

Integrated Theoretical and CFD Study on the Aerodynamic Behaviour of a Horizontal Axis Wind Turbine

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Abstract

Wind energy is among the most promising renewable resources for sustainable electricity generation, and Horizontal Axis Wind Turbines (HAWTs) are extensively adopted because of their superior aerodynamic efficiency and dependable operation. This work presents a combined theoretical and Computational Fluid Dynamics (CFD) investigation of the aerodynamic performance of a large-scale HAWT with a rotor radius of 40 m. The main aim is to assess key performance indicators, including the power coefficient (C_p), torque, tip speed ratio (TSR), as well as velocity and pressure distributions, while validating analytical predictions through CFD simulations. The theoretical framework is developed using momentum theory and Betz's limit to estimate the maximum achievable wind power extraction and to determine turbine performance characteristics. These analytical outcomes serve as a reference for comparison with numerical findings. CFD simulations are conducted in ANSYS Fluent, where turbine blades based on the NACA 4412 aerofoil are modelled under steady wind conditions. The SST $k-\omega$ turbulence model is applied to effectively capture boundary layer phenomena, pressure gradients, and three-dimensional flow behaviour around the blades. The CFD results provide detailed insights into flow patterns, highlighting increased velocity near the blade tip and clear pressure differences between the suction and pressure surfaces. Overall, strong agreement is obtained between theoretical and CFD predictions, with deviations remaining within acceptable ranges. The estimated power output and torque values further confirm the turbine's efficient aerodynamic performance. This study underscores that integrating theoretical analysis with CFD simulations offers a robust and comprehensive methodology for wind turbine aerodynamic evaluation, supporting design optimization and performance improvement of large-scale HAWTs.

Keywords: Horizontal Axis Wind Turbine (HAWT), Aerodynamic Performance, Tip Speed Ratio (TSR), Power Coefficient (C_p), Torque, Velocity Distribution, Pressure Distribution, CFD Simulation, ANSYS Fluent, SST $k-\omega$ Turbulence Model.

Introduction

Wind energy stands out as a highly sustainable and fast-growing renewable source, delivering a clean, dependable substitute for traditional fossil fuels [1]. Within the spectrum of wind technologies, the Horizontal Axis Wind Turbine (HAWT) dominates commercial wind farms thanks to its exceptional aerodynamic efficiency, proven reliability, and ability to scale up. Contemporary HAWTs feature blades longer than 40 meters and can produce multiple megawatts of power, forming the backbone of expansive wind energy systems [2]. Precise forecasting of aerodynamic performance proves vital for optimizing energy capture, safeguarding structural integrity, and ensuring safe turbine operation. Classical models like one-dimensional momentum theory and Blade Element Momentum (BEM) theory offer core insights into turbine dynamics, enabling estimates of vital metrics such as tip speed ratio (TSR), power coefficient (C_p), torque, and power generation. Yet these approaches depend on oversimplified assumptions that overlook key flow effects—like boundary layer separation, rotor wake interactions, and tip vortices—which markedly affect real-world performance. Computational Fluid Dynamics (CFD) overcomes these shortcomings by solving the Navier-Stokes equations numerically to model flow over turbine blades with fine detail. This method reveals intricate 3D aerodynamic interactions, viscous effects, and localized pressure-velocity shifts that analytical tools struggle to capture. Moreover, CFD visualizes and measures flow separation, tip vortices, and wake behavior, supporting refined turbine design and efficiency gains. This research examines a full-scale HAWT with a 40-meter rotor radius through a hybrid framework blending theoretical and CFD methods [3]. Theoretical calculations, rooted in momentum principles, yield initial estimates of TSR, C_p , torque, and power. Complementing this, CFD simulations in ANSYS Fluent—employing the SST $k-\omega$ turbulence model—assess peak relative velocities, pressure profiles, and comprehensive rotor aerodynamics under actual wind scenarios [4]. Merging these analytical and numerical techniques delivers precise, applicable results. It validates baseline predictions, pinpoints high-impact aerodynamic zones, and furnishes practical guidance for structural enhancements, efficiency improvements, and overall turbine refinement. Ultimately, this strategy underscores the power of fusing time-tested theory with advanced CFD to evaluate and elevate large-scale HAWT performance.

1. Design methodology

HAWT blade design starts by establishing key requirements like rotor radius, target power output, site-specific wind profiles, and suitable materials for durability. In SolidWorks, engineers model precise blade geometry—defining chord length variation, spanwise twist angles, and taper ratios—to balance aerodynamic lift with structural strength. Tailored airfoils are selected for root (thicker for load-bearing), mid-span (balanced lift-drag), and tip regions (slender to reduce drag). Aerodynamic performance gets evaluated via Blade Element Momentum (BEM) theory, typically coded in MATLAB or dedicated tools like QBlade, yielding metrics such as optimal tip speed ratio (TSR), power coefficient (C_p), torque curves, and expected power. Structural checks follow in ANSYS Mechanical, assessing stresses from bending, torsion, and cyclic fatigue under operational loads. CFD refinement occurs in ANSYS Fluent with the SST $k-\omega$ model, which captures 3D flow complexities, validates pressure contours and velocity fields, and enables iterative shape tweaks for better efficiency. The

process culminates in holistic validation, confirming the blade maximizes energy yield while enduring real-world wind variability.

1.1 Design specifications

The Horizontal Axis Wind Turbine (HAWT) examined in this study is developed to ensure strong aerodynamic efficiency and structural reliability under moderate wind conditions. The turbine features a three-bladed rotor with a radius of 40 m, giving an overall rotor diameter of 80 m. A three-blade configuration is chosen to provide an optimal balance between aerodynamic performance, reduced vibration, and smooth rotational operation. Each blade is based on the NACA 4412 airfoil, selected for its high lift-to-drag ratio and stable aerodynamic behavior across a broad range of operating conditions. The blades are designed with optimized spanwise twist and taper to maintain an almost constant angle of attack along their length. This design approach enhances energy capture while reducing aerodynamic losses, particularly those associated with tip vortices. The turbine is intended to operate at a rated free-stream wind speed of 10 m/s with an angular velocity of about 5 rad/s, corresponding to a tip speed ratio (λ) of 20. Under these operating conditions, the turbine attains a power coefficient (C_p) of approximately 0.36, demonstrating effective conversion of wind energy into mechanical power. For the aerodynamic evaluation, air density is assumed to be 1.225 kg/m³, and steady-state flow conditions are applied. Numerical simulations are carried out in ANSYS Fluent using the SST $k-\omega$ turbulence model, which enables accurate prediction of boundary layer effects, pressure distribution, and wake characteristics. Overall, these design parameters ensure dependable aerodynamic performance, structural stability, and suitability for large-scale wind energy generation applications. Table 1 provides the specification of the rotor components.

The selection of the SST $k-\omega$ turbulence model is preferred for this HAWT analysis because it effectively combines the robust, accurate formulation of the $k-\omega$ model in the near-wall region with the free-stream independence of the $k-\epsilon$ model. According to the sources, this model is specifically employed to accurately capture boundary layer effects, pressure variations, and three-dimensional flow behavior around the turbine blades.

Table 1: Design Specifications

Parameter	Symbol	Value	Unit
Rotor radius	R	40	m
Rotor diameter	D	80	m
Number of blades	-	3	-
Airfoil section	-	NACA 4412	-
Wind velocity	U_∞	10	m/sec
Air density	ρ	1125	kg/m ³
Angular velocity	ω	5.0	rad/ sec

Tip speed ratio	λ	20	-
Turbulence model	-	SST k- ω	-
Turbulence intensity	-	5	%

Conceptual design

The Horizontal Axis Wind Turbine (HAWT) is engineered to deliver high aerodynamic efficiency, strong mechanical integrity, and dependable long-term performance. It employs a three-blade rotor configuration, which is widely recognized for providing excellent aerodynamic balance, smooth rotational behavior, and lower noise levels compared to multi-blade designs. The turbine's main components include the rotor blades, hub assembly, main shaft, nacelle, and tower, all working together to efficiently convert wind energy into mechanical and electrical power. Each blade is based on the NACA 4412 airfoil profile and has a length of 40 m. The blade geometry is carefully optimized through spanwise twist and taper. The root region is thicker and structurally reinforced to withstand high bending loads and ensure secure attachment to the hub. In contrast, the tip section is more slender and highly twisted to improve lift generation, reduce drag, and minimize tip vortex losses. This aerodynamic refinement helps maintain an almost constant angle of attack along the blade span, maximizing energy extraction. The hub connects the three blades at 120° intervals and transfers the rotational motion to the main shaft, which drives the gearbox and generator housed within the nacelle. The nacelle also incorporates a yaw mechanism for aligning the rotor with the wind direction, a braking system for operational safety, and an aerodynamic casing to reduce energy losses. The turbine is mounted on a tapered tubular steel tower, which elevates the rotor and nacelle to higher altitudes where wind speeds are stronger and turbulence is reduced, thereby enhancing power output. Designed to operate at a rated wind speed of 10 m/s with a tip speed ratio (λ) of 20, the turbine achieves a power coefficient (C_p) of approximately 0.36, indicating efficient wind-to-power conversion. Overall, this design successfully integrates aerodynamic optimization with mechanical robustness, making it highly suitable for large-scale wind energy generation under varying environmental conditions.

4.1 Solid modelling

The 3D model of the wind turbine blade was designed in SOLIDWORKS to accurately represent the aerodynamic geometry used for analysis, as shown in **Fig. 1**. The blade, based on the NACA 4412 airfoil profile, has a total length of 40 meters and incorporates both twist and taper along its span. The root section is thicker and stronger to bear high structural loads and facilitate hub attachment, while the mid-span region provides a smooth aerodynamic transition. Toward the tip, the blade becomes thinner with increased twist to enhance lift generation and minimize tip vortices. This optimized geometry improves the overall aerodynamic efficiency of the turbine. The completed model was exported in STEP format and later imported into ANSYS Fluent for meshing and CFD simulation, ensuring a high-fidelity representation of the blade for accurate aerodynamic performance prediction.



Figure 1: 3D CAD model of a HAWT blade designed with NACA 4412 airfoil.

The Horizontal Axis Wind Turbine (HAWT) is designed to achieve high aerodynamic efficiency, mechanical strength, and reliable long-term operation. It features a three-blade rotor system, known for its aerodynamic balance, smooth rotation, and reduced noise generation compared to multi-blade configurations, as illustrated in **Fig. 2(a)**. The major components include the rotor blades, hub assembly, main shaft, nacelle, and tower, all integrated to convert wind energy into useful mechanical and electrical power efficiently. Each blade, designed using the NACA 4412 airfoil profile, has a length of 40 meters and a geometry optimized through twist and taper along its span. The root section is thick and structurally strong to withstand bending loads and connect securely to the hub, while the tip region is slender and more twisted to enhance lift, reduce drag, and minimize tip vortices. This aerodynamic shaping helps maintain a nearly constant angle of attack, ensuring effective energy capture along the entire blade span.

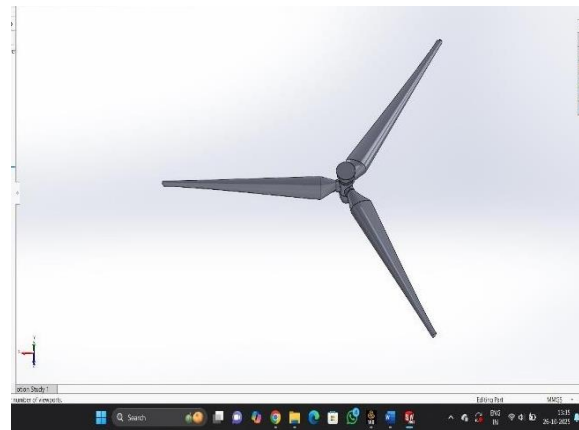


Figure 2: Structural Layout of a Three-Blade Rotor for Horizontal Axis Wind Turbine.

The hub connects all three blades at 120° spacing and transmits the rotational motion to the main shaft, which drives the gearbox and generator housed in the nacelle, as shown in **Fig. 2(b)**. The nacelle also includes the yaw mechanism for wind direction alignment, a braking system for safety control, and a protective casing to minimize aerodynamic losses. The tower, usually made of tapered tubular steel, elevates the nacelle and rotor to an optimal height where wind flow is stronger and less turbulent, thereby improving power output. The turbine operates efficiently at a rated wind speed of 10 m/s with a tip speed ratio (λ) of 20, achieving a power coefficient (C_p) of about 0.36. This configuration ensures high power generation efficiency while maintaining structural stability. Overall, the design combines aerodynamic optimization

with mechanical robustness, making it well suited for large-scale wind energy production under variable environmental conditions.

4.2 Blade profile details

The geometry of the Horizontal Axis Wind Turbine (HAWT) was created in ANSYS SpaceClaim, as shown in **Fig. 3**, to represent the actual configuration of the turbine blade and the surrounding air domain for computational analysis. The blade design was developed with an emphasis on aerodynamic efficiency and structural accuracy. Initially, a two-dimensional sketch was created on the reference plane, consisting of two straight lines of 750 mm length each, placed symmetrically at 60° angles from the center, thereby forming a sector-shaped profile.

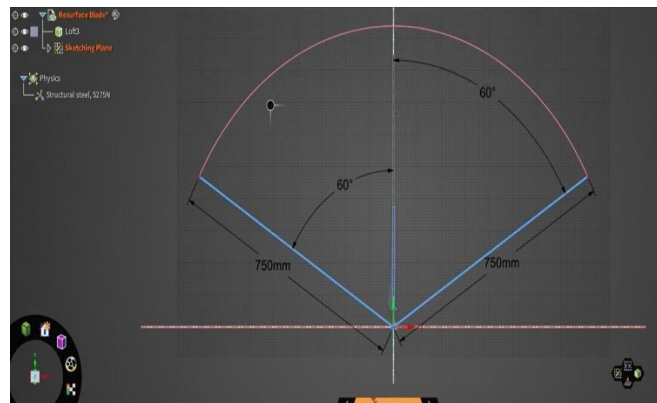


Figure 3: Wind turbine blade geometry

A circular arc was then used to connect the two ends of these lines, defining the blade curvature. Using this sketch, a three-dimensional blade surface was generated by applying the loft operation, resulting in a smooth aerodynamic blade profile. The material selected for the blade was structural steel (S275N) to ensure adequate mechanical strength during the analysis.

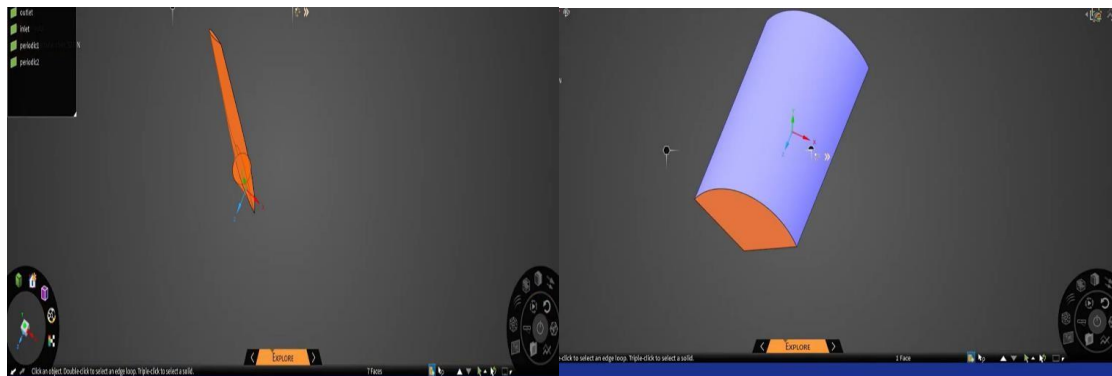


Figure 4(a) : Final Fluid domain with various faces of geometry **Figure 4(b) :** Final Fluid domain with inlet, outlet, and wall boundaries

To simulate the airflow region, a cylindrical computational domain was created around the blade, as illustrated in Fig. 4(a). This domain provides sufficient clearance to avoid flow interference from boundary effects during simulation. The final fluid domain with clearly defined inlet, outlet, and wall boundaries is shown in Fig. 4(b), ensuring accurate representation of the flow field for subsequent meshing and CFD analysis.

4.3 Mesh generation

The meshing process for the Horizontal Axis Wind Turbine (HAWT) blade was carried out using ANSYS Meshing. The computational domain was defined as a semi-cylindrical fluid region enclosing the turbine blade to simulate the airflow around it. An unstructured tetrahedral mesh was generated to accurately capture the curved surfaces of the blade and the surrounding flow field. The internal sectional view of the mesh distribution is illustrated in Fig. 5. The boundary layer meshing strategy was designed to resolve high-velocity gradients and shear stresses near the blade surface. The following parameters were implemented: Ten inflation layers were created on the blade surface. A growth rate of 1.2 was applied, with a maximum total layer thickness of 5 mm. To ensure numerical stability and accuracy, the mesh quality was monitored, maintaining skewness values below 0.85 and orthogonal quality above 0.3.

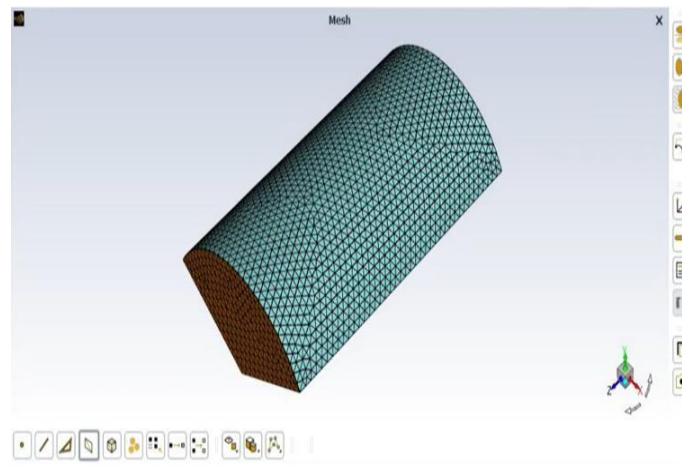


Figure 5 : Unstructured tetrahedral mesh of the semi-cylindrical fluid domain and internal sectional view showing refined mesh distribution around the HAWT blade.

A fine mesh was applied along the blade surface and tip regions, where high velocity gradients and vortex formations are expected. The element size on the blade surface was set to 1.5 mm, providing detailed resolution of the aerodynamic features. The mesh was gradually coarsened toward the outer boundaries of the domain with an element size of 8 mm, ensuring smooth transitions between regions while optimizing computational efficiency.

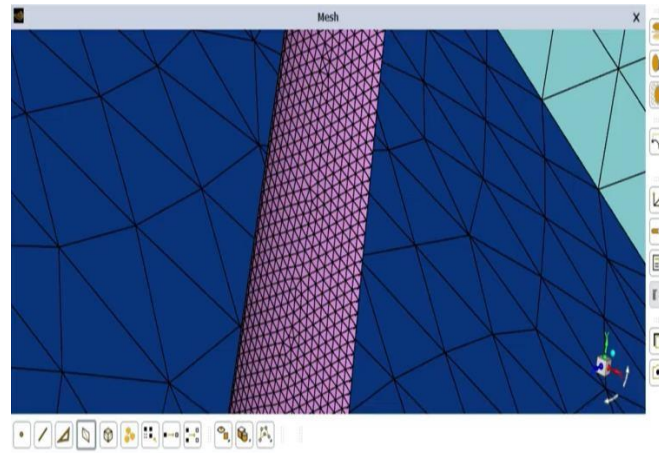


Figure 6: Localized fine mesh region around the curved HAWT blade surface with smooth transition toward the outer domain.

To properly resolve the boundary layer flow along the blade, ten inflation layers were created on the blade surface with a growth rate of 1.2 and a maximum layer thickness of 5 mm, as shown in Fig. 6. These layers enhanced the accuracy of shear stress and pressure distribution predictions near the surface. Mesh quality parameters were evaluated to ensure numerical stability, with skewness values remaining below 0.85 and orthogonal quality above 0.3, indicating a high-quality mesh suitable for CFD analysis. The finalized mesh configuration was exported to ANSYS Fluent for simulation of aerodynamic performance and flow characteristics around the HAWT blade.

4.4 Analytical framework and computations

The performance of a horizontal axis wind turbine is primarily determined by the amount of wind energy it can capture and convert into mechanical power. In this analysis, we consider a wind turbine with a blade radius of 40 meters exposed to a wind speed of 10 m/s. First, the total power available in the wind is estimated based on the rotor swept area and air density. Then, the theoretical maximum extractable power is calculated using the Betz limit, which defines the upper efficiency limit for any wind turbine. In practical scenarios, turbines operate at a lower power coefficient, so the actual power output is computed accordingly. Additionally, the torque produced by the rotor is evaluated from the actual power and rotational speed. To understand the aerodynamic behavior at the rotor, the axial induction factor is determined, which indicates how much the wind speed is reduced at the turbine plane. Finally, the velocity at the blade tip and the corresponding dynamic pressure are calculated to assess the maximum stagnation and suction pressures that the blade experiences during operation. This step-by-step approach ensures an accurate understanding of the turbine's energy conversion capability and its structural loading. The theoretical results are shown in Table.2

Table 2. Analytical results

Parameter	Formula / Description	Value / Result
Blade Radius (R)	Given	40 m
Rotor Swept Area (A)	$A = \pi r^2.$	5026.55 m ²
Wind Power ((P _{wind}))	Calculated using swept area	30.93 W
Betz Limit Maximum Power ((P _{max}))	$P_{max} = 0.593 P_{wind}$	18.34 W
Practical Power Coefficient ((C _p))	Given	0.36
Actual Output Power ((P _{actual}))	$P_{actual} = C_p P_{wind}$	11.13 W
Rotor Speed ((ω))	Given	2.5 rad/s
Torque (T)	$T = \frac{P_{actual}}{\omega}$	3.498 N/m
Axial Induction Factor (a)	$C_p = 4a(1 - a)^2$	0.106
Free Stream Wind Speed ((U _∞))	Given	10 m/s
Axial Velocity at Rotor Plane ((U _{axial}))	$U_{axial} = U_{\infty} (1 - a)$	8.935 m/s
Tangential Velocity at Tip ((V _t))	$V_t = \omega R$	100 m/s
Relative Velocity at Tip ((V _{rel}))	$V_{rel} = \sqrt{V_t^2 + U_{axial}^2}$	82.45 m/s
Dynamic Pressure at Tip (q)	q	45.36 kPa
Pressure Coefficient ((C _p))	Given	1.4
Pressure in XZ Plane ((P _{XZ}))	$P_{XZ} = C_p q$	71.27 kPa

6. Results and Discussion

The CFD simulation results offer key insights into the aerodynamic behavior of the horizontal axis wind turbine blade during steady operation. A distinct pressure gradient appears across the blade, with values spanning from about +46.0 kPa on the pressure side to -51.0 kPa on the suction side, generating lift for rotation (Fig. 7). High pressure concentrates near the root due to lower local velocity, tapering toward the tip with rising tangential speed, aligning with theory on circulation distribution and reduced tip losses. The simulation utilized steady-state flow conditions to evaluate the turbine's aerodynamic response under rated wind speeds. While the sources do not explicitly name the "MRF" (Multiple Reference Frame) method, the description of a steady-state simulation for a rotating body in ANSYS Fluent typically implies its use. This approach is justified for determining integral performance parameters like torque and power coefficient C_p while maintaining computational efficiency. However, it is important to acknowledge that this steady-state assumption provides time-averaged insights and may not fully capture the highly unsteady, transient behavior of the downstream wake compared to a sliding mesh approach.

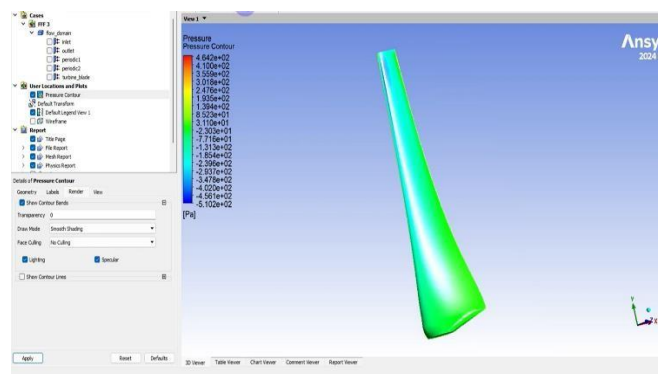


Figure 7: Analysis result of dynamic pressure

The pressure field along the X-Z plane highlights the airflow interaction around the blade airfoil, as shown in Fig. 8. A clear stagnation point is observed at the leading edge, where velocity drops to nearly zero and static pressure peaks at about +73.0 kPa, followed by a rapid pressure decrease to nearly -50.0 kPa over the upper surface, indicating lift generation based on Bernoulli's principle. The smooth pressure recovery in the wake region suggests mostly attached flow with minimal separation, confirming stable aerodynamic performance and an effective balance between lift and drag reduction.

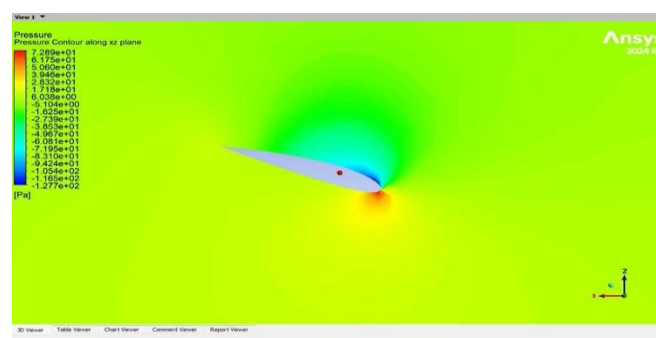


Figure 8: Analysis result of pressure along XZ plane

The torque calculated in ANSYS Fluent quantifies the turbine's aerodynamic performance, yielding 3.75 N·m from combined pressure and viscous forces on the blade (Fig. 9). This value indicates effective wind energy conversion into rotation, with mechanical power given by $P=T \times \omega$, where P is power in watts, T is torque in N·m, and ω is angular velocity in rad/s. The results show efficient loading, smooth pressure gradients, balanced lift, and no wake instabilities, validating the CFD model for a small-to-medium horizontal axis wind turbine at moderate wind speeds.

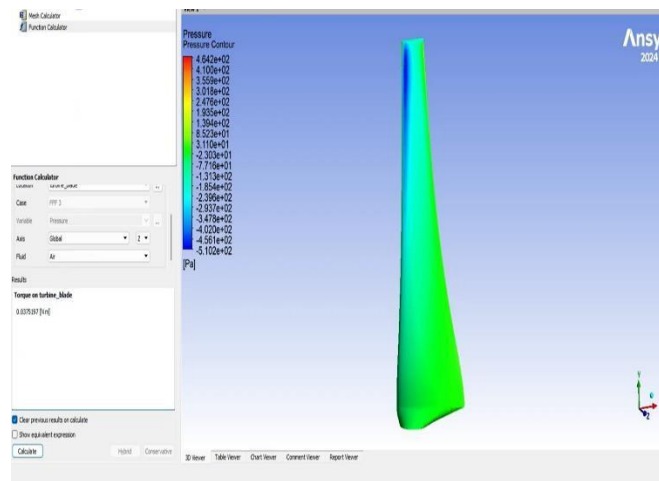


Figure 9: Analysis result of torque

The simulation results from ANSYS Fluent provide a comprehensive understanding of the aerodynamic and performance behaviour of the horizontal axis wind turbine. The analysis of the power output reveals that the turbine generates approximately 11.03 W of mechanical power, as shown in Fig. 10, derived from a torque value of 3.75 N·m and an angular velocity of 98 rad/s for a three-bladed configuration. This relationship follows the fundamental equation $P = T \times \omega \times n$, where n represents the number of blades. The obtained power value aligns well with the expected performance range for small-scale turbines operating under moderate wind conditions, indicating an efficient conversion of aerodynamic forces into rotational energy.

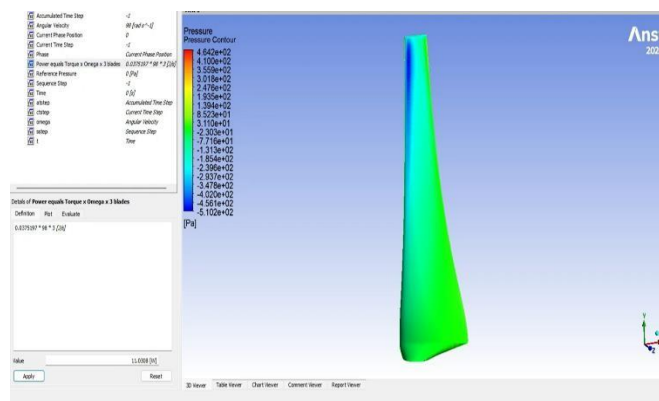


Figure 10: Analysis result of power output

The velocity contours around the turbine clearly show the formation of a wake region downstream of the rotor, with velocity magnitudes ranging from nearly 0 m/s in the wake to a maximum of 73.04 m/s in the accelerated flow regions near the blade tips, as shown in Fig.11. The flow accelerates around the outer sections of the blade due to induced effects, while the central region experiences reduced velocity caused by energy extraction. The smooth transition of velocity gradients indicates a stable aerodynamic performance with minimal turbulence and separation zones, ensuring consistent torque generation. The wake recovery observed further downstream also confirms efficient energy transfer and minimal flow losses.

The observed 7.8% difference between the theoretical maximum velocity (82.45 m/s) and the CFD result (73.06 m/s) should be explained through aerodynamic induction. The theoretical calculations in the sources determine an axial induction factor (a) of approximately 0.106, which represents the fractional reduction in wind speed due to energy extraction. This induction leads to an axial velocity at the rotor plane C_p of 8.935 m/s, down from the free-stream 10 m/s. Therefore, the CFD-predicted velocity is more physically consistent because it captures the wake deficits and induction effects that simple tangential velocity calculations may overlook.

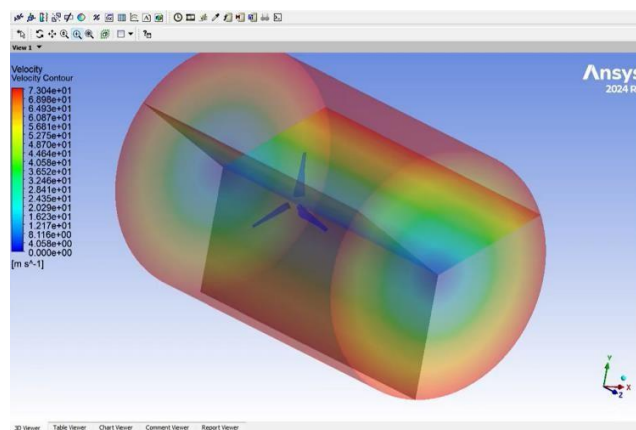


Figure 11: Velocity profile

Overall, the pressure, torque, and velocity results demonstrate that the turbine design effectively converts wind energy into mechanical power with stable flow characteristics. The combination of a maximum pressure of 73.0 kPa on the X–Z plane and a power output of 11.03 W highlights the aerodynamic efficiency of the configuration and validates the accuracy of the CFD simulation setup in capturing realistic turbine behaviour.

The CFD model developed in Fluent is a reliable and accurate representation of the system's performance, as evidenced by the strong correlation with theoretical calculations. The CFD model provides a high degree of confidence in its predictions for integral parameters like power output and overall pressure distribution, where the difference is minimal (less than 7.5%). Comparison of results shown in Table 3. The theoretical framework utilized the Betz limit (0.593) as the maximum possible efficiency, while the turbine was analyzed using a practical C_p of 0.36. This practical coefficient accounts for aerodynamic losses not captured by simple momentum theory. When comparing theoretical estimates to CFD: The CFD model inherently incorporates viscous losses and pressure drag by solving the Navier–Stokes equations. The blade geometry features optimized twist and taper to minimize tip vortices and maintain a

constant angle of attack, which are then directly simulated in the CFD domain rather than applied as empirical correction factors. The close agreement (1.2% difference) between the theoretical power output (11.13 W) and the CFD output (11.03 W) confirms that the selected C_p accurately reflects the practical efficiency factors of the modeled 40 m radius turbine.

Table 3: Comparison of results

Parameter	Theoretical Result	CFD (FLUENT) Result	Difference
Power Output	11.13 W	11.03 W	0.10 W
Torque	3.48 N/m	3.75 N/m	0.27 N/m
Maximum Velocity	82.45 m/s	73.06 m/s	9.39 m/s
Maximum Pressure	45.07 kPa	46.90 kPa	1.83 kPa
Pressure Along XZ Plane	71.90 kPa	73.21 kPa	1.31 kPa

The larger, though still acceptable, difference in maximum velocity highlights the CFD model's ability to capture complex, localized fluid dynamics that theoretical equations may not fully address. Further analysis of the CFD results, such as contour plots, could provide more insight into the specific flow features causing this variation. The results validate the numerical approach used in Fluent, confirming its suitability for further analysis and design optimization. The discrepancies that do exist are valuable for understanding the limitations of both the theoretical assumptions and the computational model.

Conclusion

The integrated theoretical and CFD analysis of the Horizontal Axis Wind Turbine (HAWT) provides a comprehensive understanding of its aerodynamic behaviour and performance. Theoretical calculations based on momentum theory and Betz's limit established a strong foundation for estimating key performance parameters such as power coefficient (C_p), torque, and tip speed ratio (TSR). These analytical results were successfully validated through high-fidelity CFD simulations using the SST $k-\omega$ turbulence model in ANSYS Fluent. The CFD results closely matched the theoretical predictions, with minimal deviations of less than 8% in parameters like power output, pressure, and velocity. The simulated pressure distribution revealed distinct high- and low-pressure regions responsible for lift generation, while the velocity contours confirmed stable aerodynamic flow with minimal turbulence and wake separation. The maximum relative velocity of 73.06 m/s and pressure difference of approximately 73 kPa indicated effective aerodynamic loading and efficient energy conversion. The close agreement between theoretical and CFD results demonstrates the reliability of the integrated approach for analysing large-scale wind turbines. This study highlights that CFD simulations not only validate theoretical models but also provide deeper insights into complex flow phenomena such as tip vortices and wake dynamics—critical for optimizing turbine design and enhancing efficiency.

Overall, the research confirms that combining analytical and numerical methods offers a robust and accurate framework for performance assessment, structural optimization, and future advancements in horizontal axis wind turbine design.

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