consistent with previous studies on Archimedes and vertical-axis wind turbines operating at low tip speed ratios.

The inlet wind velocity was set to a uniform value of 3 m/s. Air was modeled as an incompressible fluid with a density of 1.225 kg/m³ and a dynamic viscosity of $1.789 \times 10^{-5}$ kg/m·s at a reference temperature of 300 K. These conditions represent standard atmospheric conditions commonly adopted in low wind speed CFD analyses.

### *2.3 Numerically Setup*

This study employed Computational Fluid Dynamics (CFD) simulation using ANSYS 2024 R1 to evaluate the aerodynamic performance of the Archimedes Wind Turbine (AWT) [9], [10]. The simulation is done by varying the number of blades and pitch angles to determine the geometry that shows the highest effectiveness. The flow is modeled as single-phase incompressible airflow, where multiphase models and surface tension effects are not considered as they are irrelevant to the aerodynamics of wind turbines. In this study, the Tip Speed Ratio (TSR) was set at constant at a value of 1 to isolate the effect of blade count and pitch angle on turbine performance. The TSR value was chosen because Archimedes wind turbines generally operate efficiently at low TSR, so TSR = 1 is representative for low-speed rotor conditions with high solidity. The viscous SST k-ω model is used for its advantages in predicting separated and boundary layer flows with high accuracy in wind turbine applications [11]. The solution control is maintained at the default setting, while the residual convergence criterion is set at 0.001 to ensure numerical result accuracy. Standard initialization is implemented with initialized compute from across domain zones. The fluid domain is designed with adequate dimensions to avoid the blockage effect and ensure the perfect flow development around the turbine rotor. Meshing is performed using an unstructured mesh approach with refinement in the blade and wake regions to accurately capture complex flow gradients [12]. The simulation was executed for a total of 1000 iterations, where a stable solution was obtained after convergence was achieved by continuously monitoring the torque and coefficient of power parameters.

A comprehensive mesh quality assessment was performed to ensure the numerical robustness and reliability of the CFD simulations. The computational domain was discretized into 4,174,526 cells, 8,590,731 faces, and 788,582 nodes, providing sufficient spatial resolution to accurately capture the complex flow structures around the turbine. The mesh quality evaluation indicates that the minimum orthogonal quality is 0.0727, occurring in a limited number of interior cells, while the exterior regions exhibit higher minimum values ranging from 0.20 to 0.21. Importantly, the orthogonal quality histogram shows that most cells possess values above 0.6, with a strong concentration in the 0.7–0.9 range, which is generally regarded as good to excellent for unstructured meshes. In addition, the maximum aspect ratio of 97.75 is localized and associated with stretched cells in non-critical flow regions, while the remaining subdomains maintain aspect ratios below 18, which are well within acceptable limits for rotating machinery simulations. Overall, the mesh satisfies established CFD quality criteria, ensuring stable convergence and minimizing numerical diffusion, thereby providing confidence in the reliability of the numerical results without requiring further mesh refinement.

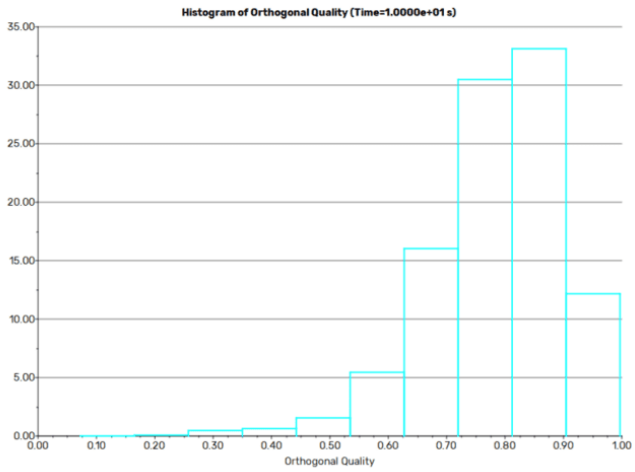



***Figure 2.*** *Histogram of orthogonal quality showing the distribution of mesh element quality*

# 3. Result and Discussions

This numerical investigation is carried out through a systematic approach by exploring two main parameters, namely blade count configuration and pitch angle variation to identify geometric designs that provide optimal efficiency. The fluid flow characteristics are represented as single-phase incompressible regimes for atmospheric air, with deliberative disregard for multiphase modeling and interfacial stress phenomena given their negligible contribution in the context of wind turbine aerodynamic analysis. The ratio of blade tip speed to free wind speed (TSR) is constant at the magnitude of unity to facilitate methodological isolation of the impact of blade configuration and pitch orientation on system performance characteristics. The determination of TSR at this singular value is based on the intrinsic operational characteristics of Archimedes wind turbines which demonstrate superior efficiency at low TSR regimes, making TSR = 1 a representative condition for high solidity rotors operating at low rotational speeds. The implementation of the k-ω SST turbulence model was chosen to capture the phenomenon of boundary layer and separated flow with precision. Numerical control parameters are set in a standard configuration with a residual convergence threshold set on an order of $10^{-3}$ to guarantee the precision of the solution. The initialization procedure adopts a standard method with computational propagation covering the entire fluid domain zone. The execution of numerical simulations is carried out throughout 1000 iteration cycles until a stable solution convergence is achieved with minimal fluctuations in monitoring parameters.

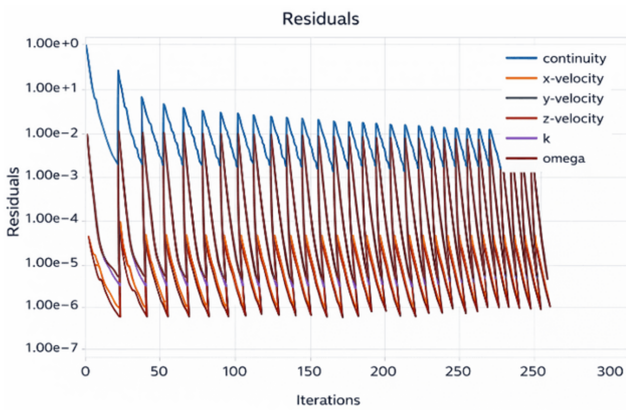



***Figure 3.*** *Residual turbine plots a pitch angle of 50° with 3 blades*

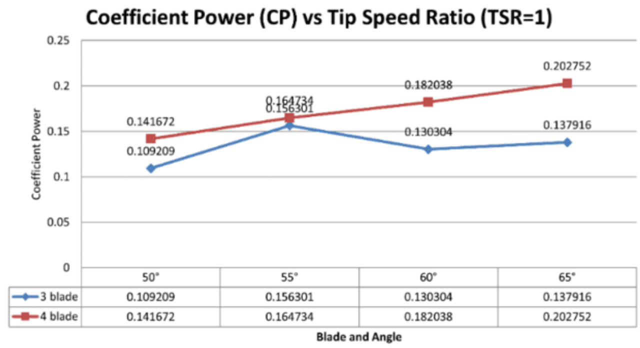



***Figure 4.*** *Graph of coefficient power value versus blade pitch angle and number of blades*

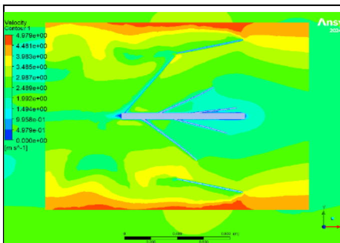
***Table 2.*** *Cp of each blade configurations*

| Yes | No of Blade | Pitch Angle | Cp | TSR |
|---|---|---|---|---|
| 1 | 3 | 50° | 0.1092 | 1 |
| 2 | 3 | 55° | 0.1563 | 1 |
| 3 | 3 | 60° | 0.1303 | 1 |
| 4 | 3 | 65° | 0.1379 | 1 |
| 5 | 4 | 50° | 0.1416 | 1 |
| 6 | 4 | 55° | 0.1647 | 1 |
| 7 | 4 | 60° | 0.1820 | 1 |
| 8 | 4 | 65° | 0.2027 | 1 |

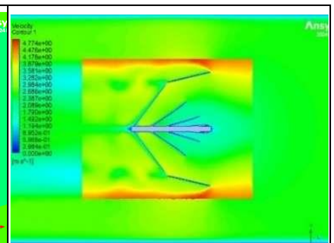
The quantitative data describe a systematic comparison of the coefficient of power for eight different configurations representing a combination of the number of blades (three and four) with four variations in pitch angles (50°, 55°, 60°, and 65°) at a constant TSR of 1. Comparative analysis revealed that the four-blade configuration consistently produced superior Cp values compared to three blades across the entire investigated pitch angle range. The most significant performance improvement was observed in the transition from three 50° blades (Cp = 0.1092) to four 65° blades (Cp = 0.2027), representing an amplification of 85.6% in energy conversion efficiency [13]. The three-blade configuration shows an optimal Cp value at a pitch angle of 55° which then degrades before re-increasing at 65°, indicating the complexity of the aerodynamic interaction between the angle of attack and the flow characteristics [14]. In contrast, the four blades demonstrate monotonous progressivity with consistent increments as the pitch angle escalates, reflecting superior aerodynamic stability and adaptability to geometric variations [15]. This phenomenon can be explained through the perspective of higher rotor solidity on the four blades, resulting in a blocking effect that optimizes the transfer of momentum from the fluid to the mechanical system [16]. The TSR constant at the unity facilitates the pure analysis of the influence of geometric parameters without interference from rotational velocity variability, consistent with the methodology of characterization of low-speed turbines [4].

The graphical visualization shows the correlation between the coefficient of power and the variation in the pitch angle and the configuration of the number of blades on the Archimedes wind turbine. The data shows a trend of progressive performance improvement in the four-blade configuration as the pitch angle escalates from 50° to 65°, where the maximum Cp value is recorded at 0.2027 at an angle of 65°. This phenomenon indicates that the increase in the number of blades increases the solidity of the rotor so that it is able to extract the kinetic energy of the wind more optimally [4]. The three-blade configuration shows inferior performance with less consistent fluctuations in Cp values, where the peak of efficiency occurs at a 55° pitch angle with a Cp of 0.1563 before decreasing and increasing again. This pattern indicates a trade-off between the aerodynamic angle of attack and the phenomenon of separated flow which is more dominant in fewer blade configurations [17]. The superiority of the four-blade configuration can be attributed to a more even aerodynamic load distribution and better continuity of wind momentum capture throughout the rotational cycle [18]. The pitch angle increment contributes to an increase in the effective angle of attack that optimizes the lift force on the convex side of the spiral blade, although at extreme angles it can trigger boundary layer separation [19]. These results are consistent with previous research that states that geometric blade modifications can increase the coefficient of power to the range of 8-12% under optimal operational conditions [20].

### *3.1. Velocity contour on blade, pitch, angle and number of blades*



a. 3 blades with a pitch angle of 50°



b. 4 blades with a pitch angle of 50°

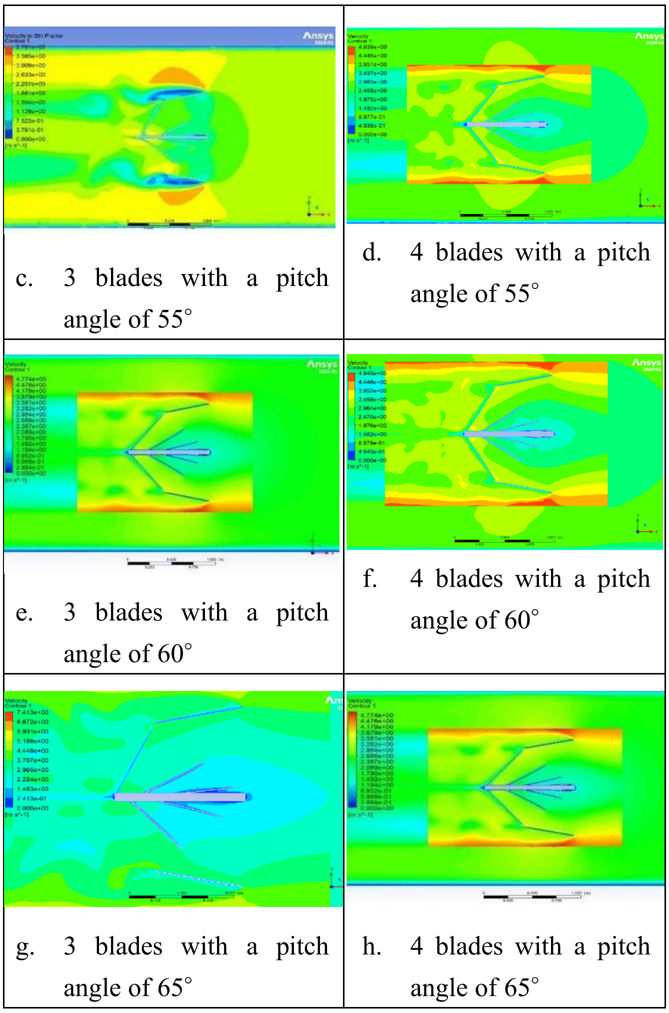

c. 3 blades with a pitch angle of 55°
d. 4 blades with a pitch angle of 55°
e. 3 blades with a pitch angle of 60°
f. 4 blades with a pitch angle of 60°
g. 3 blades with a pitch angle of 65°
h. 4 blades with a pitch angle of 65°

***Figure 4.*** Comparison of the velocity contours on the spiral blades of the turbine.

The velocity contour distribution visualizes the characteristics of the flow field around the spiral blade geometry for the eight configurations analyzed. Observations show that the magnitude of the maximum velocity varies between 3.55 m/s to 4.44 m/s depending on the geometric configuration, with three 65° blades indicating the highest values [17]. Intensification of the observed velocity gradient in the leading edge and trailing edge regions of the blade, indicates a significant acceleration of flow due to the spiral convergent geometry [4]. The four-blade configuration demonstrates a more homogeneous speed distribution with acceleration zones distributed more evenly along the blade surface, reflecting a more organized aerodynamic interaction [18]. A more pronounced wake region phenomenon observed in three-blade configurations, especially at low pitch angles, indicates higher vortex shedding intensity and potential efficiency degradation [19]. The pitch angle increment results in modifications to the flow pattern with increased flow attachments on the side of the pressure blade, contributing to the optimization of differential pressure and consequently increased torque [20]. Regions of stagnation were observed in narrower inter-blade spacing on four blades, but did not significantly hamper global performance given the compensation from the increase in catch area [14]. The boundary layer characteristics on the blade surface show varying thicknesses, with three blades showing a tendency for early separation which may explain the inferiority of performance [13].

### *3.2. Pressure contour on blade, pitch, angle and number of blades*

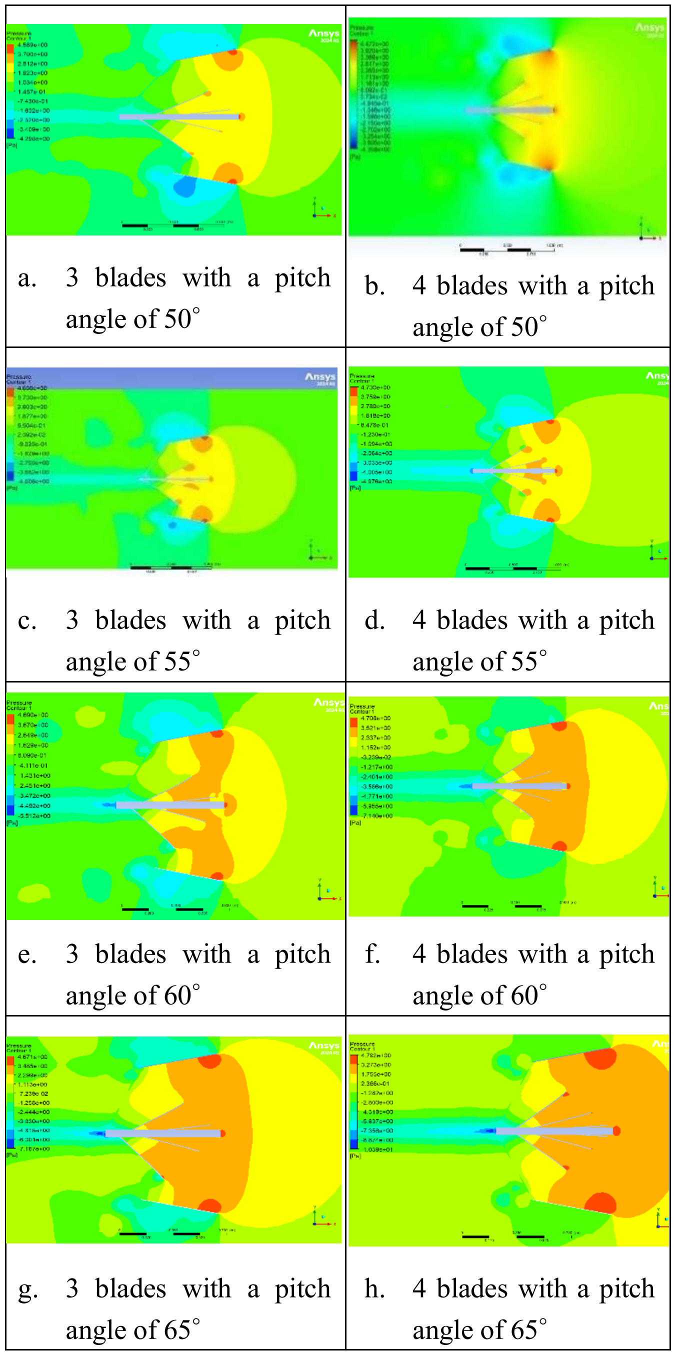
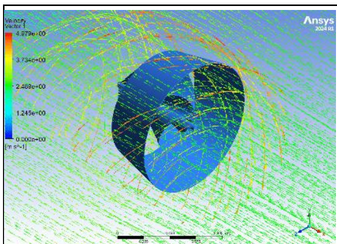

a. 3 blades with a pitch angle of 50°
b. 4 blades with a pitch angle of 50°
c. 3 blades with a pitch angle of 55°
d. 4 blades with a pitch angle of 55°
e. 3 blades with a pitch angle of 60°
f. 4 blades with a pitch angle of 60°
g. 3 blades with a pitch angle of 65°
h. 4 blades with a pitch angle of 65°

***Figure 5.*** Comparison of pressure contours on the spiral blades of the turbine.

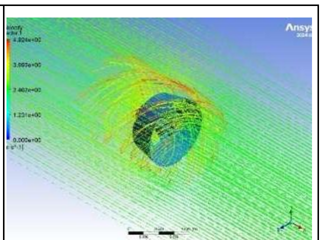
The pressure contour visualizes the distribution of the pressure field on the surface of the spiral blade for the entire investigated configuration. Maximum pressure magnitudes range from 4.47 Pa to 4.79 Pa, with four 65° blades indicating peak values indicating the optimal differential pressure for energy conversion [15]. The pressure gradient between the pressure (windward) and suction (leeward) sides of the blade indicates intensification as the pitch angle increases, reflecting the amplification of normal aerodynamic forces that contribute to rotational torque. The four-blade configuration demonstrates a more extensive high-pressure zone on the convex side of the blade, consistent with increased solidity and blocking effects that optimize transfer momentum [17]. Low-pressure regions are observed in inter-blade spacing and wake regions, with varying intensities depending on geometry; The three blades indicate a more pronounced negative pressure zone, indicating intensive recirculation flow [14]. The pitch angle increment results in a redistribution of the pressure pattern with the expansion of the high-pressure zone in the leading edge region, which contributes positively to lift-induced torque [18]. The superior uniformity of pressure distribution on the four blades reflects better aerodynamic stability and reduced cyclic load fluctuations that can reduce fatigue stress on structural components [16]. The pressure recovery phenomenon in the trailing edge region is more efficient in a four-blade configuration with an optimal pitch angle [19].

### *3.3. Velocity vector on blade pitch angle and number of blades*

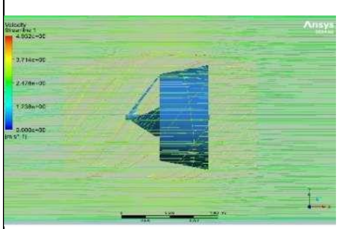
A comparison of the velocity vector at various blade pitch angles and blade numbers is presented below:



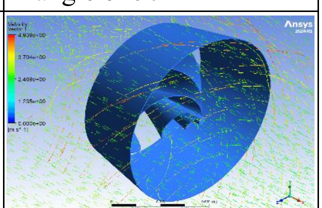
a. 3 blades with a pitch angle of 50°



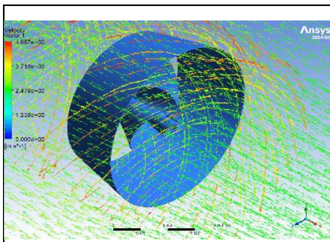
b. 4 blades with a pitch angle of 50°



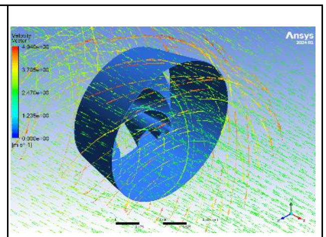
c. 3 blades with a pitch angle of 55°



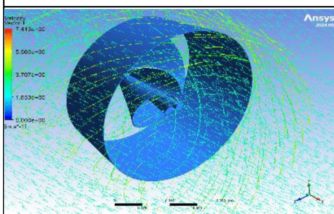
d. 4 blades with a pitch angle of 55°



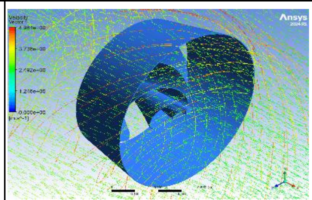
e. 3 blades with a pitch angle of 60°



f. 4 blades with a pitch angle of 60°



g. 3 blades with a pitch angle of 65°



h. 4 blades with a pitch angle of 65°

**Figure 6.** Comparison of the velocity vector on the spiral turbine blade

The velocity vector representation illustrates the directional characteristics and magnitude of the flow around the blade geometry for the analyzed configuration. The streamlined pattern shows better attachment flow on four blades with high pitch angles, indicating delayed separation and optimized lift generation [20]. Vortex formation is observed in the wake region downstream of the blade, with varying intensity and size of the vortex core; The three blades exhibit a larger vorticity structure and chaos, contributing to energy dissipation that lowers efficiency [13]. The four-blade configuration demonstrates an organized wake structure with a higher vortex shedding frequency but with lower individual intensity, reflecting more favorable aerodynamic unsteady characteristics. Flow acceleration in the inter-blade channel was observed to be more pronounced at low pitch angles, while high angles produced a blocking effect that increased the pressure differential [17]. The recirculation zone on the leeward side blade indicates extensification as the pitch angle decreases, indicating a trade-off between the flow attachment and the separated flow region [18]. Boundary layer development along the blade surface shows different characteristics between three and four blades, with the latter showing maintained attachment to locations further downstream [15]. The uniformity of the velocity vector in the exit region is better on the four blades, indicating superior energy extraction efficiency [14].

***Table 3.*** *Velocity and pressure of all blades configurations*

| Yes | Pitch angle | No of blades | Contour velocity (m/s) | | Pressure contour (Pa) | |
|---|---|---|---|---|---|---|
| | | | Min | Max | Min | Max |
| 1 | 50° | 3 | 0 | 3.98 | 0 | 4.58 |
| 2 | 50° | 4 | 0 | 3.60 | 0 | 4.47 |
| 3 | 55° | 3 | 0 | 3.58 | 0 | 4.65 |
| 4 | 55° | 4 | 0 | 3.95 | 0 | 4.73 |

| Yes | Pitch angle | No of blades | Contour velocity (m/s) | | Pressure contour (Pa) | |
|---|---|---|---|---|---|---|
| | | | Min | Max | Min | Max |
| 5 | 60° | 3 | 0 | 3.87 | 0 | 4.69 |
| 6 | 60° | 4 | 0 | 3.55 | 0 | 4.70 |
| 7 | 65° | 3 | 0 | 4.44 | 0 | 4.67 |
| 8 | 65° | 4 | 0 | 3.90 | 0 | 4.79 |

The quantitative data compilation describes the range of velocity and pressure values for the eight comprehensively investigated configurations. The minimum value for all parameters is consistent at zero, representing the condition of stagnation at a specific location in the fluid domain [19]. The variability of the magnitude of the maximum speed (3.55-4.44 m/s) and the maximum pressure (4.47-4.79 Pa) indicates the significant sensitivity of the flow characteristics to the geometric parameters of the blade [16]. The three-blade configuration shows more pronounced fluctuations in the value extremes, reflecting relative aerodynamic instability compared to the four-blade which demonstrates a more consistent trend. The correlation between the increase in pitch angle and the magnitude of the maximum pressure was observed more clearly on the four blades, indicating a more predictable and controllable aerodynamic response [13]. The disparity between velocity contour, pressure contour, and velocity vector values is minimal, indicating the consistency of the post-processing data and the reliability of the results of the CFD simulation. Three 65° blades produce the highest maximum velocity (4.44 m/s) but do not correlate with optimal Cp, indicating that the magnitude of velocity alone is not determinative of energy conversion efficiency; Distribution and Directionality of Flow More Critical [17]. The highest maximum pressure at four 65° (4.79 Pa) blades is positively correlated with optimal Cp, confirming the importance of pressure differential in the energy extraction mechanism in drag-based turbines with lift components [15].

## 4. Conclusion

Comparative numerical investigation of the performance of Archimedes wind turbines through ANSYS CFD simulations has identified the optimal configuration for low wind speed applications. The results of the analysis demonstrate that a four-blade configuration with a pitch angle of 65° produces the highest coefficient of power of 0.2027 at TSR = 1, representing an 85.6% performance improvement over the 50° three-blade configuration. The superiority of the four blades can be attributed to the higher rotor solidity, more even aerodynamic load distribution, and superior continuity of wind momentum capture throughout the rotational cycle. Velocity and pressure contour visualization revealed that the four blades demonstrated better attachment flow, delayed separation, and an organized wake structure that minimized energy dissipation. The pitch angle increment contributes positively to the pressure differential and lift-induced torque, although the three blades exhibit a non-monotonic response with a peak performance of 55°. These findings make a significant contribution to the development of efficient Archimedes wind turbine designs for low-wind speed regions, with recommendations for the implementation of a four-blade configuration in a pitch angle range of 60-65° for aerodynamic performance optimization.[21]

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