

Research Article

Performance Analysis of Different Blade Profiles of Vertical Axis Wind Turbines Using Ansys CFDShivangi Gupta^{1,*}, Daksh Mathur² and Naveen Solanki³^{1,2}Student, Department of Mechanical Engineering, Maharaja Agrasen Institute of Technology, New Delhi-110086, India³ Assistant Professor, Department of Mechanical Engineering, Maharaja Agrasen Institute of Technology, New Delhi-110086, India*Corresponding Author: Shivangi Gupta. Email: shivangig036@gmail.com

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Abstract: This study investigates the performance of Vertical Axis Wind Turbines (VAWTs) with an emphasis on blade geometry optimization to enhance torque output. Computational Fluid Dynamics (CFD) simulations performed using ANSYS, analyzed three blade designs: helical, curved, and straight (H-rotor). Harnessing urban wind energy through Vertical Axis Wind Turbines (VAWTs) offers a sustainable solution to meet energy needs in dense urban environments. This study evaluates the performance of three VAWT blade geometries helical, curved, and H-rotor under varying wind speeds and rotational velocities, with a focus on torque generation. Results highlight the helical blade as the most efficient design, delivering an average torque of 7.89 Nm at high wind speeds of 15 m/s and a blade velocity of 200 RPM. This significantly outperformed the curved blade, which averaged 2.03 Nm, and the H-rotor blade, which generated only 1.17 Nm. While the curved blade exhibited negative torque during startup, leading to delays in energy generation, and the H-rotor blade consistently delivered the lowest torque, the helical blade's minimal torque fluctuation ensured steady operation even in turbulent urban wind conditions. This stability and superior torque output position the helical blade as a highly efficient solution for urban wind energy systems. These advancements will pave the way for more efficient, reliable, and sustainable urban wind energy solutions, contributing significantly to the transition toward greener cities

Keywords: Vertical Axis Wind Turbines, Blade Curvature, Solidworks, ANSYS, CFD Analysis.

1.Introduction

The world's push for sustainable and renewable energy has made wind power a crucial player in reducing dependence on fossil fuels and combating climate change. As one of the leading forms of renewable energy, wind power converts the air's kinetic energy into electricity without polluting air or water, and without needing cooling systems. Vertical Axis Wind Turbines (VAWTs), thanks to their compact and adaptable design, offer an exciting solution for capturing wind energy, especially in urban areas or tight spaces.

Over the last 20 years, wind energy has experienced remarkable global growth, primarily due to advancements in Horizontal Axis Wind Turbine (HAWT) technology, which remains the industry leader. However, the need to harness wind energy in diverse environments has sparked interest in alternative turbine designs. Notable examples include turbines built for deep-water offshore locations using floating foundations and urban turbines integrated into buildings, like rooftop installations [1][2].

Vertical Axis Wind Turbines (VAWTs) represent an innovative approach to wind energy conversion, offering an alternative to the widely used Horizontal Axis Wind Turbines (HAWTs). Unlike HAWTs, which rely on wind alignment for optimal performance, VAWTs can operate



efficiently regardless of wind direction. This insensitivity to yaw angle eliminates the need for complex orientation mechanisms, making VAWTs particularly well-suited for urban and offshore applications where wind patterns are unpredictable.

VAWTs offer several advantages over HAWTs, including lower noise levels due to their reduced tip speed ratios and the potential for ground-level placement of heavy mechanical and electrical components, simplifying maintenance. Additionally, their compact and versatile designs allow for easier integration into urban environments, such as rooftops, where space is limited. These features make VAWTs an attractive option for harvesting wind energy in novel and challenging settings.

2.Literature Survey

VAWTs are much smaller and simpler in design, typically around 3 meters in height and 1.5 meters in diameter, compared to the large size of HAWTs (over 30 meters high and 20 meters in diameter). VAWTs are broadly classified as the lift type (Darrieus) which operates due to lift forces and drag type (Savonius) which operates due to drag forces [3].

Savonius wind turbine is a drag-based vertical axis wind turbine with the advantages of operational independence on wind direction, simple design, self-starting and stand-alone behaviours. However, the problem with a Savonius rotor is the negative torque generated on the returning blade. Its key performance parameters need to be optimized to reduce this negative torque [3]. Various flow complexities, such as vortices and recirculation zones generated in the region near the blade lead to its poor performance. To reduce or eliminate these flow complexities and thus reduce the negative torque generated in a Savonius rotor, various researchers have performed different studies to optimize the performance parameters and augmentation techniques are also used [4], [5].

The Darrieus turbine is a simple and cost-effective design due to its ease of manufacturing, transportation, and assembly. Its performance is influenced by the number of blades, wind speed, rpm, and starting characteristics. The turbine's coefficient of performance (C_p) typically ranges from 0.25 to 0.35 and is highly dependent on solidity, which can be increased by adding more blades or increasing blade chord length. Higher solidity improves starting torque, as demonstrated by studies showing that three-bladed designs outperform two-bladed ones. Despite these advantages, Darrieus turbines face challenges in urban applications due to poor performance in low and turbulent winds, inability to self-start below 4 m/s, and low rotational speeds, which require larger generators and result in higher cogging torque. Additionally, flow detachment at low Reynolds numbers and high angles of attack reduces lift and torque, further limiting their effectiveness in such environments [6], [7] (See Fig. 1).

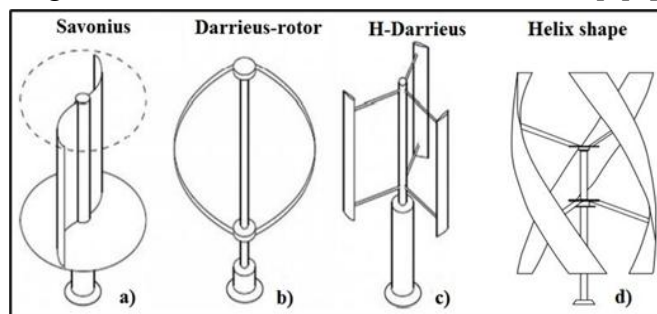


Figure 1: Different kinds of vertical axis wind turbines (VAWT): (a) Savonius curved blade; (b) Darrieus with “egg beater” design rotor; (c) H-shape blades; (d) helix shape blades [8].

2.1 Torque Dependence on Blade geometry

Blade Shape (Airfoil Profile)

- **Airfoil Shape:** The cross-sectional shape of the blades, or airfoil profile, plays a crucial role in generating lift and drag. A well-designed airfoil maximizes lift while minimizing drag, allowing the turbine to extract more energy from the wind. For example, cambered airfoils generally provide higher lift than symmetric ones, which can lead to greater torque.
- **Angle of Attack:** This is the angle between the wind and the chord line of the blade's airfoil. Adjusting the angle of attack influences the lift-to-drag ratio and therefore impacts the torque generated. Too high an angle can lead to stall, reducing torque, while an optimal angle maximizes torque.

Blade Curvature [9], [10]

- **Straight Blades:** The straight blades primarily rely on lift forces generated by the wind, although drag forces also contribute to the overall torque [11].
- **Curved Blades:** Curved blades distribute the centrifugal forces more evenly along the blade, which can reduce stress and enable higher rotational speeds, indirectly influencing torque.
- **Helical Blades:** Some VAWT's use helical blade designs to provide continuous torque during rotation, which smooth out the power output and reduces pulsations in torque.

2.2 CFD analysis and Ansys Software

Computational Fluid Dynamics (CFD) plays a crucial role in analyzing the performance of Vertical Axis Wind Turbines (VAWTs) by simulating airflow and predicting the torque generated by different blade geometries. CFD allows for the detailed study of fluid flow around the turbine blades, providing insights into aerodynamic efficiency, torque generation, and overall performance under varying wind conditions. This method helps optimize turbine design by offering a virtual platform to test different blade shapes and configurations before physical prototyping, thus saving time and resources [12].

ANSYS Fluent and ANSYS are widely used tools in CFD analysis. ANSYS Fluent is powerful simulation software specifically designed to model fluid flow, heat transfer, and related physical processes. It provides advanced capabilities for simulating complex wind turbine dynamics, including the simulation of rotational motion and turbulence effects. The k-omega SST (Shear Stress Transport) model is a widely used turbulence model in Computational Fluid Dynamics (CFD) for simulating fluid flows with high accuracy near walls and in regions of flow separation. It combines the strengths of the k-omega model for capturing near-wall effects and the k-epsilon model for modeling free-stream turbulence. The SST formulation includes a blending function that switches between the two models depending on the flow region [13].

This study evaluates the performance characteristics of three Vertical Axis Wind Turbine (VAWT) designs: helical, curved blade, and H-rotor, highlighting their respective advantages and limitations. Among the designs, the helical turbine demonstrated the highest torque and power output, attributed to its continuously varying blade geometry, which facilitates effective adaptation to fluctuating wind directions. This configuration ensures consistent lift generation throughout the rotation cycle, enhancing energy capture and overall efficiency. The curved blade turbine exhibited moderate torque generation, ranking between the helical and H-rotor designs. However, the torque output of the curved blade design was characterized by fluctuations due to

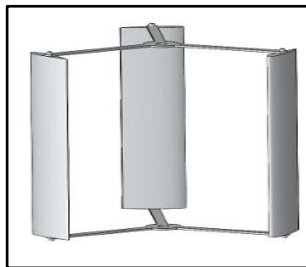
cyclic aerodynamic forces acting on the rotating blades, leading to less stability and a slightly reduced power output compared to the helical turbine. The H-rotor, on the other hand, displayed the most stable torque values, with a consistent performance under varying wind conditions. Its uniform flow pattern and constant blade pitch angle contributed to its stability, though at the expense of lower torque and power output relative to the other designs. These findings underscore the trade-offs inherent in each design, with the helical turbine emerging as optimal for maximizing energy generation, while the H-rotor and curved blade designs may be more appropriate for applications requiring enhanced stability and adaptability [14]

3.Design and simulation methodology

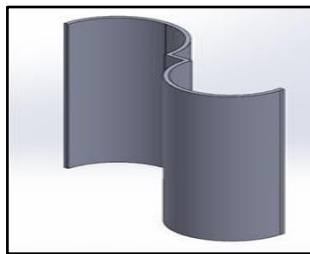
3.1 Software

- SOLIDWORKS 2021 (Student Version) to create 3D models.

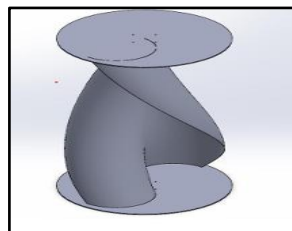
The design of the blade profile began with the creation of a 3D model using SolidWorks, focusing on achieving aerodynamic efficiency and compatibility for simulation purposes. The blade geometry was modeled with a diameter of approximately 0.54 meters and height of 0.8 meters, making it suitable for small-scale Vertical Axis Wind Turbines (VAWTs), see Fig. 2. Once the design was finalized, the CAD model was exported in formats compatible with CFD software, such as STEP, to facilitate meshing and further analysis.



(a)



(b)



(c)

Figure 2: CAD Models of blades (a) H-Rotor (b) Curved (c) Helical

- Ansys 2024 R2 (student version) to perform fluent analysis.

3.2 Simulation setup

The next step involved importing the blade geometry into the CFD preprocessor, ANSYS Design Modeler, to define the simulation domain and boundary conditions. The different parameters of Ansys Fluent are shown in Fig. 3. The flow domain was configured with appropriate inlet and outlet boundaries to replicate realistic urban wind conditions, including

airflow direction and velocity. The blade geometry was assigned as a rotating body within a rotating reference frame, allowing the simulation to accurately represent the turbine's rotational dynamics. A dedicated rotation zone was established to capture the blade's movement relative to the stationary air, which was essential for precise torque calculations [15].

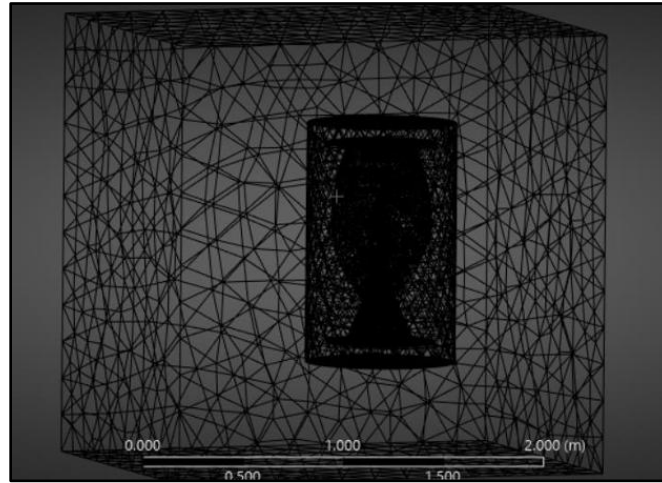


Figure 3: Different parameters of Ansys Fluent

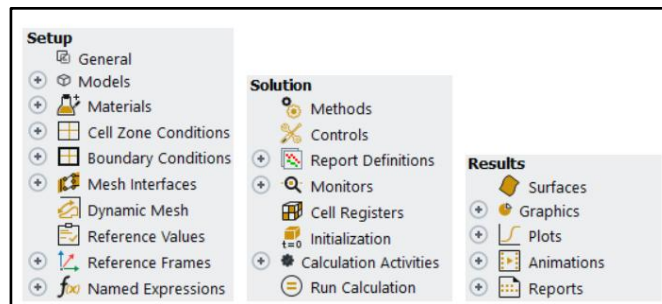


Figure 4: Mesh of Turbine in Ansys Fluent

To ensure accurate simulation results, a computational mesh was generated around the blade profile using ANSYS Fluent. A fine mesh was applied near the blade's surface to capture boundary layer effects critical for torque prediction, while a coarser mesh was used further from the blade to optimize computational efficiency as shown in Fig. 4.

With the mesh complete, the solver parameters and boundary conditions were defined. The fluid properties and turbulence models, such as the k-epsilon models, were selected to suit wind energy applications.



Figure 5: Rotational Velocity of Turbine

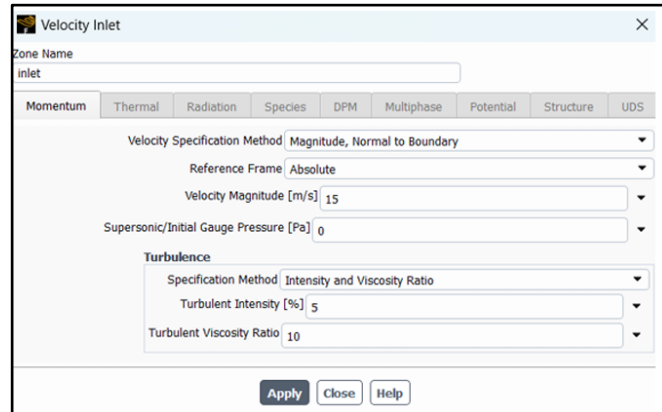


Figure 6: Inlet Boundary Conditions

Angular velocity was specified for the rotating blade ranging from 100–300 RPM, as shown in Fig. 5, to simulate realistic operational speeds, while the inlet boundary conditions were set according to typical urban wind velocity ranges of 5–15 m/s; see Fig. 6.

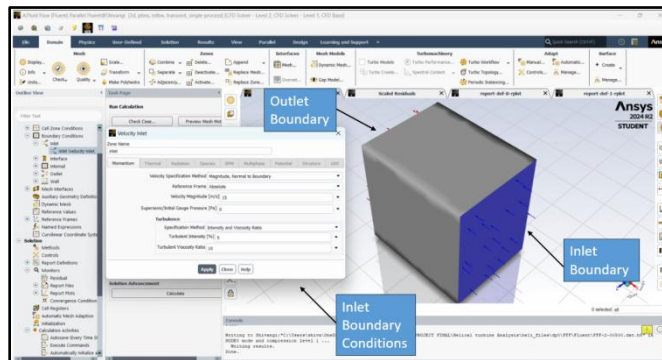


Figure 7: Simulation on Ansys Fluent showing enclosures and Inlet and Outlet boundaries

The simulation was then run to collect torque data over time, providing insights into the turbine's power generation capabilities. Fig. 7 shows the inlet and outlet boundaries of the enclosure defined using the Named selections feature in Fluent Geometry. Report files were set up to log torque output continuously, allowing performance monitoring throughout the simulation (see Table 1).

Table 1: Outputs at each iteration.

A	B	C	E	F	G	H
Time step	Flow time	Torque (200 RPM)		Time step	Flow time	Torque (150 RPM)
1	0.001	9.71989		1	0.001	4.409416942
2	0.002	9.901029		2	0.002	4.223583449
3	0.003	10.48896		3	0.003	4.419740984
4	0.004	10.94154		4	0.004	4.687595597
5	0.005	11.2144		5	0.005	4.844594054
6	0.006	11.37906		6	0.006	4.958047631
7	0.007	11.47208		7	0.007	5.031091099
8	0.008	11.51084		8	0.008	5.090092505
9	0.009000001	11.50603		9	0.009	5.1297146
10	0.01	11.46698		10	0.01	5.152407155

Torque data was recorded until fluctuations stabilized, representing a steady state. Results were saved periodically, and solver settings were adjusted when necessary to achieve convergence.

Finally, the process was repeated for multiple blade profiles, including H-rotor, curved, and helical designs, to compare their performance under identical conditions. Torque outputs for each blade profile were recorded and analyzed and torque vs. time graphs were generated using Fluent post-processing tools; see Section 3. A flowchart of the methodology is represented in Fig. 8.

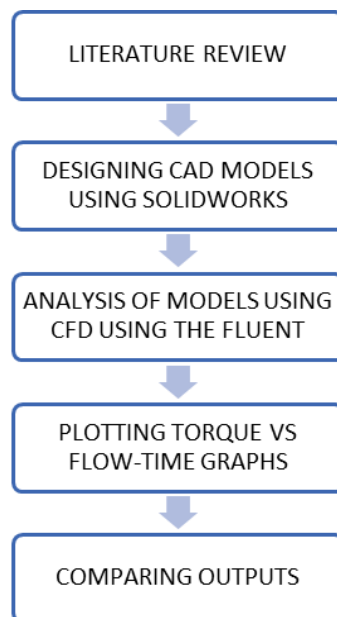


Figure 8:Flowchart for methodology

3.3 Torque Output Estimation

For the ideal maximum power output calculation from wind for a Vertical Axis Wind Turbine (VAWT), the formula is:

$$P_{Wind} = 0.5 \times A \times V^3 \times \rho \quad (1)$$

This formula reflects the theoretical maximum power that can be harnessed from wind, assuming 100% efficiency, which is not practically achievable.

For our analysis we use a predefined value of ω (angular velocity of rotor) in cell zone boundary condition and use the calculated value of Torque (given by Ansys solver) to find the

actual power output as :

$$P_{Actual} = T \times \omega \quad (2)$$

The power coefficient C_p is defined as the ratio of the actual power output P (Actual) of the wind turbine to the theoretical maximum power available in the wind P (Wind) [7]:

$$C_p = \frac{P_{Actual}}{P_{Wind}} \quad (3)$$

4. Results and Discussions

4.1 H-Rotor

The torque generated by the VAWT with a maximum of 5.6 Nm, minimum of 0.0066 Nm with an average value of 1.17 Nm; refer to Fig. 9. This fluctuating behavior is characteristic of VAWT operation due to the unsteady nature of the wind flow and the intermittent blade loading, even under constant wind speed and flow conditions. As the VAWT blades rotate, they encounter varying wind angles and velocities, leading to periodic fluctuations in the aerodynamic forces acting on them (see Table 2).

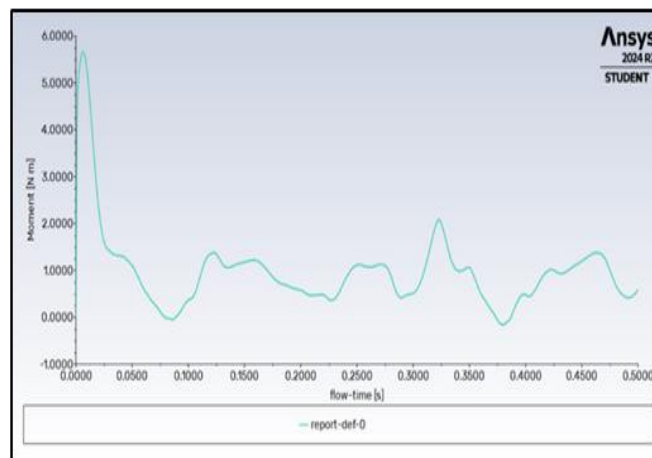


Figure 9: Torque Vs Flow time plot of H- Rotor Turbine at 200 RPM

Table 2: Statistical Values of Torque of H-Rotor calculated by Ansys Solver.

RPM	Max Torque (Nm)	Min Torque (Nm)	Avg. Torque (Nm)
200	5.66	0.0066	1.17

4.2 Curved

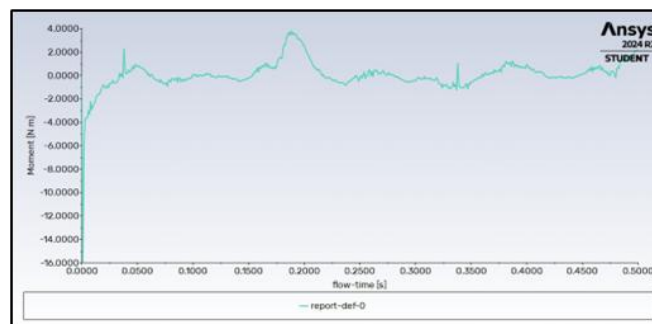


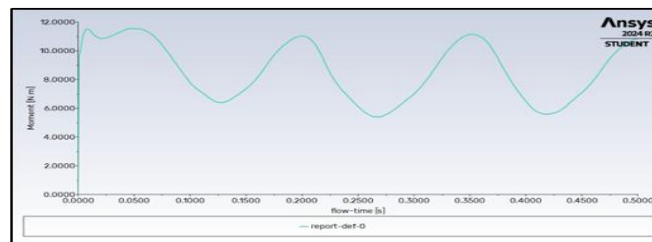
Figure 10: Torque Vs Flow time plot of Curved blade Turbine at 200 RPM

This torque versus flow-time graph shows torque fluctuating over time due to the cyclic aerodynamic forces acting on rotating blades. Initial sharp oscillations indicate the start of blade interaction with airflow, followed by alternating positive and negative torque values, which reflect changing blade positions relative to wind direction (see Fig. 10). Peaks in torque suggest moments of optimal alignment, while negative torque points reveal periods of drag (see Table 3).

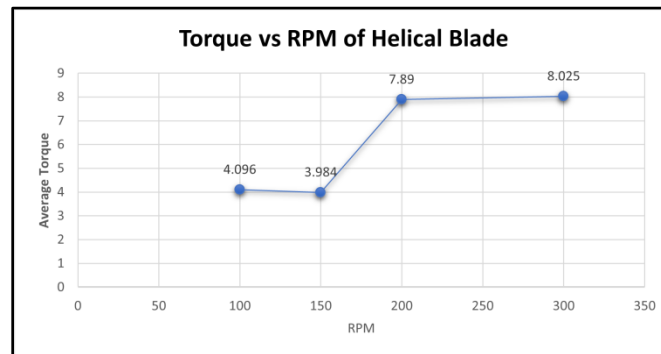
Table 3: Statistical values of Torque of curved blade calculated by Ansys Solver.

RPM	Max Torque (Nm)	Min Torque (Nm)	Avg. Torque (Nm)
200	15.9778	0.034	2.03

4.3 Helical

**Figure 11:** Torque Vs Flow time plot of Helical Turbine at 200 RPM

At the rotational speed of 200 RPM, the helical blade displayed a significant improvement in performance, achieving an average torque of 7.89 Nm; see Fig. 11.

**Figure 12:** Torque vs. RPM for helical blade

The torque versus RPM analysis for the helical blade provides insights into its performance across various rotational speeds. At lower RPM values (100 and 150 RPM), the torque output was relatively low, with values of 4.096 Nm and 3.984 Nm, respectively. This indicates that at lower wind speeds or startup conditions, the helical blade produces less torque, which is consistent with the expected performance for such designs. However, the torque values at these conditions were stable, showcasing minimal fluctuations, which is an advantage in ensuring consistent performance in variable wind environments.

This jump highlights its capability to harness energy efficiently at moderate wind speeds. Further increasing the speed to 300 RPM resulted in a marginal increase in torque to 8.025 Nm, as depicted in Fig. 12 (see Table 4), suggesting that the helical blade reaches near-optimal efficiency at around 200 RPM, with minimal additional gains at higher speeds; see Fig. 13.

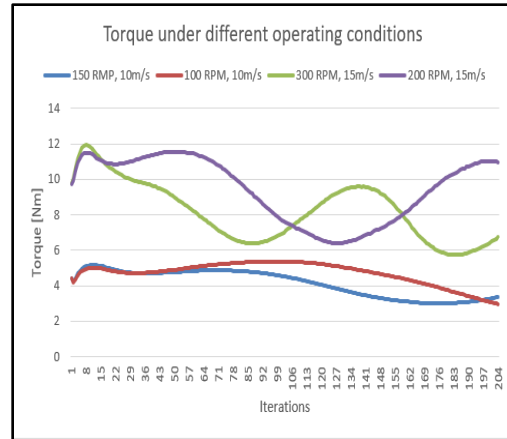
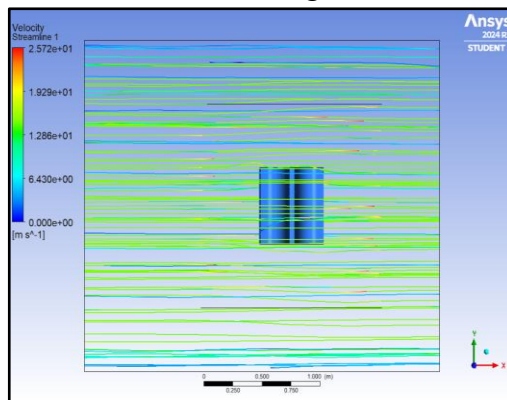


Figure 13: Torque Vs Flow time plot at different operating conditions for helical blade
Table 4: Statistical values of Torque of helical blade at different RPM calculated by Ansys Solver

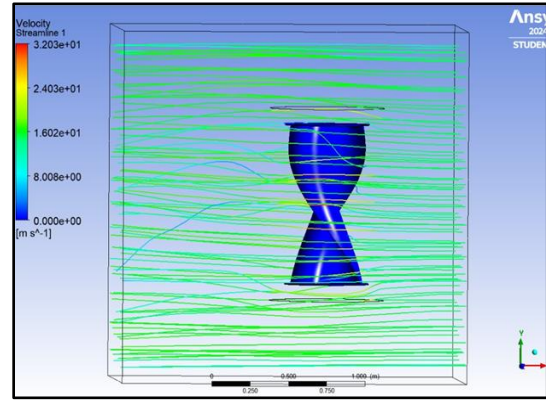
RPM	Max Torque (Nm)	Min Torque (Nm)	Avg. Torque (Nm)
100	5.3586	2.458	4.096
150	5.1685	2.651	3.984
200	11.564	5.82	7.89
300	11.922	5.64	8.025

3.4 Velocity- Streamline plots

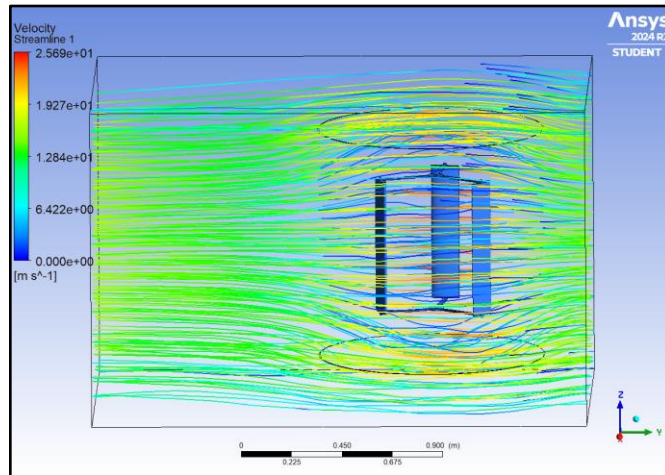
A velocity streamline plot around a Vertical Axis Wind Turbine (VAWT) represents the flow pattern and velocity distribution of the air moving around the turbine. As shown in Figs. 14(a), 14(b), and 14(c), the plots shown by Ansys for the three types of blades being studied, as seen the air around the turbine gets accelerated.



(a)



(b)

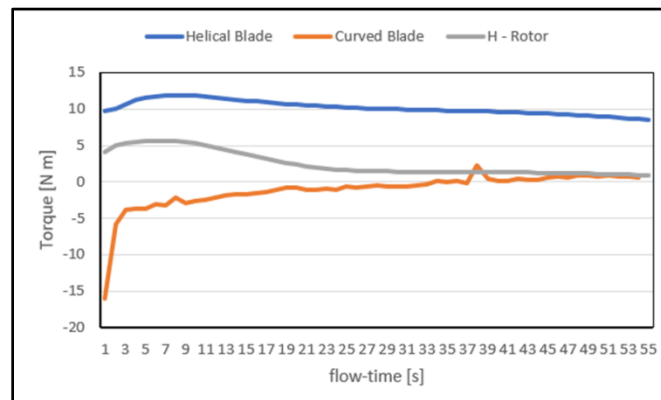


(c)

Figure 14: Velocity streamlines plots for (a) H rotor, (b) Curved and (c) Helical

4.5 Comparing the Outputs

As shown in Fig. 15, the graph compares the torque of three different types of vertical-axis wind turbine blades: helical blade, curved blade, and H-rotor at the same RPM and wind velocity.

**Figure 15:** Comparison of the three blades for same rotational speed and inlet velocity

The helical blade consistently produces the highest torque, peaking at 11.564 Nm and lowest value of 5.82 Nm. At high RPM it creates some fluctuations but produces the highest power, making it the most effective design for steady energy production. In contrast, the curved blade shows an initial negative torque of 15.9778 Nm, indicating potential drag and lower efficiency, especially at startup. The H-rotor provides moderate and stable torque from a peak value of 5.66 Nm stabilizing around 1.17 Nm, making it suitable for balanced performance. Overall, the helical blade appears to be the best choice for high torque and stability, while the H-rotor offers reliable, balanced output.

5. Conclusion

The comparative analysis of helical, curved, and H-rotor blade geometries for Vertical Axis Wind Turbines (VAWTs) has provided valuable insights into their performance, particularly in the context of urban wind energy applications. Among the three geometries, the helical blade emerged as the most suitable choice based on its consistent and superior performance under various operating conditions. At low RPMs and wind speeds, the helical blade demonstrated low torque values of 3.984 Nm (at 150 RPM) and 4.096 Nm (at 100 RPM);

however, the torque was notably less fluctuating, ensuring stable and predictable performance even in variable wind environments. This stability makes it highly advantageous for urban settings, where wind conditions are often turbulent and inconsistent. Under high wind speed conditions, specifically at 15 m/s and blade velocity of 200 RPM, the helical blade outperformed the other designs with an average torque of 7.89 Nm, indicating its capacity to generate significant rotational force efficiently.

In comparison, the curved blade produced an average torque of 2.03 Nm, and the H-rotor blade lagged behind with an average torque of 1.17 Nm. Furthermore, the curved blade displayed a critical drawback: it generated negative torque values during the initial startup phase, potentially causing performance inefficiencies and delays in energy generation. The H-rotor blade, while structurally simpler and easier to manufacture, consistently delivered the lowest torque among the three, limiting its suitability for scenarios demanding high energy output.

The findings underscore that the helical blade's superior torque generation and stable performance make it the optimal choice for VAWT designs tailored for urban environments. Its ability to maintain efficiency across varying wind conditions aligns well with the goals of urban renewable energy solutions. However, to fully harness the potential of VAWTs in real-world applications, further research is recommended, including advanced computational fluid dynamics (CFD) simulations, material optimization, and real-world prototype testing. These efforts will refine blade geometries and improve the integration of VAWTs into urban energy systems.

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