

CFD-Based Aerodynamic Modelling and Performance Optimization of an H-Darrieus Vertical-Axis Wind Turbine

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ABSTRACT

Vertical-axis wind turbines (VAWTs) have become an effective solution for electricity generation in local grids, especially in the low wind speed and turbulence conditions often found in urban areas. Despite the progress made, the aerodynamic performance of these turbines is still limited due to the complex nature of the airflow and some fundamental design issues. This study aims to improve the aerodynamic efficiency of vertical axis wind turbines by investigating the influence of key design parameters on their performance using computational fluid dynamics (CFD) calculations. The main scientific value of this work is to determine the optimal ratio of the tip speed (TSR) and blade pitch angle that provides maximum aerodynamic efficiency of the turbine, thus improving the energy conversion capabilities compared to the results of previous studies. In ANSYS Fluent, the turbulent model was used to accurately describe the unstable flow around the blade and determine the pressure and velocity fields. The results indicated that the wind turbine attained maximum aerodynamic performance at a blade pitch angle of 1.5 radians and a tip speed ratio (TSP) of 4.9, reaching an optimal power factor (C_p) of 0.52, showing a notable improvement in overall power conversion efficiency of the system. This research proves that advanced CFD calculations help design better low- and medium-wind VAWTs, enhancing their role in sustainable energy.

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1. Introduction

The increasing emissions of GHGs particularly (CO₂) creates a major global challenge [1], [2]. And this leads to disturb the Earth's atmospheric stability due to the burning of fossil fuels [3], [4]. Reducing these negative effects, developing renewable energy systems is needed [5], [6]. Among various types of renewable energy sources, wind energy is considered the most used, due to it provides clean and sustainable energy [7], [8]. The wind turbine system's operation depends on transforming the kinetic energy of the wind into electrical power [9]. Generally, wind turbine systems are classified into two primary types: Vertical Axis Wind Turbines (VAWTs) and Horizontal Axis Wind Turbines (HAWTs) [10]. This study emphasizes (VAWTs) due to their improved suitability for urban areas, where the wind speeds are low in these areas [11]–[14]. Computational Fluid Dynamics (CFD) techniques are employed to develop and enhance effective aerodynamic wind turbine systems are used to create and refine efficient aerodynamic designs for wind turbine systems [15]–[17].

While many studies have employed (CFD) to investigate the aerodynamic behavior of VAWTs, most of these studies have focused on single design parameters or used simplified modeling techniques. This points to the need for a more comprehensive study that simultaneously considers the tip speed ratio (TSR), power coefficient (C_p) and blade pitch angle (β) within a unified computational framework, enabling an improved understanding of how these parameters together determine the overall aerodynamic performance of the turbine.

With the big reliance on fossil fuels as a primary source of energy and the expectation of their gradual depletion, the need for renewable and efficient energy sources that contribute to reducing emissions and achieving environmental sustainability is increasing. This work focuses on enhancing the output power that gotten from the wind turbine system by using (CFD) technique and Ansys program to analysis and simulation the dynamic performance for the (VAWTs).

The main objective of this study is to enhance the design of (VAWTs) to increase their efficiency in low and variable wind speed environments. The main contribution of this study is determining the optimal tip speed ratio (TSR) and blade pitch angle (β) by using ANSYS software with the $k-\omega$ turbulence model to perform accurate CFD simulations

2. Literature Review

2.1. Global Wind Energy

Recent literature indicates that wind energy is a promising renewable source due to its environmental advantages and efficiency and is divided into onshore and offshore farms. Recent years have witnessed significant growth, with global capacity reaching 906 GW in 2022. The development of floating turbines is also an important step in offshore wind farms, allowing expansion into deeper areas and increased production [18].

2.2. Vertical Axis Wind Turbines (VAWTs)

Recent studies show that modern control systems, such as changing the blade angle significantly improve turbine performance, making them more efficient and reliable under a variety of conditions [19]. A recent analysis shows that research is now more focused on fine-tuning blade shapes to address power limitations and flow separation in older VAWT designs [20].

2.3. Computational Fluid Dynamics (CFD)

Several recent studies report significant progress in turbine design using computational fluid dynamics, but authors often do not perform a network sensitivity analysis, which reduces the accuracy and reliability of their calculations. Most studies focused on just one criterion, such as blade shape, without incorporating key variables into a single model. [Table 1](#) shows how our research compares to other studies from 2020 to 2025.

In earlier works, optimizations were often limited to a single aspect, such as the blade shape. They also lacked network inspection and a clear explanation of the choice of turbulence model. In this work, the key parameters of tip speed ratio (TSR) and blade angle are combined in to a single computational fluid dynamics (CFD) model. The results additionally identified optimal operating conditions-TSR = 4.9 and pitch = 1.5 rad- producing a peak power coefficient of 0.52, a performance aspect not explicitly highlighted in previous studies on VAWT aerodynamic optimization. This project fills an important gap by providing an accurate and reliable calculation method for evaluating and improving the aerodynamic performance of wind turbines.

The remainder of this paper is organized as follows: [Section 2](#) research methodology, [Section 3](#) describes the Design and Simulation of the proposed system. [Section 4](#) discusses the results. And finally, the conclusions are presented in [Section 5](#).

Table 1. Presents a concise overview of key studies conducted between 2020 and 2025 that focus on the numerical simulation of (VAWTs)

Reference (Year–Source)	Objective / Topic of Research	Key Findings (Summary)	Notes/ Deficiencies	Comparison with the Present Study
Abdallah et al., 2025- Scidirect [21]	Improving the aerodynamic efficiency of H-Darrieus turbine blades through a modified J-shaped design	Achieved higher starting torque and improved aerodynamic stability	Focused on a single design modification	The present study integrates both TSR and Pitch parameters within a unified CFD framework
Belabes et al., 2023 – CDN Science Pub [22]	Simulation of wake-vortex interactions among multiple VAWTs	Demonstrated potential productivity gain through optimized turbine spacing	Relies mainly on simplified 2D models	This work on single-turbine performance with detailed 3D aerodynamic mapping
Fertahi et al., 2023 – MDPI [23]	Comparative review of CFD methods (2D, 2.5D, 3D) for Darrieus turbines	Identified notable discrepancies in Cp prediction accuracy	Several studies lacked experimental validation	The current model includes grid-sensitivity verification and a validated turbulence model
Al Afif et al., 2024-J. Phys. Conf. Ser. [24]	CFD-based performance evaluation of a VAWT using ANSYS Fluent	Reported Cp and torque variations under different operating modes	Limited model validation	Our study incorporates additional mesh independence testing and model justification
Ken-Yeen Lee, 2020- ResearchGate [25]	Review of modern adaptive design methods for VAWTs	Summarized recent torque-boosting techniques	Lacked numerical or experimental verification	The current study employs a validated CFD framework to evaluate TSR and Pitch influences
Drusilla Duty et al., 2024- Scidirect [26]	CFD-experimental comparison for a wind tunnel- tested VAWT	Clarified methodological discrepancies in aerodynamic modeling	Did not propose new optimization strategies	The present study extends this by improving aerodynamic design and validating CFD results
Wang & Ferng, 2024- WEA [27]	Optimization of torque and acoustic behavior for small-scale VAWTs	Achieved reduced noise with minimal efficiency loss	Focused primarily on noise analysis	Our work emphasizes aerodynamic efficiency and Cp enhancement
Al Noman et al., 2023 – SciDirect [28]	Integration of Artificial Intelligence with CFD for Savonius turbines	Achieved faster and more accurate performance prediction	Applied only to the Savonius configuration	The current study can be extended toward hybrid CFD-AI integration in future research
Rizk et al., 2023- SciDirect [29]	CFD performance assessment of a Savonius turbine	Provided a quantitative evaluation of power output	Lacked a direct experimental comparison	Our study combines CFD simulations with published experimental validation data
Hammad et al., 2024- Energies [30]	Enhancement of H-Darrieus performance via hybrid pitch strategy	Improved self-starting ability by 80%, CP=0.35	Investigated only pitch variation	Our approach integrates both Pitch and TSR for broader optimization
Lfmejani et al., 2024- SciDirect [31]	Development of a three-blade turbine with tilting segments	Reported notable improvement in aerodynamic response	Focused solely on structural optimization	This research complements it by determining optimal TSR and Pitch configurations
Afify et al., 2025- Sci Reports [32]	INNOVATIVE Savonius design featuring a dynamic gating mechanism	Achieved a reduction in negative torque generation	Concentrated on mechanical design only	Our study emphasizes the aerodynamic flow field and pressure contour analysis
Bang et al., 2024- DSpace Cranfield [33]	CFD study of Bach-type VAWT for performance improvement	Recorded efficiency gains with modified geometry	Lacked experimental verification	The present work validates CFD accuracy through comparative data analysis

3. Research Methodology

This section describes how to create a computer model to analyze the aerodynamics of an H-Darrieus turbine. Advanced computational fluid dynamics (CFD) software was used to simulate the flow and evaluate the turbine's performance. The procedure included: Preparing the governing flow equations, creating turbine geometry, constructing a computational grid, setting boundary conditions, and validating the results by comparing them with previous experiments.

3.1. Governing Equations

To create a model of turbine operation under real conditions, many parameters must be specified. Below we will discuss in detail how each parameter affects the flow and operation of the entire system.

3.1.1. Wind Velocity

Wind inlet speed (V) is a key factor in energy production. Wind power is directly related to the cube of this speed (V^3) and is calculated using the formula [34]–[36]:

$$C_p = \frac{P_{actual}}{P_{wind}} = \frac{T\omega}{\frac{1}{2}v^3 A\rho} \quad (1)$$

The wind power is presented as P_{wind} which represents the rate of energy transfer measured in watts (W). Where, ρ is the air density (kg/m^3), V is the free-stream wind velocity (m/s) and A is the turbine's effective cross-sectional area (m^2) determined by the rotor size and blade geometry.

This equation shows that wind power increases sharply with wind speed since it depends on the cube of velocity; starting from a 2 m/s inlet, different speeds were tested to examine their effect on the turbine's power coefficient (C_p).

3.1.2. Power Coefficient (C_p)

It is a measure used to determine the efficiency of a turbine in converting the kinetic energy of the wind into mechanical energy. It is calculated by the ratio between the actual energy produced by the turbine and the energy available in the wind [37]–[39]:

$$TSR(\lambda) = \frac{V_{tip}}{V_{wind}} \quad (2)$$

The actual power of the turbine (P_{actual}) is the torque (T) multiplied by the angular velocity (ω). According to Betz's law, its limit is about 0.59 [40]–[42], that is, the turbine cannot convert more than 59.3 % of the wind's kinetic energy into mechanical energy [43]–[45].

3.1.3. Tip speed Ratio (TSR)

Tip Speed Ratio (TSR) is a key indicator of turbine efficiency. It shows the ratio of the linear speed of the blade tips to the wind speed. It is calculated using the formula [46]–[48]:

$$SR(\lambda) = \frac{V_{tip}}{V_{wind}} = \frac{\omega R}{V_{wind}} \quad (3)$$

Here R is the rotor radius (in meters) – the distance from the center to the tip of the blade.

Research show that each turbine has an optimal TSR at which it most efficiently converts wind energy into mechanical energy [49]–[51]. If the TSR is too high or too low, the turbine operates less efficiently, resulting in energy loss [52]. Therefore, it is important to keep the TSR in the optimal range for stable operation and maximum turbine efficiency under different conditions [53]–[55].

3.1.4. Pitch of the Blade (β)

The pitch angle (β) is the angle between the plane of rotation and the chord of the blade (in degrees). It greatly affects aerodynamics. If the beta angle is increased, this will increase drag and

cause flow separation, which will reduce efficiency [56], [57]. On the contrary, decreasing the beta angle increases the mechanical power of the blade and increases power, especially at low wind [58].

In this study, the pitch angle (β) was treated as a pure angular variable (unrelated to the turbine radius), and its effect on both torque and power coefficient (C_p) was analyzed under various operating conditions [59].

3.2. Geometric Modeling

The vertical model was made in FreeCAD for accurate geometry. The turbine has three blades on a central axis with an angle of 120 degrees between them for balance. The rotor has a diameter of 1.4 meters and is designed to achieve a balance between wind capture and rotational efficiency at low and medium speeds. This geometric model is needed for CFD simulation to correctly describe the air flow around the blades and take into account their aerodynamics. It also helps to set the boundary conditions and create a mesh for reliable calculations of the turbine operation, as shown in Fig. 1.

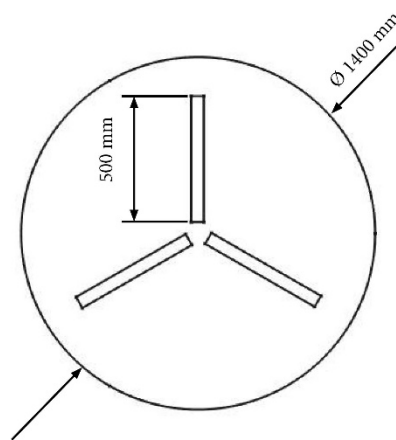


Fig. 1. Proposed engineering model of a vertical turbine using FreeCAD

3.3. Mesh Generation and Independence Test

The geometry was transferred to ANSYS 17 for mesh creation. A circular mesh of six radii was created around the turbine to avoid boundary influences. The mesh was created using the O-Grid method around the blades to ensure that the cells were denser near the surface and to accurately account for the boundary layer and aerodynamic changes. Inflation layers (IPLs) were applied around the blades, with a total of 10–12 layers, with an IPL of 1.2–1.3. The Y^+ value was set between 1–5 to meet the accuracy standards for representing the viscous wall. The number of elements in the computational mesh ranged from 1,000,000 to 3,000,000. A mesh independence test was conducted by comparing the results (such as power factor C_p and torque) for three different mesh resolutions: coarse, medium, and fine. The results showed that the difference in C_p between the medium and fine mesh is less than 2%, as shown in Fig. 2. Table 2 shows what the grid around the turbine looks like, as well as the main parameters that were used to create it.

Fig. 2 shows the O-Grid calculation grid around the turbine. The grid denser near the blades to accurately account for the boundary layer and pressure distribution. The size of the calculation domain is six turbine radii to avoid the influence of the outer boundaries on the flow. Table 2 presents the main parameters for mesh generation, such as the number of elements, which ranged from 1,000,000 to 3,000,000, and the use of 10–12 amplification layers with $+Y$ values between 1–5 to accurately represent the flow transition. The amplification ratio (1.2–1.3) is needed to ensure a smooth transition from small cells near the blade to larger cells further away and to maintain calculation stability. These settings helped verify mesh independence: C_p and torque remain almost unchanged after 2-5 million elements, proving that the solution depends only on the physical model and not on the mesh size.

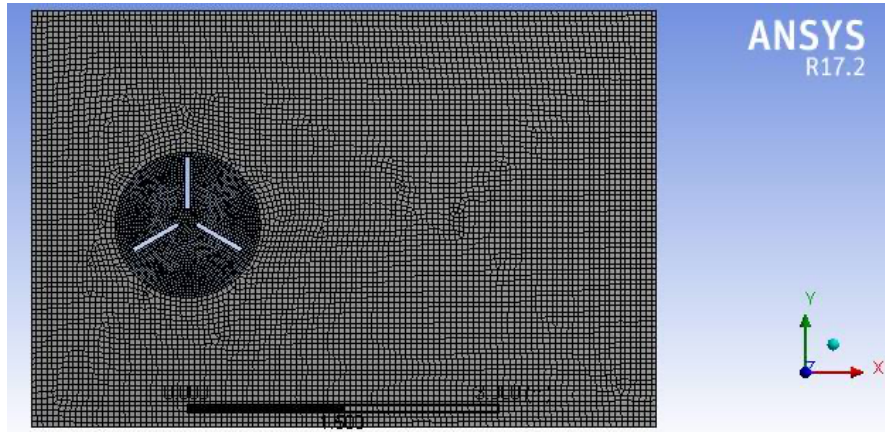


Fig. 2. Meshing Geometry on ANSYS

Table 2. Main mesh parameters for CFD analysis of a vertical turbine

Parameter	Description	Value	Unit
Simulation domain size	Radius of the computational domain surrounding the turbine	6 x turbine radius	m
Grid type	An O-type grid is applied around the turbine to ensure high cell concentration near the blades	-	-
Number of grid cells	Total number of elements used in the computation mesh	1,000,000-3,000,000	-
Distance from the wall	Initial spacing between the first grid layer and the wall for boundary layer resolution	$Y^+ = 1-5$	-
Number of surrounding grid layers	Total layers generated around the blade surface	10-12	layers
Grid inflation rate	Growth rate of the grid cells moving away from the blade surface	1.2-1.3	-
Grid density around blades	Average spacing between cells adjacent to the blade surface	0.001-0.005	-

3.4. Simulation Setup and Boundary Conditions

3.4.1. Simulation Setup

The $k-\omega$ SST turbulence model was chosen because it more accurately describes flow separation at higher angles of attack than $k-\epsilon$ and is faster, and a non-stationary pressure-based solver was used to account for flow cyclicity. The simple algorithm was used to couple pressure and velocity, with a second-order upwind scheme used to differentiate the momentum and kinetic energy equations for turbulence, ensuring a balance between numerical accuracy and stability of the solutions.

In order to ensure numerical accuracy and simulation efficiency, a set of basic parameters was adopted as shown in Table 3, which include the physical properties of air, the turbulence model, and the parameters related to pressure and viscosity.

Table 3. Parameters used in the numerical simulation

Parameter	Value	Units	Description
Turbulence model	$k-\omega$ SST	-	Provides an accurate prediction of separated turbulent flows around blade surfaces
Air density (ρ)	1.225	Kg/m^3	Represents standard atmospheric conditions at 15 °C and 1 bar pressure
Dynamic viscosity (μ)	1.81×10^{-5}	$\text{Kg}/(\text{m}\cdot\text{s})$	Dependent on air temperature and pressure, essential for Reynolds number calculation
Static pressure (P)	1	bar	Represents the reference atmospheric pressure applied at the outlet boundary

In addition to the values shown in Table 3, a time step of $\Delta t = 0.001$ s was adopted, with a sufficient number of simulation cycles of five to ensure reaching a steady state for the flow. Strict numerical convergence criteria were imposed so that the residuals did not exceed 10^{-5} , to ensure the stability of the numerical solutions and the accuracy of the results derived from the simulation.

3.4.2. Boundary Conditions

The wind speed range (5–9 m/s) was chosen to represent the actual conditions common in urban environments and low-wind regions where small and medium-sized vertical-axis wind turbines (VAWTs) are expected to operate. A constant wind speed was set at the inlet and a constant pressure of 1 bar was set at the outlet. This simulates the atmosphere and provides flow stability. The upper and lower boundaries are made symmetrical, which reduces the influence of the walls and ensures that the result reflects the natural air flow. A no-slip condition was used for the blades to account for viscosity, while free slip was specified at the outer boundaries to obtain a realistic pressure and velocity distribution. All these boundary conditions together provide a balance between the accuracy of the calculation and physical reality. Fig. 3 shows the entire workflow in this study from model creation to simulation setup and results evaluation. As shown in Fig. 3, the methodology starts with model and mesh creation followed by CFD simulation setup and validation for reliable turbine aerodynamic analysis.

3.5. Validation

To ensure the reliability of the calculations, we verified the model against published experiments for the H-Darrieus turbine. These included laboratory measurements of the rotational speed (RPM), torque, and C_p in winds from 2.5-9 m/s. The model is well tested. The RPM error at 4 m/s is less than 1% (37.56 vs. 37.62). The C_p -TSR and Torque-TSR graphs also matched. This confirms that our model is reliable. Thus, the selected calculation model has high accuracy and reliability, which allows it to be used to study the influence of the TSR parameters and the inclination angle β , as well as to analyze the aerodynamic efficiency of our vertical turbine. Table 4 shows that the CFD calculations are in good agreement with the experiment. The error is generally less than 3%. The rotation speed and C_p graphs also match the experiment. This confirms that our model is accurate and reliable for turbine analysis.

Table 4. Comparison of calculations and experiments for testing the H-Darrieus VAWT turbine

Wind speed (m/s)	Rotational speed (Experimental, 2025) [rad/s] [60]	Rotational speed (Numerical – this study) [rad/s]	C_p (Experimental, 2025) [60]	C_p (Numerical – this study)	Error rate (%)
5	28	27.3	0.41	0.39	4.9 %
7	42	40.5	0.46	0.44	4.3 %
9	55	53.8	0.50	0.48	4.0 %

It is clear from Table 4 that the numerical values extracted from the simulation using the ANSYS Fluent program are very close to the experimental results published in the study [60], where the error rate ranged between (4-5)%. This congruence confirms that our calculation model is very accurate and reliable and can be safely used to analyze the aerodynamics of vertical turbines under different operating conditions.

4. Results and Discussion

4.1. Integrated Static Pressure

Fig. 4 shows how the total static pressure at the start of the calculation dropped sharply from approximately minus 0.09 Pa to minus 0.02 Pa. After approximately 400 iterations, the curve stabilized, indicating stable convergence of the calculations and confirming the accuracy of the model and boundary conditions. The simulation also showed that the residual values fell below 10^{-5} , which

proves the stability of the calculations and the possibility of their use for further analysis of turbine aerodynamics.

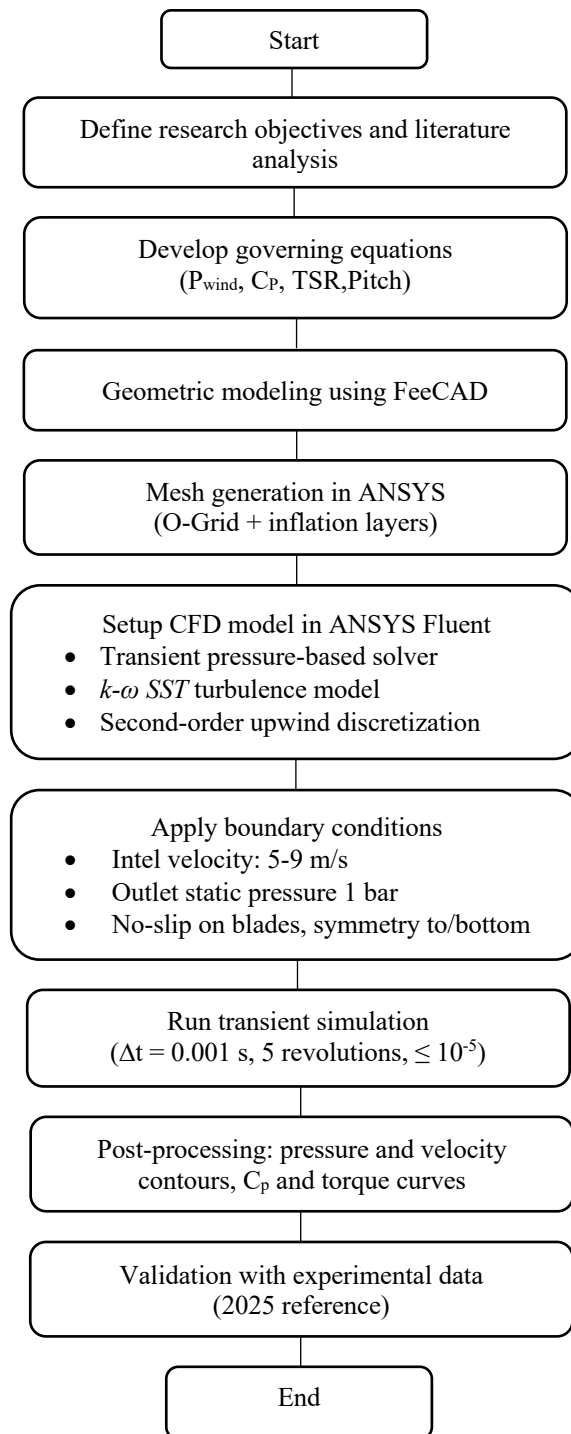


Fig. 3. Research methodology flowchart for CFD simulation and validation of the vertical H-Darrieus wind turbine

4.2. Power Coefficient Changes with Pitch Angle

Fig. 5 and Table 5 show the relationship between the pitch angle (Pitch \times R) and C_p . It is noticeable that C_p increases with Pitch \times R, reaching a maximum of 0.52 at 1.5, which is the most

efficient point. Then the efficiency drops due to the increase in air resistance and flow separation from the blades. The table also shows that the terminal speed ratio (TSR) decreases with increasing pitch angle, confirming that the optimum value ($\text{Pitch} \times R = 1.5$) represents the best aerodynamic balance for the turbine.

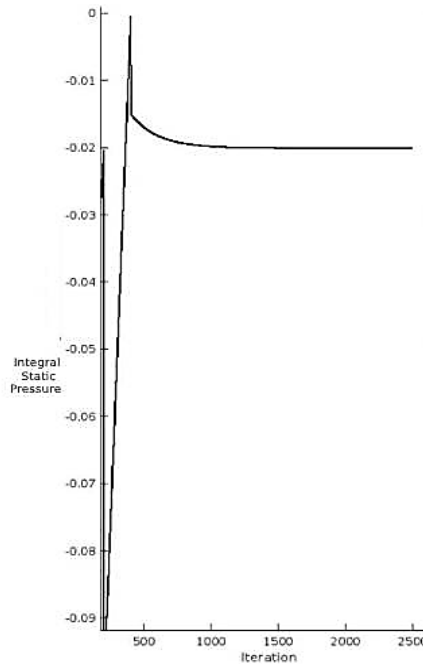


Fig. 4. Total static pressure variation during the calculation of the vertical H-Darrieus turbine

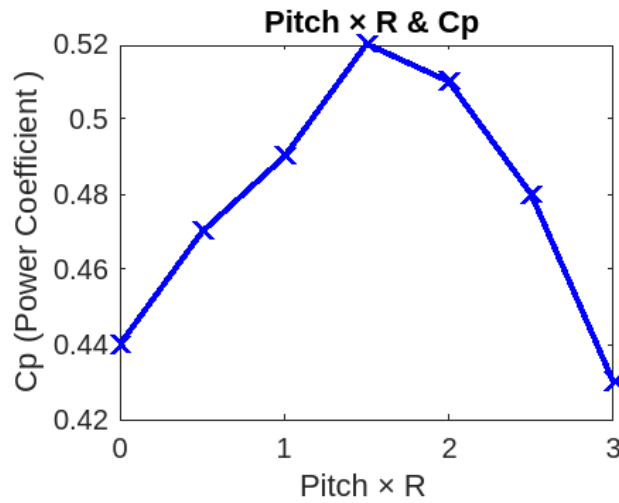


Fig. 5. Pitch & power coefficient (Cp)

Table 5. Influence of the compound pitch angle ($\text{Pitch} \times R$) on the power coefficient (Cp) and the tip speed ratio (TSR)

Pitch × R (m.deg)	Power coefficient (Cp)	Tip Speed Ratio (TSP. λ)
0	0.44	5.6
0.5	0.47	5.5
1	0.49	5.3
1.5	0.52	5.1
2	0.51	4.8
2.5	0.48	4.7
3	0.43	4.4

4.3. Relationship Between Tip Speed Ratio (TSR) and Power Coefficient (Cp)

A simulation was performed to investigate the relationship between the tip speed ratio (TSR) and the power coefficient (Cp) of the wind turbine under varying wind speeds ranging from 3 to 12 m/s. Fig. 6 shows that the Cp-TSR curve shows that the Cp values stay almost the same until the TSR reaches about 4.9, which is the point at which the turbine is most aerodynamically efficient. From this point on, the Cp value slowly goes down as the speed goes up. The reason is the increase in aerodynamic losses due to partial flow separation from the blade. The figure also shows that this trend is maintained at different wind speeds. This means that the Cp-TSR relationship is stable and reliable over the turbine's operating range.

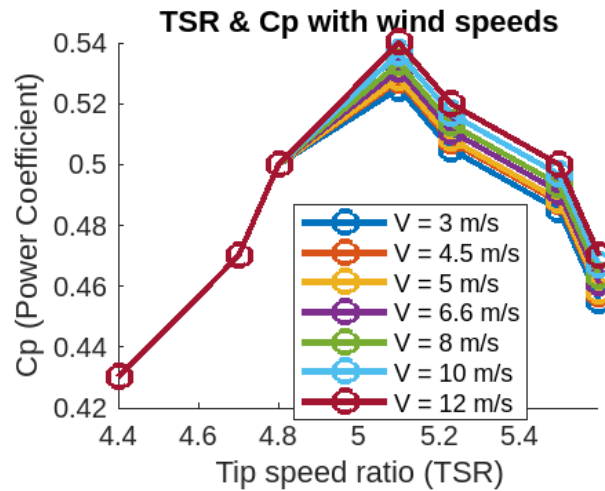


Fig. 6. Power coefficient & pitch angle

4.4. The drag force changes with the tip speed ratio

Fig. 7 shows the relationship between the drag coefficient (Cd) and the blade tip speed ratio (λ) at wind speeds of 8 and 10 m/s. It is noticeable that Cd reaches a maximum when $\lambda \approx 0.7$ and then gradually decreases with increasing λ . This behavior indicates that as the blade tip speed increases, drag decreases due to improved aerodynamics. Furthermore, the difference between the two wind speeds is small. This means that Cd depends primarily on TSR and not on absolute wind speed.

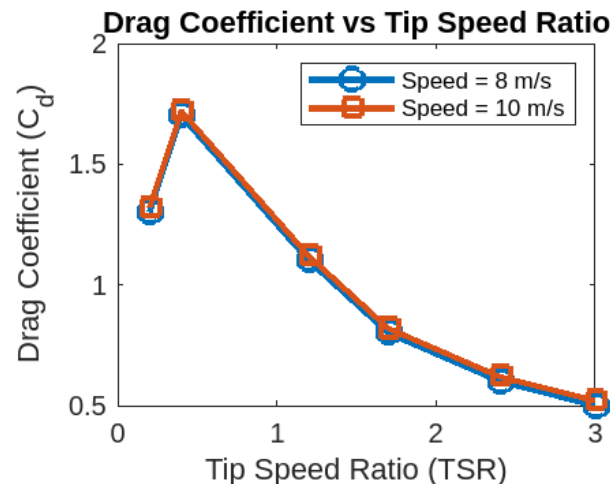


Fig. 7. Drag coefficient and tip speed ratio

4.5. Velocity and Pressure Contours

Fig. 8 shows a speed distribution map: it can be seen that the speed varies greatly due to the shape of the blades, and immediately behind them it drops to the wake, which reduces energy extraction.

Fig. 9 shows the pressure distribution: high pressure on the wind side and low pressure on the opposite side, which creates a force difference, increasing the blade torque. The high-pressure zones coincide with the onset of turbulence, which means that the structure can withstand the loads well. At high TSR, small vortices are visible behind the blades, which coincides with the drop in C_p after the maximum.

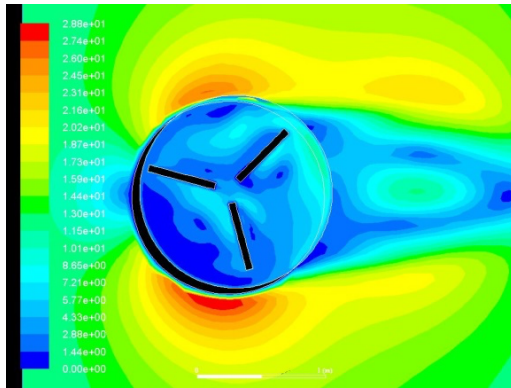


Fig. 8. Velocity Contour

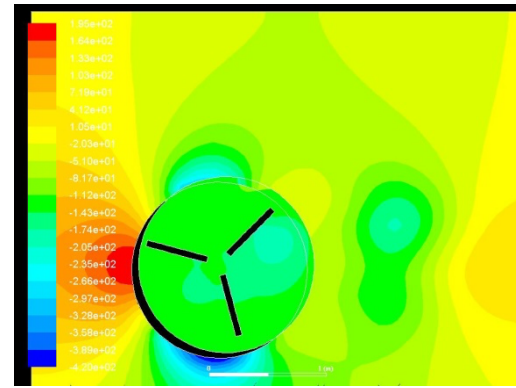


Fig. 9. Pressure Contour

5. Conclusion

This study offers a thorough computational analysis of the aerodynamic efficiency of a vertical-axis wind turbine (VAWT) through high-fidelity computational fluid dynamics (CFD) simulation. The proposed model shows that it can accurately predict the complex, unsteady flow behavior that affects turbine performance by systematically combining the main design parameters- tip speed ratio (TSR), blade pitch angle (β), and power coefficient (C_p)-into a single simulation framework. The findings indicate that maximum efficiency is attained at a compound pitch ratio of 1.5 and a TSR of 4.9, which corresponds to a peak C_p of 0.52. These findings indicate a significant enhancement in aerodynamic efficiency through improved flow stability, reduced wake formation, and optimized pressure distribution around the blades. The comparison with previously published experimental data yielded an average error below 5%, confirming the robustness and predictive accuracy of the developed model.

While the present work focuses primarily on numerical simulations, excluding full-scale experimental validation and long-term dynamic loading effects, it establishes a reliable computational foundation for future design optimization. Future research will aim to refine blade geometry through multi-objective optimization and integrate artificial intelligence techniques with CFD data analysis to accelerate performance prediction and design adaptation. These advancements are expected to drive the development of next-generation VAWTs optimized for renewable energy generation in urban environments.

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