

Aerodynamic analysis of Savonius and 3-bladed Darrieus-type vertical axis wind turbine utilizing NACA0012 and NACA0015 airfoils

Received: 16 December 2025

Accepted: 16 July 2026

Published online: 23 July 2026

Cite this article as: Bagade P., Chaudhari A., Somatkar A. *et al.* Aerodynamic analysis of Savonius and 3-bladed Darrieus-type vertical axis wind turbine utilizing NACA0012 and NACA0015 airfoils. *Sci Rep* (2026). <https://doi.org/10.1038/s41598-026-63045-6>

Pramodkumar Bagade, Ashish Chaudhari, Avinash Somatkar, Masuk Abdullah, Preeti Gaikwad, Atul Kulkarni & József Menyhárt

We are providing an unedited version of this manuscript to give early access to its findings. Before final publication, the manuscript will undergo further editing. Please note there may be errors present which affect the content, and all legal disclaimers apply.

If this paper is publishing under a Transparent Peer Review model then Peer Review reports will publish with the final article.

Aerodynamic Analysis of Savonius and 3-Bladed Darrieus-type Vertical Axis Wind Turbine Utilizing NACA0012 and NACA0015 Airfoils

Pramodkumar Bagade¹, Ashish Chaudhari², Avinash Somatkar^{3*}, Masuk Abdullah^{4*}, Preeti Gaikwad⁵, Atul Kulkarni⁶, József Menyhárt⁴

¹Department of Mechanical Engineering, TSSM's Bhivarabai Sawant College of Engineering & Research, Savitribai Phule Pune University, 411041 Pune, India; pramodbagade@gmail.com (P.B.)

²Department of Mechanical Engineering, JSPM's Jayawantrao Sawant College of Engineering, Savitribai Phule Pune University, 411028 Pune, India; ashishchaudhari11@gmail.com (A.C.)

³Department of Mechanical Engineering, Vishwakarma Institute of Information Technology, Savitribai Phule Pune University, 411048 Pune, India; avinash.somatkar@viit.ac.in (A.S.)

⁴Department of Vehicles Engineering, Faculty of Engineering, University of Debrecen, Ótemető str. 2-4, 4028 Debrecen, Hungary, masuk@eng.unideb.hu (M.A.); jozsef.menyhart@eng.unideb.hu (J.M.)

⁵TSSM's Pamabhooshan Vasantdada Patil Institute of Technology, Savitribai Phule Pune University, 411021 Pune, India; preetibagade10@gmail.com (P.G.)

⁶Department of Mechanical Engineering, Vishwakarma Institute of Technology, Savitribai Phule Pune University, 411048 Pune, India; atul.kulkarni@vit.edu (A.K.)

*corresponding author(s): avinash.somatkar@viit.ac.in (A.S.); masuk@eng.unideb.hu (M.A.)

Abstract: This study investigates the aerodynamic performance of vertical axis wind turbines (VAWTs) operating under low wind-speed conditions representative of inland and urban environments. A combined numerical-experimental approach was adopted, wherein the aerodynamic characteristics of a three-bladed Darrieus-type VAWT employing NACA0012 and NACA0015 airfoils were evaluated numerically, while complementary wind tunnel experiments were conducted on a geometrically accurate Savonius rotor to examine its low-speed performance. The numerical methodology for the Darrieus turbine was first validated against established benchmark studies and subsequently employed to perform transient Computational Fluid Dynamics (CFD) simulations using the sliding-mesh technique in ANSYS Fluent. Simulations covered Reynolds numbers (Re) ranging from 5.3×10^4 to 2.67×10^5 , with a near-wall grid resolution of 10^{-5} m, convergence criterion of 10^{-6} , and appropriate viscous models (laminar and $k-\omega$ SST) selected according to the flow regime. Experimental investigations on the Savonius turbine were carried out in a calibrated subsonic wind tunnel using 3D-printed Polylactic Acid (PLA) models over a Re range of 2.53×10^4 to 1.27×10^5 . The numerical study examined the influence of freestream velocity and tip speed ratio ($2.0 \leq TSR \leq 3.0$) on the lift coefficient, drag coefficient, and aerodynamic torque of the Darrieus turbine. At $TSR = 2.5$ and 6–10 m/s, the NACA0015 airfoil produced 21.9–84.3% higher cycle-averaged aerodynamic torque while reducing the Moment Fluctuation Index (MFI) by 14.8–22.6% compared to the NACA0012 airfoil. The experimental observations on the Savonius rotor further confirm its suitability for low-wind-speed operation and provide practical validation of VAWT performance under realistic conditions. The study highlights the influence of airfoil geometry on Darrieus turbine performance while demonstrating the effectiveness of Savonius rotors for low-speed applications, offering useful design insights for decentralized wind energy systems in regions with limited wind resources.

Keywords: Aerodynamic Performance, Computational Fluid Dynamics (CFD), Low Wind Speed, Tip Speed Ratio (TSR), Vertical Axis Wind Turbine (VAWT)

1. Introduction

1.1 Need for development of VAWTs for Low-Wind Regimes

Wind energy is among the fastest-growing renewable energy sources globally, with cumulative installed capacity surpassing 1TW by 2030 (GWEC, 2023)^{1,2}. The continued expansion is driven by declining

costs, technological advances, and urgent climate-mitigation targets. However, most grid-scale deployment remains dominated by Horizontal Axis Wind Turbines (HAWTs), which require high, steady wind speeds and unobstructed terrain. In contrast, many developing regions experience complex wind profiles characterized by high turbulence and low average speeds. India represents a prime example of such heterogeneity. According to the National Institute of Wind Energy^{3,4}, coastal states such as Gujarat, Tamil Nadu, Karnataka, and Maharashtra exhibit wind speeds above 7 m/s at 100 m height, whereas inland urban and semi-urban regions experience significantly lower wind speeds ranging between 2-6 m/s and higher directional variability. These conditions limit the performance of conventional HAWTs but align well with the operational characteristics of VAWTs. In particular, Savonius-type VAWTs offer omnidirectional operation, high structural robustness (Lee et al.)⁵, low acoustic emissions, lower cut-in speed, and adaptability to geographically constrained or turbulent environments. Nonetheless, Savonius rotors suffer from comparatively low aerodynamic efficiency, strong dynamic stall, and unsteady wake interactions at low Re ($<1 \times 10^5$), which are typical in Indian wind regimes (Kumar et al.)⁶. These challenges necessitate refined geometric design, improved flow control, and systematic performance evaluation across extended tip-speed ratio (TSR) ranges. Additionally, insights on Darrieus type VAWTs are necessary to explore wind energy conversion in such low wind speed terrains. In the present study, these are explored via experimental and numerical approach.

The present study investigates the aerodynamic performance of a three-bladed Darrieus-type vertical axis wind turbine employing NACA0012 and NACA0015 airfoils under low-wind-speed conditions representative of inland and urban environments. Unlike many previous investigations that compare modified airfoils or geometrically dissimilar rotors, the present work performs a controlled numerical comparison by maintaining identical rotor geometry, computational domain, operating conditions, Re range, and tip-speed-ratio range, thereby isolating the influence of airfoil thickness on unsteady aerodynamic characteristics. The numerical methodology is first validated against well-established benchmark airfoil data available in the literature before being applied to the Darrieus rotor simulations. In parallel, complementary wind tunnel experiments conducted on a Savonius rotor provide experimental insight into low-speed VAWT operation and demonstrate the applicability of the experimental facility under similar operating conditions. The study therefore provides a consistent numerical assessment of NACA0012 and NACA0015 Darrieus rotors, supported by experimentally investigated low-speed VAWT behavior, offering useful design guidance for small-scale wind energy systems operating in low-wind regions.

1.2 Problem Statement

Despite increasing interest in VAWTs for decentralized and urban wind energy applications, their technological maturity remains significantly lower than that of HAWTs. Several critical performance limitations hinder their wider adoption. Most VAWTs exhibit poor self-starting characteristics, particularly at low wind speeds (Abul-Ela et al.)⁷, which are common across large parts of India and other developing regions⁸. This limits their ability to generate useful torque without external assistance. VAWTs experience strong cyclic torque variation due to their inherently unsteady aerodynamics and continuous variation in angle of attack during rotation. This results in vibration, mechanical stress, and reduced energy conversion efficiency⁹.

VAWTs, especially drag-based Savonius designs, operate at low Re , where flow separation, dynamic stall, and wake recirculation dominate, causing substantial power losses (Rezaeiha et al., 2017)¹⁰. These unsteady flow mechanisms also increase aerodynamic noise and structural fatigue. Fourth, the performance of VAWTs is highly sensitive to rotor geometry, solidity, blade curvature, and tip-speed

ratio (TSR), yet there is no standardized design methodology applicable across different wind regimes. Most existing studies limit their analysis to narrow TSR ranges or evaluate a single geometry, making it difficult to generalize performance trends.

Furthermore, blockage effects in confined wind-tunnel testing of Savonius turbines introduce additional uncertainties, and the lack of consistent blockage-correction methodologies leads to variability in reported power coefficients. In practical deployment, VAWTs must also contend with high spatial wind variability, turbulence induced by buildings, and fluctuating gust loads, conditions under which conventional models are poorly validated. These challenges collectively limit the efficiency, reliability, and scalability of VAWTs, underscoring the need for systematic, experimentally validated studies spanning multiple geometries, extended TSR ranges, and realistic low-wind operating conditions.

1.3 Literature Review

Recent research on VAWTs has focused on addressing fundamental limitations such as weak self-starting characteristics, strong dependence on low- Re aerodynamics, high torque ripple, and sensitivity to dynamic stall. Several numerical and experimental studies have examined airfoil performance under controlled conditions, but their applicability to small-scale, low-wind VAWTs remains limited.

Wang et al.¹¹ optimized blade geometry using genetic algorithms for $U_\infty = 4\text{--}10$ m/s and chord-based Re s in the range of $1 \times 10^5\text{--}4 \times 10^5$, reporting performance gains for cambered airfoils; however, these improvements were achieved using modified blade sections not suitable for low-cost manufacturing. Bausas et al.¹² conducted wind-tunnel tests on cambered airfoils ($c = 0.06\text{--}0.10$ m) at $Re \approx 3 \times 10^4\text{--}7 \times 10^4$ and concluded that camber improves lift-to-drag ratio at low TSR (<1.5), but these benefits diminished at higher TSRs due to premature stall. Several comparative analyses of NACA airfoils exist in literature. Balduzzi et al.⁹ investigated dynamic stall behavior through unsteady CFD for TSR = 1-3 and highlighted that airfoil performance under cyclic angle of attack (AoA) is dominated by hysteresis effects that cannot be predicted from static lift curves. These unsteady effects are particularly critical in small-scale VAWTs but are often neglected in simplified analytical models. At lower Re ($Re < 6 \times 10^4$), Davari et al.^{13,14} conducted multiple studies comparing NACA0015, NACA4412, and S-series airfoils. They reported that NACA0015 consistently produced the highest peak power coefficient ($C_p = 0.15\text{--}0.33$ depending on Re and TSR), making it favorable for low-wind-speed applications. However, these studies involved either computational optimization, shape modification, or large-scale 43-rotor databases, conditions that differ substantially from small-scale physical prototypes.

Furthermore, many experiments were conducted at higher wind speeds ($U_\infty = 8\text{--}12$ m/s) or with significant blockage ($>20\%$), which affects C_p reporting accuracy and limits comparability. At low Re ($Re \approx 4 \times 10^4$), Davari et al.¹³ demonstrated that NACA0015 delivers the highest peak power coefficient among NACA and Selig profiles and offers favourable self-starting behaviour. These findings further justify its selection as a baseline airfoil for low-wind-speed VAWT applications. A recent optimisation study^{13,14} analysing 43 Darrieus VAWT configurations at a chord-based $Re = 45,192$ demonstrated that NACA0015, NACA4412 and NACA4415 airfoils yielded the highest power coefficients. Using double-multiple stream-tube (DMST) modelling combined with particle swarm optimisation (PSO), the authors identified an optimized NACA0015 geometry that achieved the highest C_p among all candidates. This reinforces the suitability of NACA0015 for low- Re VAWT applications and supports its selection as a baseline airfoil in the present study. A recent low- Re investigation¹⁰ evaluated several symmetric NACA 4-digit, NACA 5-digit and Selig airfoils at chord-based Re s ranging from 17,890 to 53,670. The study concluded that NACA0015 offered the most favourable aerodynamic performance in this regime, with lift coefficients increasing from 0.788 to 0.936 at $Re = 35,780$ and from 0.925 to 1.027 at $Re = 53,670$.

following moderate thickness-chord adjustments. The modified NACA0015 profile also achieved up to 34% and 17.9% improvements in lift-to-drag ratio at $Re = 35,780$ and $Re = 53,670$, respectively, and produced the highest power coefficient across $Re = 1 \times 10^5 - 3 \times 10^5$.

A detailed URANS investigation by Rainbird¹⁵, comparing four widely used VAWT airfoils (DU-06-W200, NACA0015, NACA0018, and S-1046) demonstrated that NACA0015 consistently provided the highest torque and power coefficient over the range of tip-speed ratios analysed. A CFD-based optimisation study (Cao et al.)¹⁶ comparing NACA0015 with four S-series airfoils using the $k-\omega$ SST turbulence model demonstrated that NACA0015 consistently delivered the highest torque and power coefficients across the operating TSR range. Rocha et al.¹⁷ and Barnes et al.¹⁸ has reported calibration and rationale for employing this model for small wind turbines investigations. These findings reinforce NACA0015 as a robust baseline airfoil for lift-type VAWTs and thus motivate its use in the present work. Post-stall behaviour of VAWT airfoils is particularly important because blades experience large angles of attack during each rotation, especially during startup. An investigation on NACA0015 demonstrated that uncertainties in existing post-stall datasets are large enough to influence VAWT torque prediction models, with wind-tunnel blockage identified as a major contributor to discrepancies¹⁶.

Recent research on vertical axis wind turbines (VAWTs) emphasizes advanced control, optimization, and material innovation to enhance aerodynamic efficiency and structural adaptability. Adaptive pitch regulation using aerodynamic oscillator models has demonstrated improved dynamic performance under variable winds (Hao et al., 2024)¹⁹, while multi-objective optimization frameworks combining DOE-RSM and MOPSO enable robust hybrid Darrieus configurations (Shen et al., 2024)²⁰. Airfoil-focused numerical optimization further refines performance characteristics (Dutta et al., 2025)²¹, supported by computational design methodologies (Dennis et al., 2022)²². Studies on morphing materials highlight structural adaptability for load mitigation (Riley et al., 2025)²³, building on earlier pitch-adjustment strategies validated for H-type VAWTs (Zhang et al., 2020)²⁴. Table-1 shows the representative summary of relevant representative studies using NACA0012 and NACA0015 airfoils for VAWT Applications in recent past.

Table-1: Recent Studies Using NACA0012 and NACA0015 Airfoils for VAWT Applications.

Study Category & Representative References	Airfoil(s)	Method / Configuration	Operating Conditions Reported	Key Outcomes
High-fidelity aerodynamic characterization Athkuri et al. (2025) ²⁵ ; Guo & Zou (2022) ²⁶	NACA0012, NACA0015	RANS/LES aerodynamic evaluation of airfoils	$Re \approx 4 \times 10^4 - 7 \times 10^5$; AoA 0-180°	CI-Cd datasets for VAWT AoA cycles; validated stall onset; suitable for dynamic analysis
Airfoil comparison studies (steady 2D) Rogowski et al. (2025) ²⁸ ; Berger et al. (2024) ²⁹ ; Umar et al.(2022) ³⁰	NACA0012, NACA6412, NACA2415	2D steady CFD, isolated airfoil comparison	$U_\infty = 5-8$ m/s; $Re \approx 1 \times 10^5 - 10^6$	Quantified lift-drag variation; documented stall and separation differences among airfoils
Micro-scale VAWT studies (low Re)	NACA0015, NACA00-series	Micro-Darrieus/VAWT	$U_\infty = 1-9$ m/s; $Re \approx$	NACA0015 performs well at

Davari et al. ^{13,14} , Sharma et al. (2023) ³¹		experimental + CFD	4×10^4	low Re; improved starting behaviour under micro-scale operation
Optimization and parametric refinement Wang & Zhang (2025) ³² , Gosselin et al.(2016) ³³ ; Kong (2025) ³⁴ ; Bianchini et al.(2014) ³⁵	NACA0012, NACA0015	GA/ANN/Kriging optimization; leading-edge & thickness refinement	$Re \approx 1 \times 10^5$ - 3×10^5 ; TSR ≈ 2 -5	Optimized blade shapes increase C_p by ~ 10 -14%; identified geometry-performance correlations
Dynamic stall & transient modelling Balduzzi et al. (2012) ⁹ ; Athkuri et al. (2025) ²⁵ ; Tavernier et al.(2021) ²⁶	NACA0012	URANS modeling of VAWT dynamic AoA changes	TSR ≈ 2 -4; $Re \approx 10^5$	Captured unsteady loads, vortex shedding, dynamic stall cycles; useful for predicting torque ripple
Start-up enhancement & modified blades Moon et al. (2016) ³⁶ ; Saad et al. (2025) ³⁷	NACA0015 + modified variants	J-blades, embossed blades, twisted profiles	TSR = 0.2-1.6; $Re \approx 10^5$	Enhanced starting torque; reduced cyclic loading; improved flow attachment
Low-Re airfoil behaviour & control Chen et al. (2021) ³⁸ ; Chang et al. (2022) ³⁹	NACA0012/0015 variants	Separation bubble and stall analysis; flow control features	$Re \approx 5 \times 10^4$ - 1×10^5	Identified laminar-turbulent transition, bubble dynamics, and stall characteristics relevant to VAWTs

1.4 Critical Summary and Gap Identification:

While existing research demonstrates performance enhancements under specific conditions, most improvements rely on modified or highly specialized blade geometries, high- Re conditions, or external flow-control devices. Very few studies evaluate simple, manufacturable, constant-thickness rotor designs across multiple geometries using identical dimensions, identical Re range (8×10^4 - 4×10^5), identical wind tunnel conditions, and a unified TSR. Likewise, previous studies do not offer standardized datasets that allow geometry-to-performance comparison under low-wind, low- Re conditions typical of Indian inland and other similar regions globally⁴⁰.

This gap motivates the present work, which systematically analyzes multiple baseline rotor configurations using consistent experimental and CFD frameworks, enabling benchmarking and addressing the performance variability. The studies discussed in previous section and Table-1; collectively demonstrate that NACA0012 and NACA0015 are well-established benchmark airfoils for VAWT aerodynamic research. However, many of the existing work focuses either on isolated airfoil behaviour or on large-scale VAWTs operating at moderate-high Re s. Comparatively fewer investigations examine compact rotors under low inflow velocities (2-10 m/s) and consistent geometric constraints. The

present study provides combined experimental and CFD analysis of multiple rotor configurations using these canonical airfoils in a low- Re operational regime.

1.5 Research Gap

Although numerous investigations have reported performance improvements in vertical-axis wind turbines, most studies focus either on experimentally evaluating drag-type Savonius rotors or numerically analysing lift-type Darrieus turbines under different operating conditions and geometric configurations. Consequently, direct comparison of the aerodynamic influence of airfoil thickness under identical rotor geometry, operating conditions, and computational framework remains limited, particularly for low-wind-speed applications.

The present study addresses this gap through a combined experimental and numerical investigation. Wind tunnel experiments are conducted on a Savonius rotor to characterize the aerodynamic behaviour of drag-type VAWTs under representative low-wind conditions, while the aerodynamic performance of a three-bladed Darrieus turbine employing NACA0012 and NACA0015 airfoils is investigated numerically using a validated transient CFD methodology. The numerical comparison is performed under identical geometric and operating conditions to isolate the influence of airfoil thickness on aerodynamic performance. This complementary approach provides practical experimental insight into low-speed VAWT operation together with a systematic numerical assessment of Darrieus airfoil performance, thereby contributing useful design guidance for decentralized wind energy applications.

1.6 Article Outline

The present manuscript reports investigation specifically to address the performance of VAWTs for low wind speed terrains. The remainder of this manuscript is structured as follows. Section 2 presents the overall methodology adopted in the study, including the experimental setup, wind tunnel testing procedure, fabrication of turbine models, blockage analysis, and the numerical framework used for CFD simulations. Details of the governing equations, boundary conditions, turbulence modeling are provided in this section. Section 3 discusses the numerical and experimental validation of the adopted computational model, including comparison with benchmark Savonius rotor data from the literature to establish confidence in the CFD methodology. Section 4 presents the detailed results and discussion for the three-bladed VAWT configurations employing NACA0012 and NACA0015 airfoils. Section 5 provides a comparative assessment of NACA0012 and NACA0015 airfoils, highlighting differences in torque stability, lift-drag behavior, dynamic stall characteristics, and suitability for low wind-speed operation. Table-2 summarizes all operating conditions investigated, including freestream velocity, TSR range, corresponding Re , and wind-regime classification. This table is provided to enhance clarity, reproducibility, and alignment between the abstract, methodology, and results. Section 6 summarizes the key findings of the study, outlines the practical implications for low-wind and urban VAWT applications, and discusses the limitations of the present work along with directions for future research.

2. Methodology

The aerodynamic performance of various VAWT profiles was thoroughly evaluated using a combination of experimental and computational methods. The experimental study was conducted at PVPIT, Pune, using a calibrated subsonic wind tunnel for both Savonius and Darrieus-type turbines. The results obtained for 2-bladed Savonius turbine are validated with the results of Saha et al.⁴³ in recent study by Bagade et al.^{41,42}. The experimental investigations reported in this study were conducted using a subsonic wind tunnel whose design, operating characteristics, calibration procedures, and measurement

uncertainties have been documented in our earlier peer-reviewed publications^{41,42}. The same wind tunnel configuration, instrumentation, and data acquisition methodology are adopted here without modification. In the present work, wind tunnel experiments were conducted only for drag-type (Savonius) and nature-inspired blade profiles, and the corresponding experimental procedures and validation results have been reported in our earlier studies (Bagade et al.)^{41,42}. These experimentally tested configurations are used here as reference and validation benchmarks. The NACA0012 and NACA0015 blade profiles (for Darrieus type) are investigated exclusively through numerical simulations under low wind speed and low Re conditions representative of the experimental environment. All numerical comparisons between NACA0012 and NACA0015 were performed under identical computational domains, boundary conditions, mesh resolution, turbulence modeling, and tip speed ratio (TSR) ranges, ensuring a consistent and fair comparative assessment.

2.1 Design considerations for Savonius rotor

The dimensions of the Savonius type rotor are based on wind tunnel blockage ratio and experimental constraints. The detailed calculations for different rotors are shown in Table-2.

Table-2: Details of various parameters for experimentation on Savonius rotor.

Parameter	Symbol / Formula	2-Bucket Savonius Rotor	3-Bucket Savonius Rotor	Remarks
Rotor diameter	(D)	0.19 m	0.19 m	
Rotor height	(H)	0.173 m	0.173 m	
Swept area	$A_{\text{swept}} = D \times H$	$0.19 \times 0.173 = 0.03287 \text{ m}^2$	0.03287 m	Used for geometric blockage
Wind tunnel area	A_{tunnel}	$0.30 \times 0.30 = 0.09 \text{ m}^2$	0.09 m ²	
Geometric blockage	$\beta_{\text{geo}} = A_{\text{swept}} / A_{\text{tunnel}}$	$0.03287 / 0.09 = 36.5\%$	36.5%	Visual blockage; overestimates
Blade thickness	(t)	0.002 m	0.002 m	PLA bucket wall
Solid blade area	$A_{\text{solid}} = N(tH)$	$(2(0.002 \times 0.173) = 0.000692 \text{ m}^2)$	$(3(0.002 \times 0.173) = 0.001038 \text{ m}^2)$	Actual obstructing area
Solid blockage	$\beta_{\text{solid}} = A_{\text{solid}} / A_{\text{tunnel}}$	$0.000692/0.09 = 0.77\%$	$0.001038/0.09 = 1.15\%$	True physical blockage
Porosity correction (no overlap)	—	none	None	Zero overlap → no reduction
Wake blockage	Literature Ndindayino et al.(2025) ⁴⁴ Suryanarayana et al. (2021) ⁴⁵ :10-15%	10-15%	10-15%	Savonius wake expands strongly
Effective blockage	$\beta_{\text{eff}} = \beta_{\text{solid}} + \beta_{\text{wake}}$	10.8% - 15.8%	11.15% - 16.15%	Recommended to report as a range
Recommended report value	—	$\approx 13\%$ (representative)	$\approx 14\%$ (representative)	Based on midpoint of wake range

From Table-2, it is noted that the geometric blockage based on rotor swept area is 36.5%. However, the actual physical obstruction is determined by bucket thickness and height, giving a solid blockage of 0.77% for the 2-bucket rotor and 1.15% for the 3-bucket rotor. Wake blockage depends on flow condition and typically ranges between 10-16% for Savonius rotors, as reported in literature. Therefore, the effective blockage lies between 10.8-16.15%.

For a Savonius rotor, the characteristic length is typically taken as the rotor diameter (D), rather than the blade chord. With rotor diameter, $D=0.19$, the corresponding Re range over which the experimentation was carried out is as under

Free-stream Velocity, (V_∞) (m/s)	Reynolds Number (Re_D)
2	2.43×10^4
4	4.87×10^4
6	7.30×10^4
8	9.73×10^4
10	1.22×10^5

2.2 Geometrical Specifications of the Three-Bladed Darrieus Rotor

To ensure complete reproducibility of the numerical investigation, the geometric specifications of the three-bladed Darrieus rotor employed in the CFD simulations are summarized in Table 3. Both NACA0012 and NACA0015 airfoils were analysed using identical rotor dimensions so that the influence of airfoil thickness could be isolated without introducing geometric variations. Apart from the airfoil profile, all geometric and operating parameters remained unchanged throughout the numerical investigation.

Table 3. Geometric Parameters of the Darrieus Rotor

S.N.	Parameter	Value
1	Rotor configuration	Three-straight bladed H-type Darrieus VAWT
2	Airfoil profiles	NACA0012, NACA0015
3	Number of blades, N	3
4	Rotor radius, R	1.25m
5	Rotor diameter, D	2.5m
6	Blade chord length, c	0.42m
7	Rotor height, H	(2D assumption)
8	Blade spacing	Uniform (120° apart)
9	Direction of rotation	Counter-clockwise
10	Computational model	Two-dimensional transient URANS
11	Turbulence model	$k-\omega$ SST
12	Pressure-velocity coupling	SIMPLE
13	Spatial discretization	Second order

A schematic of the Darrieus rotor showing the principal geometric parameters (rotor radius, chord length, blade spacing, and rotor diameter) is presented in Figure 1.

Table-4. Summary of Operating Conditions Investigated in the Present Study (Darrieus rotor).

Case ID	Freestream	Tip Speed Ratio	Chord-based Reynolds	Wind Regime
---------	------------	-----------------	----------------------	-------------

	Velocity, V_∞ (m/s)	(TSR)	Number (Re)	Classification
1	2	2.0 - 3.0	$\approx 5.3 \times 10^4$	Low wind
2	4	2.0 - 3.0	$\approx 1.06 \times 10^5$	Low wind
3	6	2.0 - 3.0	$\approx 1.59 \times 10^5$	Transition (upper bound of low wind)
4	8	2.0 - 3.0	$\approx 2.12 \times 10^5$	Medium wind
5	10	2.0 - 3.0	$\approx 2.65 \times 10^5$	Medium wind

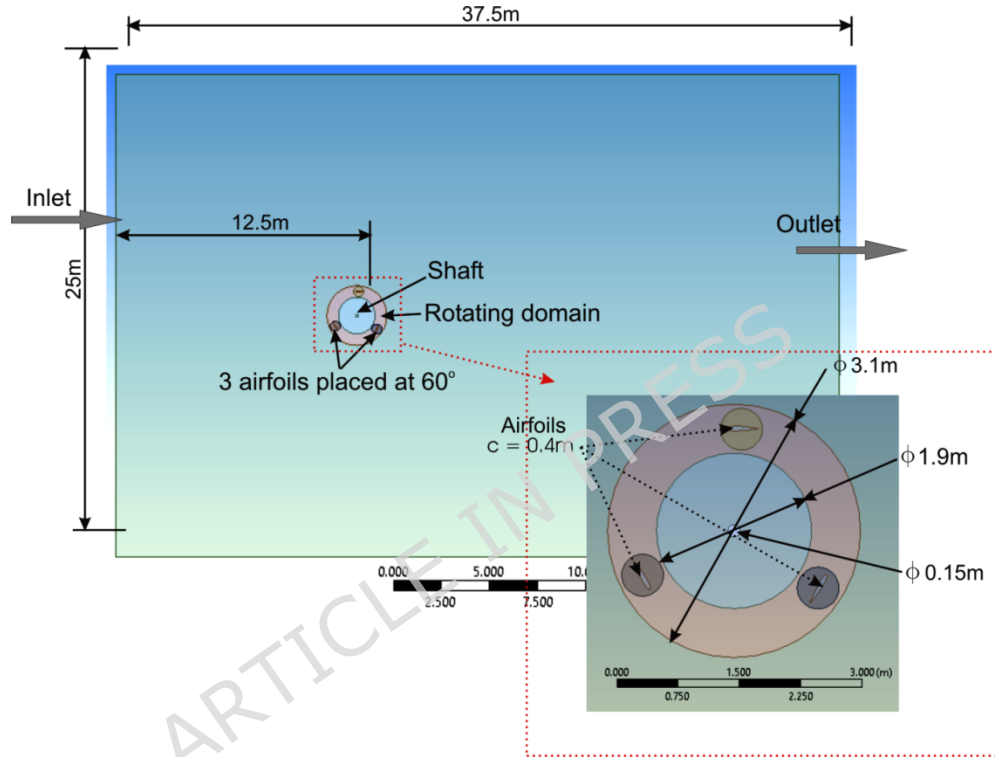


Figure 1: Computational domain and boundary-condition setup used for the CFD analysis

Figure-1 shows the computational domain and boundary-condition setup used for the CFD analysis of a three-bladed vertical axis wind turbine (VAWT). The aerodynamic analysis of the three-bladed VAWT was performed using 2D, unsteady CFD simulations in ANSYS Fluent employing a sliding-mesh approach. The computational domain consists of a rectangular stationary outer region with a total length of 37.5 m and a height of 25 m, within which a circular rotating sub-domain enclosing the rotor is embedded. The turbine center is located 12.5 m downstream of the inlet to minimize inlet-induced flow disturbances, as shown in Figure 1.

Evaluation of Aerodynamic Performance Parameters

The aerodynamic performance of the turbine is evaluated using the following nondimensional parameters.

The **Tip Speed Ratio (TSR)** is defined as: $TSR = \omega R / V_\infty$, where ω is the angular velocity of the rotor (rad/s), R is the rotor radius (m), and V_∞ is the free-stream wind velocity (m/s).

The **Lift Coefficient** is expressed as: $C_l = \frac{L}{\frac{1}{2}\rho V_\infty^2 A}$, where L is the aerodynamic lift force (N), ρ is the air density (kg/m³), V_∞ is the free-stream velocity (m/s), and A is the reference area (m²).

The **Drag Coefficient** is given by: $C_d = \frac{D}{\frac{1}{2}\rho V_\infty^2 A}$, where D denotes the aerodynamic drag force (N).

The **Torque Coefficient** is calculated as: $C_t = \frac{T}{\frac{1}{2}\rho A R V_\infty^2}$, where T is the aerodynamic torque (N·m).

The **Power Coefficient** is determined using $C_p = \frac{P}{\frac{1}{2}\rho A V_\infty^3}$, where the turbine power is $P = T\omega$.

Here, A is the projected swept area of the rotor, ρ is the air density, V_∞ is the free-stream wind velocity, R is the rotor radius, T is the aerodynamic torque, and ω is the angular velocity.

The numerical investigation was performed on a three-bladed H-type Darrieus vertical axis wind turbine employing NACA0012 and NACA0015 airfoils. To isolate the influence of airfoil thickness on aerodynamic performance, all geometric parameters, computational domain dimensions, and operating conditions were maintained identical for both airfoil configurations. The complete rotor geometry used in the CFD simulations is summarized in Table 3, while Figure 1 illustrates the principal geometric dimensions adopted in the numerical model.

2.3 Fabrication of Test Models Using 3D Printing

The material science has progressed significantly and several light weight materials are available today (Lagos et al.)⁴⁶ The models we tested the aerodynamics with were 3D-printed, which is one form of additive manufacturing. We used this because it is versatile and precise, allowing us to create exact shapes. This technology works well for learning about aerodynamics because it allows you to create airfoil shapes that are highly detailed and precise. It uses a computer-controlled heated nozzle, which moves in the x-y plane to force thermoplastic filament through it. When the machine completes the last layer, it moves the platform in the z-direction to restart with the next layer. The system repeats this cycle to construct the final shape. The researchers selected PLA as the material due to its environmental friendliness, simplicity to work with, and compatibility with the fused deposition modelling (FDM) process.

2.3.1 Material Properties of PLA

The crystallinity dictates the mechanical properties of PLA, which are set between semi-crystalline to amorphous. The 3D printing deposition process rapidly quenches the filament, most often resulting in amorphous parts with sufficient structural integrity for aerodynamic testing. High surface energy, strong layer adhesion, and mechanical properties close to Polyethylene Terephthalate (PET) and polystyrene are displayed by PLA under standard Fused Filament Fabrication (FFF) conditions. Although its application in high-temperature uses is restricted by its heat deflection temperature (approximately 60°C), ambient wind tunnel testing is still feasible through the use of PLA. Scientists attempted to enhance layer bonding and mechanical properties by maintaining a constant printing environment and controlling print parameters such as extrusion temperature, nozzle rate, and cooling rates.

2.4 Experimental Setup

During the experimental stage, subsonic wind tunnel was used, which has a uniform velocity profile with controlled turbulence levels suitable for aerodynamic studies. A contraction cone, a transparent windowed test section to visualize the flow, and a diffuser section constitute the tunnel. The turbine models were

mounted on a rotary shaft that was connected to a load-measuring device. Torque, speed, and rotation rate were gauged in the test section so that performance indicators such as power coefficient and tip speed ratio could be computed. Standardized hubs were utilized for the mounting of FDM-printed turbine blades to ensure interchangeability. The structure ensured minimal structural distortion under operating wind speeds. Data were gathered utilizing digital anemometers, torque sensors, and tachometers. Multiple experiments were conducted to ensure repeatability, and uncertainty was minimized by averaging the results. Figures 2 through 5 illustrate the entire experimental setup and specific regions of testing in the wind tunnel.



Figure 2: Full View of the Subsonic Wind Tunnel Setup

Figure 2 shows a pre-calibrated subsonic wind tunnel used for the present investigation. Such types of wind tunnels are widely used in aerodynamic experiments, since these provide controlled airflows with low turbulence intensity and consistent velocity profiles. The setup supports experiments involving performance analysis of VAWTs, measurement of torque and rotational speeds and visualization of flow characteristics and wake formation. Each experimental condition was tested multiple times and the results were ensemble-averaged to ensure repeatability. Minor variations between repeated measurements were within the accuracy limits of the wind tunnel instrumentation. While measurement uncertainty is acknowledged, a detailed uncertainty propagation analysis is beyond the scope of the present study.

2.4.1 Flow Characteristics and Data Acquisition

Prior to experimentation, the subsonic wind tunnel was calibrated to ensure uniform flow conditions throughout the test section. The free-stream velocity distribution was measured at several locations within the test section using a calibrated vane anemometer, and the variation in velocity across the measurement plane was found to be within $\pm 2.6\%$ of the mean value. The corresponding free-stream turbulence intensity was approximately 1.5%, which is considered suitable for aerodynamic investigations of small-scale wind turbines. All measuring instruments, including the anemometer, torque sensor, and tachometer, were calibrated according to the manufacturer's recommended procedures before commencement of the experiments. The calibration was verified periodically throughout the testing programme to ensure measurement consistency.

The experimental data were acquired digitally at a sampling frequency of 20 Hz for a duration of 45s under each operating condition. Each test was repeated three times under identical operating conditions, and the reported values represent the arithmetic mean of the repeated measurements. The maximum

deviation among the repeated measurements remained within $\pm 3\%$, confirming good experimental repeatability. The measurement uncertainty was estimated using the instrument accuracies listed in Table 4 together with standard uncertainty propagation techniques. The combined uncertainty associated with the calculated performance parameters was found to be within acceptable limits for aerodynamic performance evaluation.

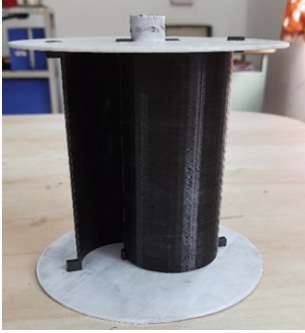


Figure 3: 3D-Printed Savonius rotor used for wind tunnel validation

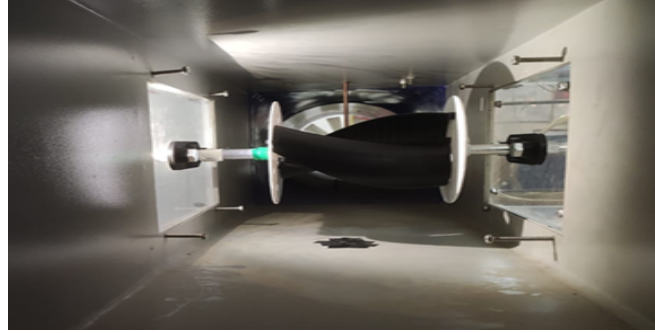


Figure 4: Test Section with twisted Savonius rotor blade used for wind tunnel validation

Figure 3 illustrates the actual 3D-printed Savonius VAWT model used in the experiments. The rotor comprises two semi-cylindrical blades oriented to capture and convert wind energy into rotational motion. It is fabricated using PLA material via FDM to ensure dimensional accuracy and lightweight structure suitable for wind tunnel testing. Figure 4 shows a 3D-printed Savonius wind turbine model mounted inside the test section of the subsonic wind tunnel. The model is aligned centrally between the transparent acrylic sidewalls and is secured to a rotating shaft for dynamic testing under controlled airflow conditions. The setup enables precise evaluation of turbine performance and aerodynamic behavior under various wind speeds and turbulence intensities.

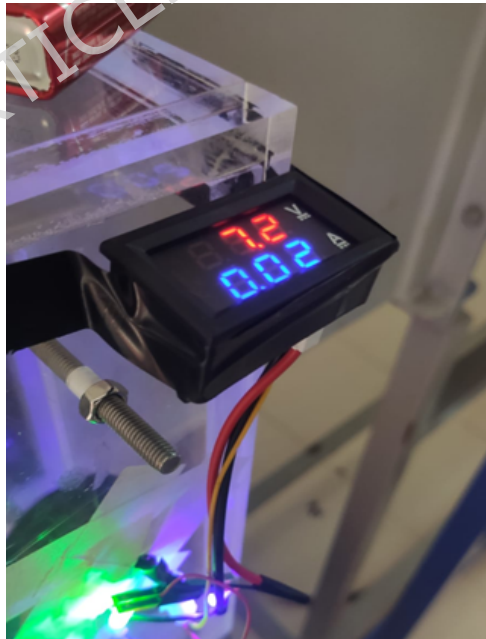


Figure 5: Digital Data Acquisition Unit used during wind tunnel validation of Savonius rotor.

Figure 5 the digital data acquisition setup used to monitor the turbine's output. The system includes a voltage and current display unit integrated with microcontroller-based sensors and wiring, mounted in a

transparent casing. It measures real-time electrical outputs (voltage and current) generated by the turbine and helps in assessing power performance, efficiency, and experimental repeatability. The following instrumentation was employed during measurements, as given in Table-5.

Table-5: Instrumentation employed during measurements.

Instrument	Model / Make	Measurement Range	Resolution	Accuracy	Purpose in Study
Anemometer	Testo 410-2 Testo Vane Anemometer	0.4-20 m/s	0.01 m/s	$\pm(1-2)\%$	Freestream wind velocity measurement
Torque Sensor	TTT-SS Dynamic Torque Transducer	0-100 N·m	0.01 N·m	$\pm 0.1-0.5\%$ FS	Shaft torque measurement
Tachometer	HTM-560 Non-Contact Digital Tachometer	60-90000 RPM	+0.05% + 1 digit	$\pm 0.05\%$	Rotational speed measurement

Prior to the experimental campaign, all measuring instruments were calibrated in accordance with the manufacturer's recommended procedures to ensure measurement reliability. The calibration of the anemometer was verified against the reference wind tunnel velocity, while the torque sensor and tachometer were checked using standard calibration procedures before the commencement of testing. Calibration was periodically verified throughout the experimental programme to minimize systematic measurement errors.

Experimental data were acquired using a digital data acquisition system under steady operating conditions. For each test case, measurements of wind velocity, rotor speed, and aerodynamic torque were recorded at a sampling frequency of **20 Hz** over a period of 45s. Each operating condition was repeated **three** times, and the reported results correspond to the arithmetic mean of the repeated measurements. The repeatability of the measurements was assessed using the standard deviation of the repeated experiments, and the corresponding uncertainty is reported in the experimental validation results.

2.5 Validation of Experimental and Numerical setup

2.5.1 Validation of Experimental setup for Savonius Turbine

The main indicator of turbine output, power P , is obtained by multiplying torque by angular velocity Ω . Power is normalized against the available kinetic energy flux through swept area A by the power coefficient C_p . This allows for direct comparison of designs by making performance independent of scale and wind speed. In VAWTs, dynamic stall, blade number, and tip-speed ratio all have a significant impact on torque and power. These formulas serve as a link between the predictions of fluid dynamics and the actual energy conversion efficiency.

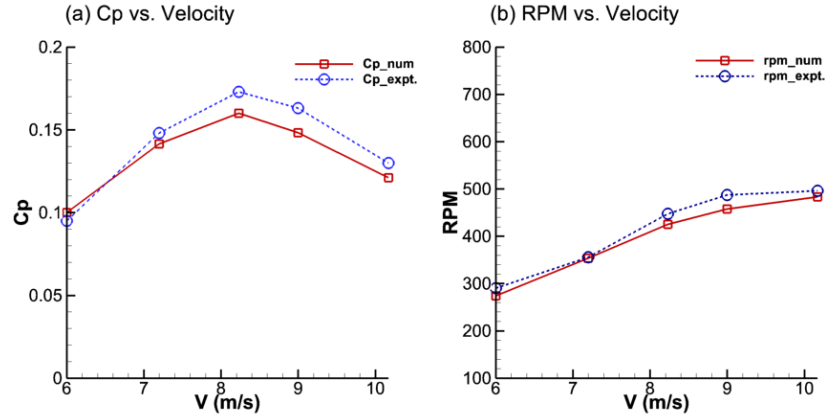


Figure 6: Validation of numerical setup with the experimental results of Saha et al.⁴³

Figure 6 present the validation of CFD simulation results against experimental data obtained by Saha et al.⁴³ for a Savonius rotor with endplates. These comparative plots evaluate two performance parameters, Coefficient of Performance (C_p) and Rotor Speed (RPM), across a range of inlet wind velocities (6 to 10 m/s).

Figure 5 compares the numerical predictions with the experimental measurements of Saha et al. [43] for a Savonius rotor and is presented to verify the experimental methodology and the numerical implementation for a representative drag-type VAWT. The comparison demonstrates good agreement between the numerical and experimental trends over the investigated wind-speed range, thereby providing confidence in the adopted experimental facility and computational framework for low-speed VAWT applications. It should be noted, however, that this comparison is not intended as direct validation of the three-bladed Darrieus rotor investigated in the present work. The numerical methodology employed for the Darrieus rotor is independently validated against benchmark aerodynamic data reported in the literature, as presented below.

2.5.2 Validation of Numerical setup for 3-Bladed Darrieus Turbine

2.6 CFD Model Setup

Simulations were conducted using ANSYS Fluent. The computational domain encompassed a 2D cross-section of the VAWT. The $k-\omega$ SST turbulence model was employed for its accuracy in resolving flow separation (Younoussi et al., 2024)⁴⁷. Grid independence was carried out before finalizing the most suitable grid. The results reported here are with the fine grid. Structured meshing with boundary layer refinement ensured accurate capturing of near-wall effects. Time-dependent sliding mesh technique captured the rotor motion. The work reported here is extension of the work reported in Bagade et al.^{41,42}.

2.6.1 Governing equations

The unsteady flow field around the vertical axis wind turbine is simulated using the Unsteady Reynolds-Averaged Navier-Stokes (URANS) equations, as implemented in ANSYS Fluent. The equations are solved in an inertial reference frame using a pressure-based, transient solver, with rotor motion handled through a sliding-mesh technique.

Continuity Equation

For incompressible flow, the continuity equation is expressed as:

$$\nabla \cdot \mathbf{u} = 0 \quad \dots\dots\dots(1)$$

$\mathbf{u} = (u, v)$ is the instantaneous velocity vector.

URANS Momentum Equations

The URANS momentum equations in tensor form are written as:

$$\frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j} = -\frac{1}{\rho} \frac{\partial p}{\partial x_i} + \nu \frac{\partial^2 u_i}{\partial x_j^2} - \frac{\partial}{\partial x_j} (\overline{u'_i u'_j}) \dots\dots\dots(2)$$

Where u_i is the time-averaged velocity component, p is the mean pressure, ρ is the fluid density, ν is the kinematic viscosity, and $\overline{u'_i u'_j}$ represents the Reynolds stress tensor arising from turbulent velocity fluctuations.

Turbulence Closure: In ANSYS Fluent, the Reynolds stresses are closed using the **Boussinesq eddy-viscosity hypothesis**, which relates the Reynolds stress tensor to the mean strain rate:

$$-\overline{u'_i u'_j} = \nu_t \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) - \frac{2}{3} k \delta_{ij} \dots\dots\dots(3)$$

Where, ν_t is the turbulent (eddy) viscosity, k is the turbulent kinetic energy, and δ_{ij} is the Kronecker delta. The turbulent viscosity ν_t is computed using the $k-\omega$ SST turbulence model, which combines the near-wall accuracy of the $k-\omega$ formulation with the robustness of the $k-\varepsilon$ model in the free stream. This model is well suited for unsteady separated flows and dynamic stall phenomena typical of VAWT aerodynamics.

Transport Equations for $k-\omega$ SST Model: The transport equations for turbulent kinetic energy k and specific dissipation rate ω are solved as:

$$\frac{\partial k}{\partial x_j} = P_k - \beta^* k \omega + \frac{\partial}{\partial x_j} \left[(\nu + \sigma_k \nu_t) \frac{\partial k}{\partial x_j} \right] \dots\dots\dots(4)$$

$$\frac{\partial \omega}{\partial t} + u_j \frac{\partial \omega}{\partial x_j} = \alpha \frac{\omega}{k} P_k - \beta \omega^2 + \frac{\partial}{\partial x_j} \left[(\nu + \sigma_\omega \nu_t) \frac{\partial \omega}{\partial x_j} \right] \dots\dots\dots(5)$$

where P_k is the production of turbulent kinetic energy, and α , β , β^* , σ_k , and σ_ω are model constants defined within Fluent.

Treatment of Rotor Motion: Rotor motion is handled using a **sliding-mesh approach**, in which the computational domain is divided into a stationary outer region and a rotating inner region containing the turbine blades. The rotating zone is assigned a **prescribed angular velocity**, corresponding to the desired tip speed ratio. The URANS equations are solved in the **inertial frame**, and grid motion is accounted for internally by the solver through the mesh motion equations. No rotating-frame source terms are introduced.

3. Validation of Numerical Setup for Darrieus Rotor

3.1 Validation of Numerical setup and Comparison with earlier studies

The numerical framework was validated against (a) the experimental investigations of Aranda *et al.*⁴⁸ over a representative range of Re s and α s of attack to ensure the reliability of the aerodynamic predictions and (b) 3-bladed VAWT analysis using NACA0012 airfoils by Bucur *et al.*⁵¹.

(a) Validation with the experimental investigations of Aranda *et al.*⁴⁸

The computational domain adopted for the two-dimensional single NACA airfoil is illustrated in Figure 6, which also shows the imposed boundary conditions. A sufficiently large far-field region was considered to minimize blockage effects and allow proper flow development around the airfoil. The inlet was defined as a velocity inlet using component-wise specification, while the outlet was modeled as a pressure outlet with zero gauge pressure. The airfoil surface was treated as a no-slip wall to accurately capture viscous boundary-layer effects. The computational domain consists of a sufficiently large far-field region to

minimize blockage and boundary interference effects. The airfoil surface is modelled as a stationary no-slip wall, whereas the outer boundary is prescribed using symmetry boundary conditions to represent the undisturbed free stream. The inlet and outlet boundaries are specified as velocity inlet and pressure outlet, respectively. The complete specification of the boundary conditions is summarized in Table 6.

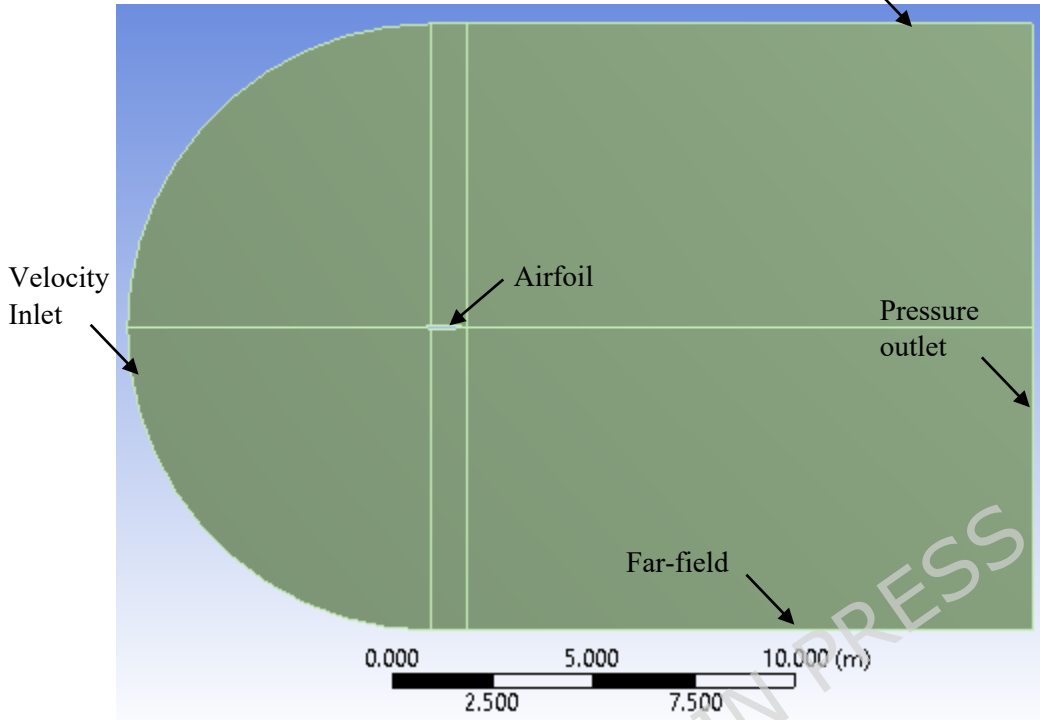


Figure 7: Computational setup for single NACA airfoil and boundary conditions

Table-6: Boundary conditions for single NACA airfoil simulation.

S.N.	Location	Boundary Condition	Specification
1	Airfoil surface	No-slip wall	Stationary wall ($V = 0$)
2	Far-field boundary	Symmetry	Free-stream conditions
3	Inlet	Velocity inlet	Velocity components specified
4	Outlet	Pressure outlet	Gauge pressure = 0 Pa

Simulations were performed using a pressure-based steady solver with absolute velocity formulation. A laminar model was employed for $Re=33,300$, whereas the $k-\omega$ SST turbulence model was adopted for $Re=133,000$ to resolve near-wall gradients and mild separation accurately. Spatial discretization utilized a least-squares cell-based gradient scheme, second-order pressure interpolation, and second-order upwind momentum formulation. Numerical stability was ensured using a Courant number of 5 and relaxation factors of 0.25 for both pressure and momentum.

The generated mesh topology is shown in Figure 7, where a nearly orthogonal structured grid with local refinement near the airfoil surface was used to capture the viscous sublayer and wake structure. Mesh quality parameters for the selected grid are presented in Figure 8, confirming acceptable orthogonality and skewness for accurate and stable computations. A grid convergence study was carried out using three progressively refined meshes, the details of which are provided in Table 6. The variation in lift coefficient between Grid-2 and Grid-3 was found to be minimal (e.g., C_l changing from 0.4085 to 0.3943 at $Re=133,000$ and $\alpha=8^\circ$), indicating that the solution had reached grid independence. Therefore,

Grid-3, comprising approximately 177,000 elements, was selected for subsequent simulations. Similar grid independence test was conducted for 3 bladed rotor also.

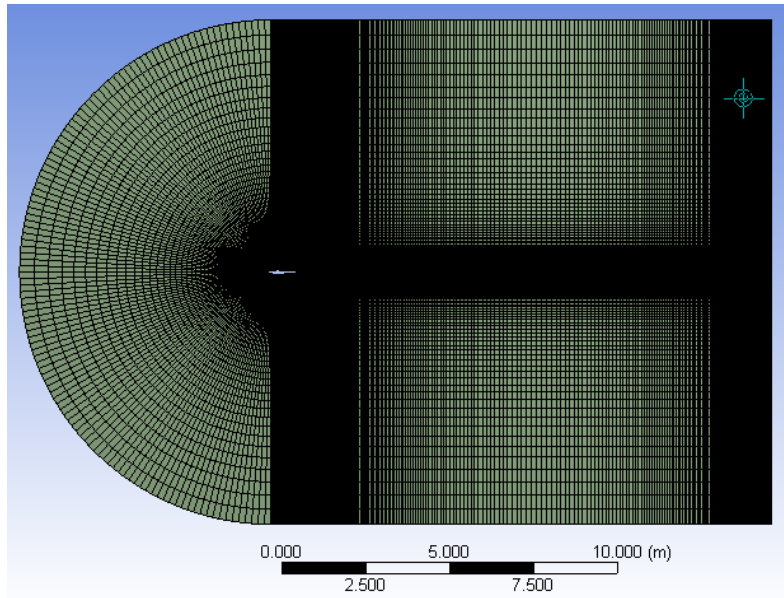


Figure 7: Nearly orthogonal grid generated over NACA airfoil.

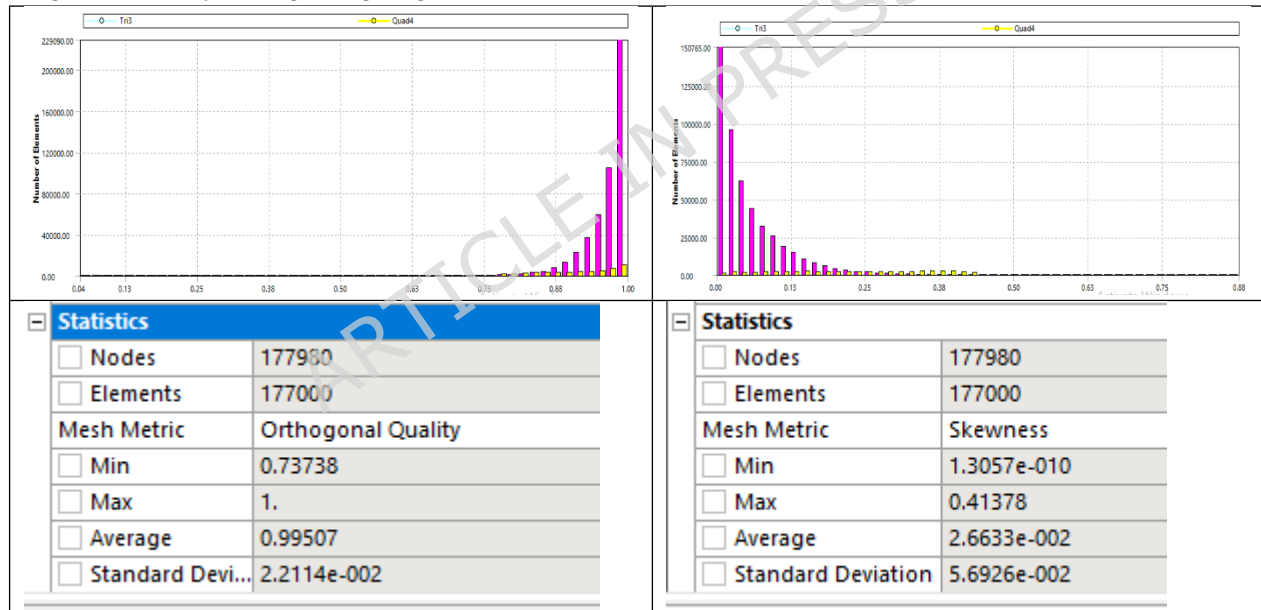


Figure 8: Mesh metrics for Grid 3: (No of nodes: 177980; No. of elements: 177000)

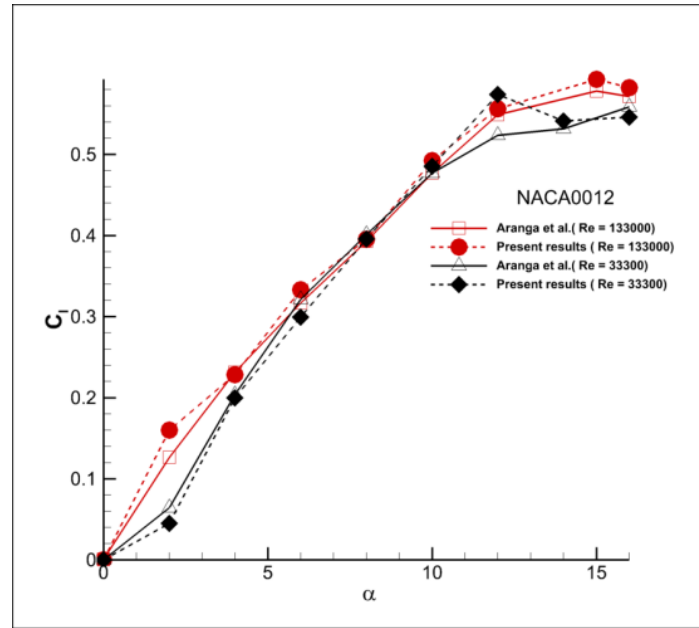


Figure 9: Comparison of numerical results with experimental studies of Aranda et al.48

Particulars	Grid-1		Grid-2		Grid-3	
	No. of elements	No. of Nodes	No. of elements	No. of Nodes	No. of elements	No. of Nodes
	155330	154500	165900	165000	177980	177000
No. of points on airfoil surface	205		250		300	
Parameters	$C_{l_Grid1} = 0.4122$ $C_{l_Expt.}[48] = 0.3930$ $(Re=133000, \alpha=8^\circ)$		$C_{l_Grid2} = 0.4085$		$C_{l_Grid3} = 0.3943$	

The comparison of numerical predictions with experimental measurements is presented in Figure 9, demonstrating close agreement within the linear aerodynamic regime. This confirms that the adopted numerical schemes, turbulence modeling approach, and mesh resolution reliably reproduce the physical flow behavior and are suitable for extension to multi-bladed rotor performance analysis.

(b) Validation of the transient CFD methodology with results of Bucur et al.[51] for 3-bladed VAWT with NACA0012 profiles

The numerical predictions made in this study were compared with the benchmark results published by Bucur et al.⁵¹, who conducted transient moving-mesh URANS simulations of a vertical-axis wind turbine under well-documented computational conditions, in order to confirm the application of the transient CFD methodology. To precisely resolve the near-wall flow, their study used a quadrilateral-dominant mesh with structured inflation layers surrounding the blade surfaces. A moving-mesh formulation with a freestream velocity of 10 m s⁻¹ was used to perform the transient simulations. Tip speed ratios (TSRs) between 0.5 and 3.5 were obtained by varying the rotor angular velocity. Each operating condition was simulated for seven full rotor revolutions using 2520 time steps, corresponding to an angular increment of 1° per time step, with a residual convergence criterion of 10⁻⁶.

The current simulations used the identical transient solution technique, operational conditions, temporal discretization, and convergence criteria as those published by Bucur et al. in order to provide a relevant

benchmark comparison. To ensure sufficient resolution of the boundary layer and unsteady wake structures, a similar mesh topology with near-wall inflation layers and similar spatial resolution around the rotating blades was used, despite a slight difference in the overall number of nodes and elements from the reference study.

For four example operating circumstances (TSR = 1.5, 2.0, 3.0, and 3.5), Figure 10 compares the instantaneous moment coefficient (C_m) obtained in the current investigation with the benchmark results of Bucur et al.⁵¹ The comparison is based on how the moment coefficient changes as a function of the rotor azimuth angle during a whole rotor revolution. With a minor underprediction close to the negative troughs, the predicted moment coefficient at TSR = 1.5 (Figure 10a) nearly tracks the benchmark solution throughout the rotor revolution. The periodic trend and phase are faithfully replicated at TSR = 2.0 (Figure 10 b), despite some variations in peak amplitude around the positive maxima. Excellent agreement is achieved for nearly the whole revolution for TSR = 3.0 (Figure 10c), with only minor variations in the amplitude of the positive peaks. Similar to this, at TSR = 3.5 (Figure 10d), the reference solution and the projected cyclic behavior correspond well, and the little phase discrepancies seen close to the peak values stay within the range typically reported for transient URANS simulations of vertical-axis wind turbines.

The selected transient sliding-mesh methodology effectively replicates the unstable aerodynamic loading of a rotating vertical-axis wind turbine, as evidenced by the strong agreement between the current predictions and the published benchmark. Before applying it to the three-bladed NACA airfoil rotor examined in the next sections, this validation creates confidence in the numerical implementation and temporal resolution used in the current work.

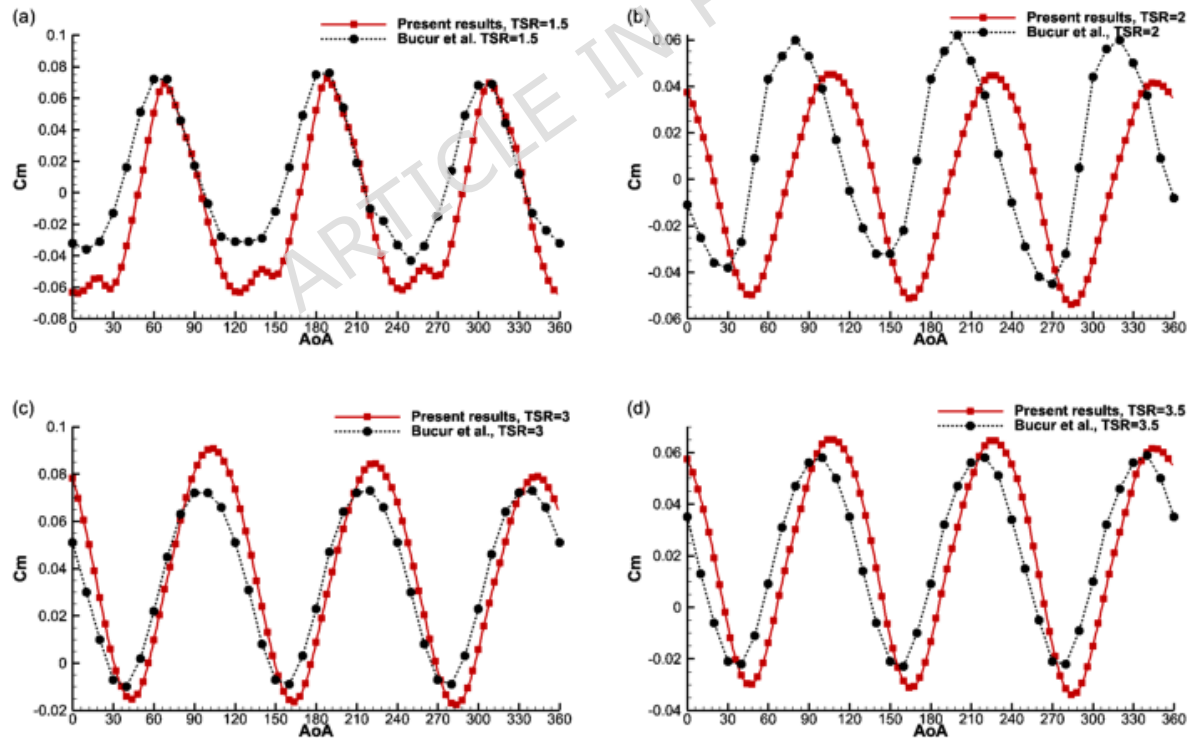


Figure 10: Verification of the transient moving-mesh CFD methodology through comparison of the instantaneous moment coefficient (C_m) with the benchmark numerical results of Bucur et al. for TSRs of (a) 1.5, (b) 2.0, (c) 3.0, and (d) 3.5.

The current simulations show excellent agreement with the benchmark data, reproducing the typical periodic fluctuation of the moment coefficient with rotor azimuthal angle for all operating circumstances. Over the whole range of tip speed ratios, the expected locations of the positive and negative peaks, the aerodynamic loading phase, and the overall waveform are all reliably recorded. Both the current results and the benchmark data show the anticipated shift toward smoother and more sinusoidal torque characteristics as the TSR rises from 1.5 to 3.5, suggesting decreased cyclic aerodynamic loading at higher rotational speeds.

3.2 Numerical Analysis of 3-bladed Darrieus turbine

The computational domain was selected sufficiently large to minimize the influence of the outer boundaries on the flow field surrounding the rotor. The inlet, outlet, and lateral boundaries were located several rotor diameters away from the turbine, allowing adequate development of the wake and preventing artificial blockage effects. The upper and lower boundaries were modelled as symmetry walls to provide numerical stability while remaining sufficiently distant from the rotor. Owing to the large computational domain, these boundaries have a negligible influence on the local flow field and the predicted aerodynamic forces.

Near-Wall Mesh Resolution and y^+ Estimation: The near-wall mesh resolution was determined based on the non-dimensional wall distance (y^+) to ensure accurate resolution of boundary-layer phenomena. Air was considered as the working fluid, with a density of $1.225 \text{ kg}\cdot\text{m}^{-3}$ and a dynamic viscosity of $1.789 \times 10^{-5} \text{ kg}\cdot\text{m}^{-1}\cdot\text{s}^{-1}$, corresponding to a kinematic viscosity of $1.46 \times 10^{-5} \text{ m}^2\cdot\text{s}^{-1}$.

The free-stream velocity was obtained from the Re definition, $U_\infty = Re \nu / c$, resulting in velocities corresponding to different Re . For conservative estimation of wall shear stress during mesh design, the turbulent skin friction correlation for a smooth flat plate, $C_f = 0.0576 / (Re)^{1/5}$ was adopted. The wall shear stress was computed using $\tau_w = 0.5 \rho U_\infty^2 C_f$ and the friction velocity was subsequently evaluated as $u_\tau = \sqrt{\tau_w / \rho}$. From the resulting friction velocities, the height of the first grid point normal to the wall was then determined from the definition of y^+ , $y = y^+ \nu / u_\tau$ with a target value of $y^+ \approx 1$ to enable full resolution of the viscous sublayer.

Accordingly, the first cell heights were estimated as $5.0 \times 10^{-4} \text{ m}$ to $5.8 \times 10^{-5} \text{ m}$ for lowest and highest Re . These values were employed in defining the inflation layer parameters during mesh generation. A minimum of 20-30 inflation layers with a growth rate not exceeding 1.2 was used to adequately capture the boundary-layer development. The resulting meshes consistently satisfied the near-wall resolution requirement of the SST $k-\omega$ turbulence model, with y^+ values maintained below unity over the airfoil surface.

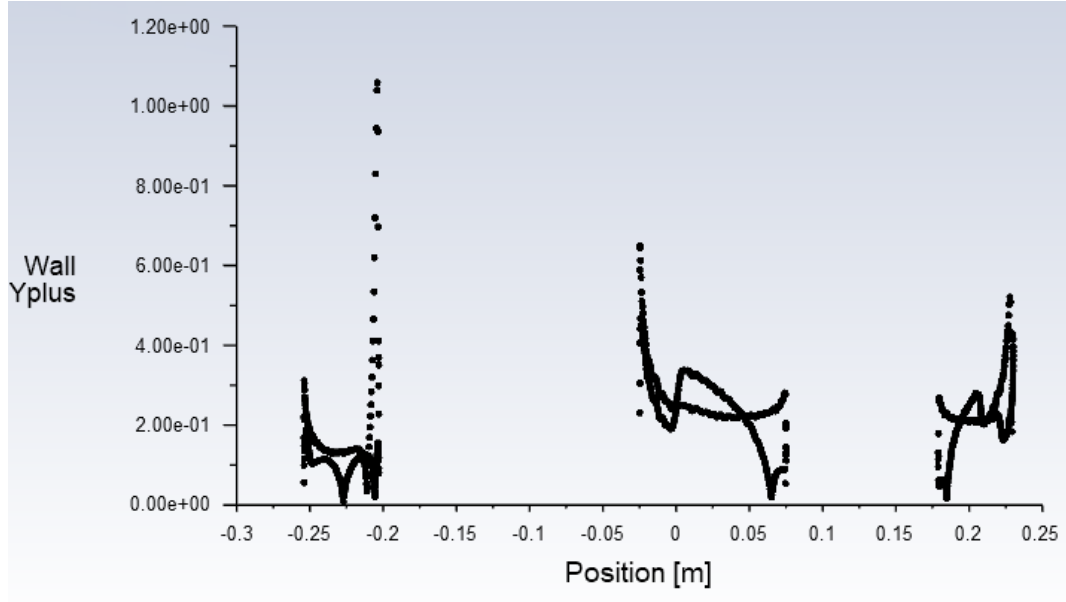


Figure 11: Distribution of wall y^+ along the blade surfaces of the full three-bladed rotor.

The near-wall mesh quality was further assessed by examining the distribution of the non-dimensional wall distance (y^+) over the complete three-bladed rotor, as shown in Figure 11. The y^+ values remain well below unity over the majority of the blade surfaces, confirming that the first computational cell is located within the viscous sublayer. The maximum y^+ observed on the rotor is approximately **1.07**, while the vast majority of the blade surface exhibits values considerably lower than this limit.

Small localized increases in y^+ are observed near the leading-edge regions and blade extremities, where the local curvature and rapid variation in flow direction require mesh transitions. These isolated peaks are spatially limited and remain close to the recommended value of $y^+=1$, indicating that the near-wall resolution is maintained throughout the computational domain. The adopted mesh, consisting of a first-layer height of 1.0×10^{-5} m with ten inflation layers and an inflation growth rate of 1.2, therefore provides adequate resolution of the boundary layer for the SST $k-\omega$ turbulence model employed in the present study.

These results demonstrate that the generated computational mesh is sufficiently refined to accurately resolve the near-wall flow and predict the unsteady aerodynamic loads on the rotating blades with confidence.

Turbulence model: Turbulence effects are modeled using the $k-\omega$ SST turbulence model, which is suitable for capturing flow separation and unsteady aerodynamic behavior in VAWT applications. A fine near-wall mesh with boundary-layer refinement is employed to resolve viscous effects accurately. The simulations are performed using a pressure-based transient solver, with second-order spatial discretization applied to pressure, momentum, and turbulence transport equations. Pressure-velocity coupling is achieved using the Coupled algorithm. Time integration is carried out using a fixed time step selected to ensure at least 360 time steps per rotor revolution, enabling adequate resolution of unsteady blade-wake interactions and dynamic stall phenomena. Each case is simulated for a minimum of six complete rotor

revolutions, and aerodynamic coefficients and torque are cycle-averaged over the final revolutions after periodic steady state is achieved. Convergence within each time step is ensured by reducing all residuals below 10^{-6} and by monitoring the periodic convergence of lift, drag, and torque histories.

The SST $k-\omega$ model was adopted because it has been shown to provide reliable prediction of boundary-layer development, separation onset and overall aerodynamic coefficients for airfoils and small-scale wind turbines within Re ranges comparable to the present study; its efficiency relative to DES/LES makes it appropriate for parametric URANS studies constrained by computational cost. (Rocha et al., 2016). It is to be noted that that URANS with SST $k-\omega$ does not fully resolve strongly unsteady vortex dynamics (e.g., deep dynamic stall, coherent leading-edge vortices); such phenomena are better captured by DES/LES at much higher spatial and temporal resolution (Younoussi, 2024)⁴⁷.

3.3 Grid Independence Study for the Three-Bladed Darrieus Rotor

In addition to the single-airfoil validation, a separate grid independence study was performed for the three-bladed Darrieus rotor to ensure that the computed aerodynamic performance was independent of mesh resolution. Three progressively refined computational meshes were generated while maintaining identical boundary conditions, numerical schemes, and operating parameters.

The cycle-averaged aerodynamic torque was selected as the convergence criterion because it directly represents the principal performance parameter of the rotating turbine. The results of the mesh independence study are summarized in **Table 7**.

Table 7. Grid Independence Study for the Three-Bladed Darrieus Rotor $V = 2$ m/s, TSR = 2.5

Mesh	Number of Nodes	Number of Elements	Avg, Orthogonality	Avg. Skewness	Average Torque (N·m)	Deviation from Fine Grid (%)
Coarse	68859	135314	0.96112	6.33E-02	1.16	17.14
Medium	144829	169510	0.96335	6.49E-02	1.37	2.142
Fine	159237	233142	0.95961	6.78E-02	1.4	0.00

The variation in the cycle-averaged aerodynamic torque between the medium and fine meshes was less than **1–2%**, indicating that further mesh refinement had a negligible influence on the predicted aerodynamic performance. Consequently, the fine mesh was adopted for all subsequent numerical simulations.

4. Results and Discussion

To ensure consistent comparison between different operating conditions, all aerodynamic performance parameters reported in this section correspond to cycle-averaged values obtained over the final complete rotor revolutions after periodic convergence of the transient solution had been achieved. Instantaneous flow-field contours are interpreted together with the corresponding cycle-averaged aerodynamic coefficients to establish a direct relationship between the observed flow structures and turbine performance.

Figures 12-14 present instantaneous velocity, stream-function, and pressure contours for the three-bladed VAWT with a NACA0012 airfoil operating at a freestream velocity of 6 m/s and $TSR = 2$. These contours are used to interpret the unsteady flow mechanisms responsible for the time-dependent torque response discussed later in Fig. 15.

Velocity contours, as shown in Fig. 12 reveal strong acceleration of flow near the blade tips due to rotational motion, accompanied by pronounced velocity deficits in the downstream wake. The formation and downstream convection of these low-velocity regions indicate substantial momentum extraction by the rotor. Temporal variations in wake strength and blade-tip acceleration contribute directly to the fluctuating aerodynamic loads observed in the torque-time history. Streamfunction contours, as shown in Fig. 13) highlight the development of rotational flow structures and circulation around the blades. Periodic distortion and asymmetry of streamlines in the rotor region indicate unsteady blade-wake interaction. These variations correspond to the cyclic torque oscillations observed after the initial transient phase in Figure 15, confirming that unsteady circulation plays a key role in torque modulation.

Figure 14 shows Pressure contours alternating high-pressure regions on the windward blade surfaces and strong suction zones on the leeward sides. The magnitude and temporal variation of this pressure differential govern instantaneous torque production. At certain time instants, intensified low-pressure regions and adverse pressure gradients near the blade surfaces are observed, which contribute to abrupt torque fluctuations rather than smooth power delivery.

The improved pressure distribution observed for the NACA0015 rotor is reflected in its higher cycle-averaged aerodynamic torque and power coefficient compared with the NACA0012 configuration. Similarly, the delayed flow separation and reduced wake asymmetry contribute to lower cyclic fluctuations in the aerodynamic loading, resulting in improved torque stability throughout the rotor revolution. These observations demonstrate a direct relationship between the instantaneous flow structures and the corresponding time-averaged aerodynamic performance.

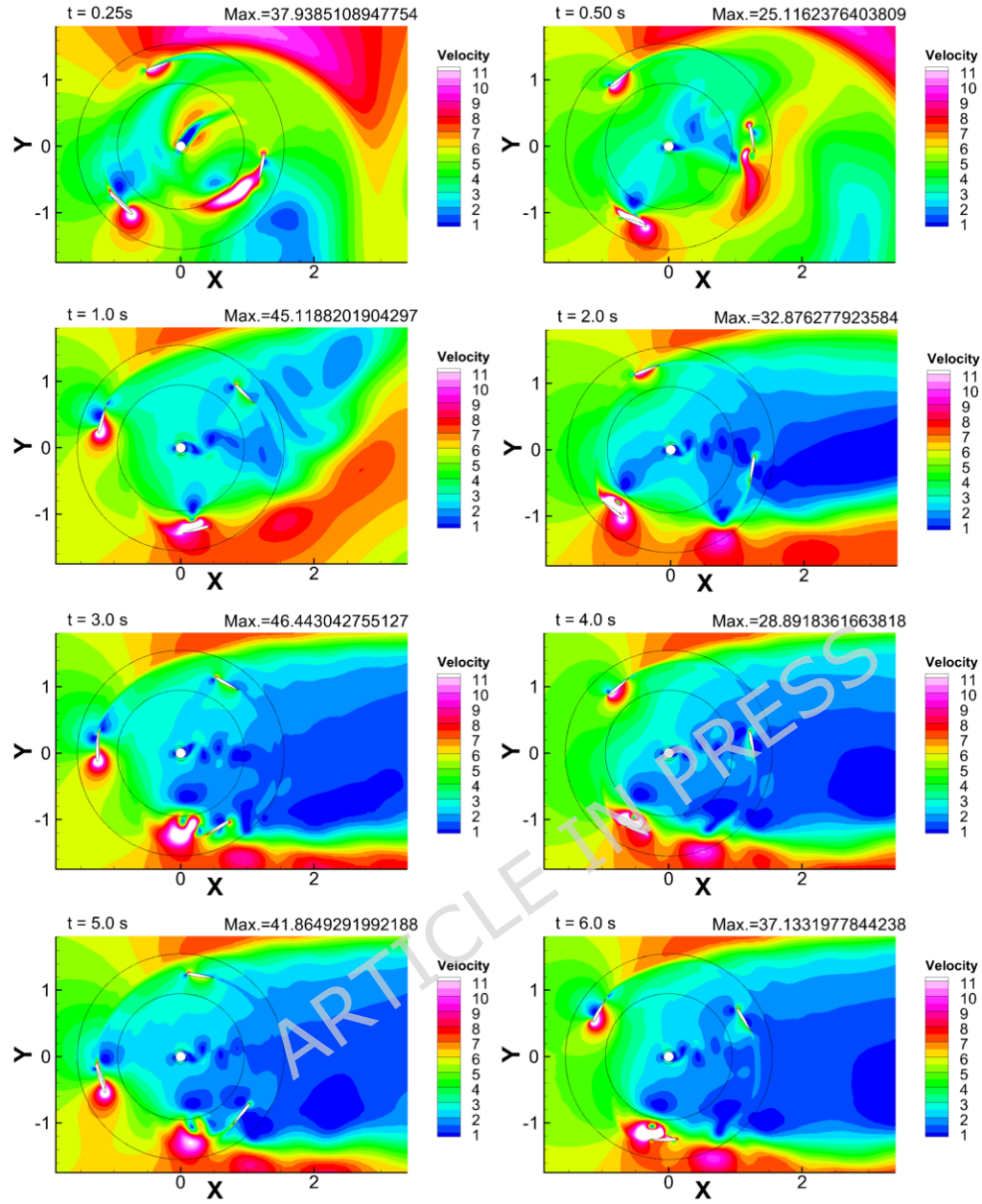


Figure 12: Velocity contours of 3-bladed NACA0012 VAWT at different times, $V = 6\text{m/s}$, $\text{TSR} = 2$

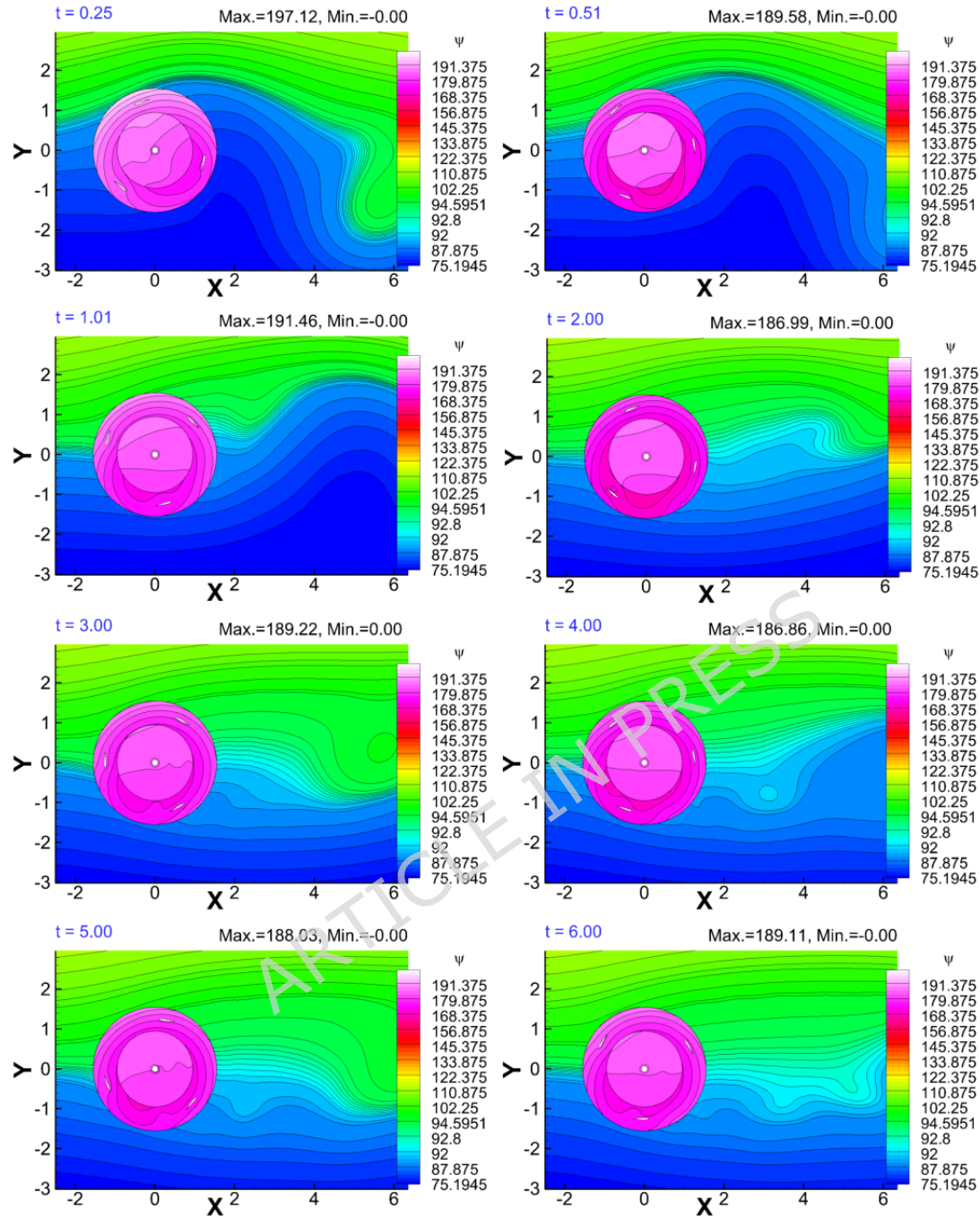


Figure 13: Streamline contours of 3-bladed NACA0012 VAWT at different times, $V = 6\text{m/s}$, $\text{TSR} = 2$.

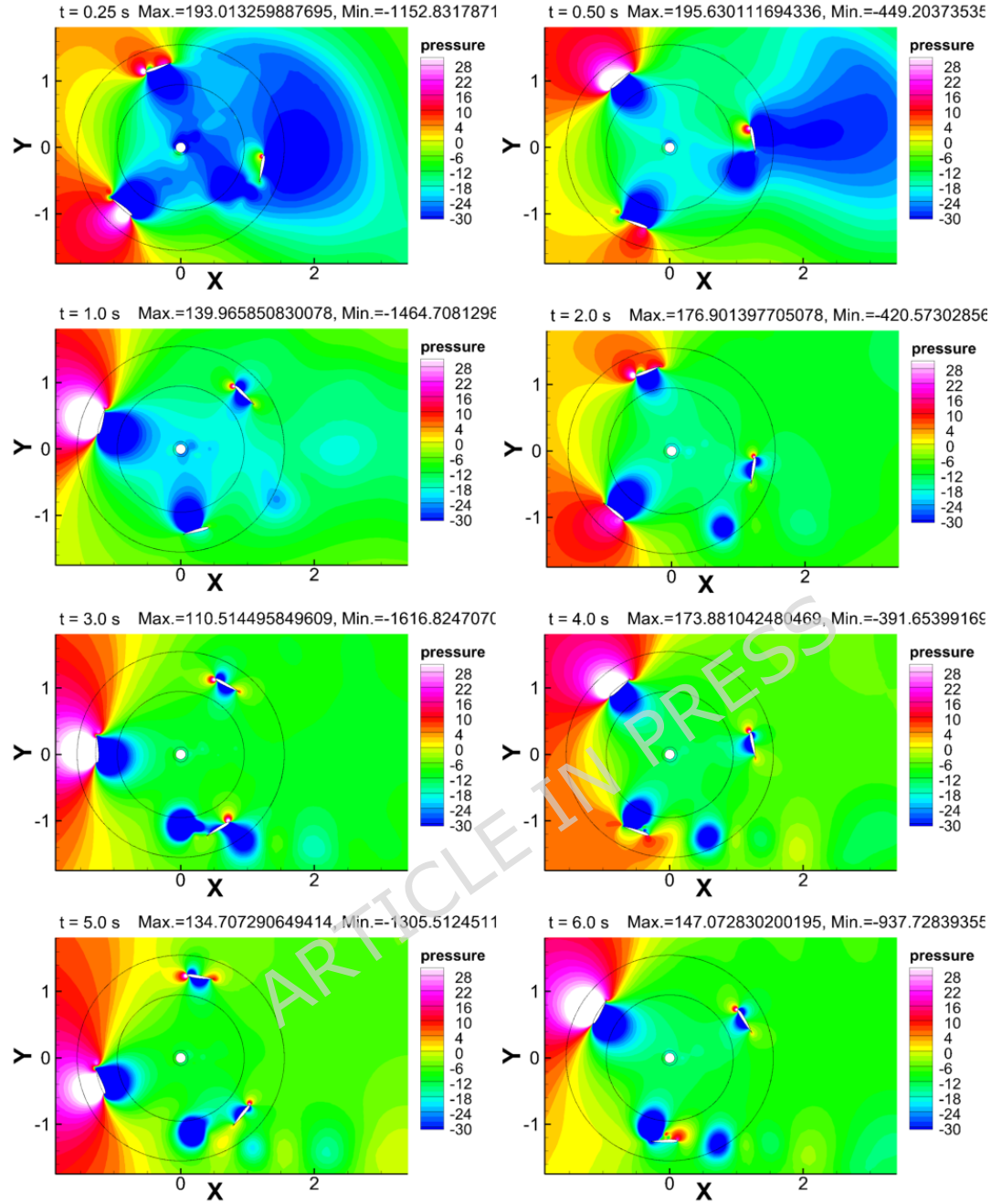


Figure 14: Pressure contours of 3-bladed NACA0012 VAWT at different times, $V = 6\text{m/s}$, $\text{TSR} = 2$

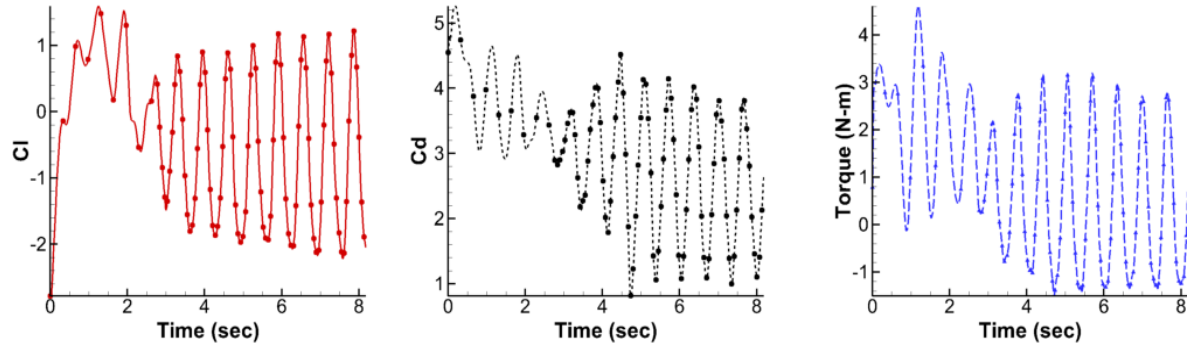


Figure 15: Transient Aerodynamic Coefficients and Torque at $V = 2$ m/s, $TSR = 2.5$ for NACA0012

Figure 15 presents the time-dependent variation of lift coefficient (C_l), drag coefficient (C_d), and aerodynamic torque for a VAWT with a NACA0012 airfoil operating at a freestream velocity of 2 m/s and $TSR = 2.5$. The leftmost plot illustrates the cyclic nature of C_l , which stabilizes after the initial 2 seconds, indicating periodic aerodynamic behavior as the turbine reaches steady rotational speed. The amplitude of C_l oscillates between -2.5 and +1.5, suggesting strong unsteady effects and the presence of dynamic stall during blade rotation.

The middle plot shows the evolution of C_d , which initially peaks above 4 and then settles into a stable oscillatory pattern between 2 and 4. The periodicity of the C_d curve corresponds to the rotor's azimuthal position, reflecting consistent wake development and flow separation.

The rightmost plot shows torque variations over time. The torque amplitude fluctuates between -1 Nm and +3 Nm, signifying the alternating load experienced by the rotor blades due to asymmetrical flow exposure during rotation. The cyclic torque behavior indicates that although positive average torque is generated, high-frequency oscillations may induce fatigue in the shaft and rotor assembly. These results confirm the accuracy of transient CFD simulations in capturing unsteady aerodynamic behavior typical in VAWT applications.

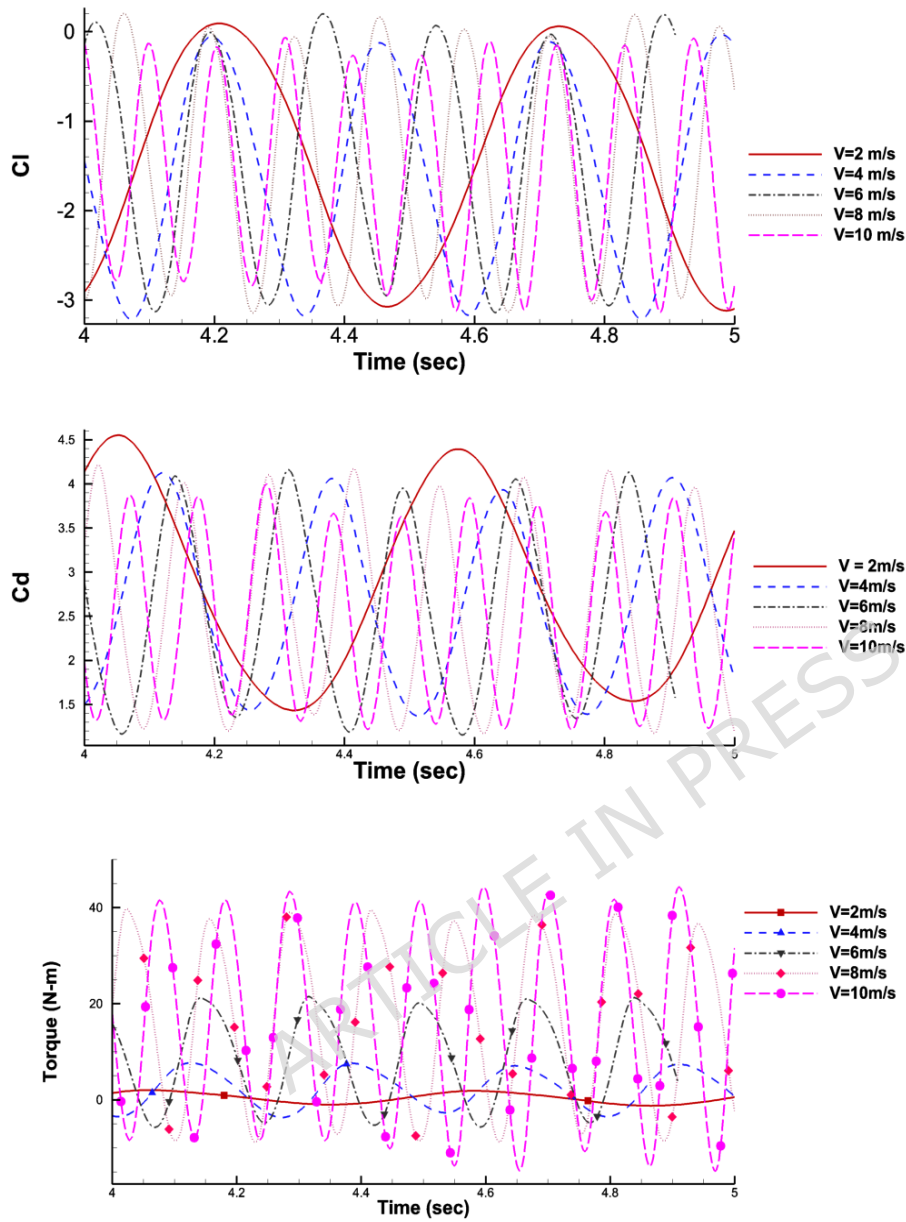


Figure 16: C_l , C_d , and Torque Variation at different freestream velocities for 3-bladed VAWT (NACA0012) at $TSR = 2.5$.

Figure 16 explores the influence of freestream velocity on aerodynamic characteristics and torque output of a VAWT equipped with a NACA0012 airfoil at a constant $TSR = 2.5$. The top plot displays C_l for five different wind velocities (2-10 m/s) over a one-second time interval. As wind velocity increases, both the frequency and amplitude of C_l oscillations increase. At 10 m/s, C_l oscillates more sharply and frequently, suggesting intensified aerodynamic loading and dynamic stall, particularly during upwind-to-downwind transitions.

The middle plot compares C_d behavior at varying velocities. C_d curves show increased frequency and a slight reduction in peak values with increasing velocity. At lower speeds, flow separation is more persistent, while higher velocities result in more frequent, yet shorter-duration, separation events. The

phase shift in C_d among different velocities highlights the changing flow attachment/detachment characteristics around the blades.

The bottom plot presents torque generation as a function of time. At 2 m/s, torque oscillates with low amplitude, rarely exceeding ± 5 Nm. However, at 10 m/s, torque reaches peak amplitudes above 40 Nm, indicating a substantial increase in aerodynamic power. The sharp rise in torque output with velocity confirms the positive impact of freestream velocity on power extraction, although the pronounced oscillations necessitate mechanical robustness in turbine design. These observations validate the CFD model's ability to simulate real-world performance trends across a range of operating conditions.

ARTICLE IN PRESS

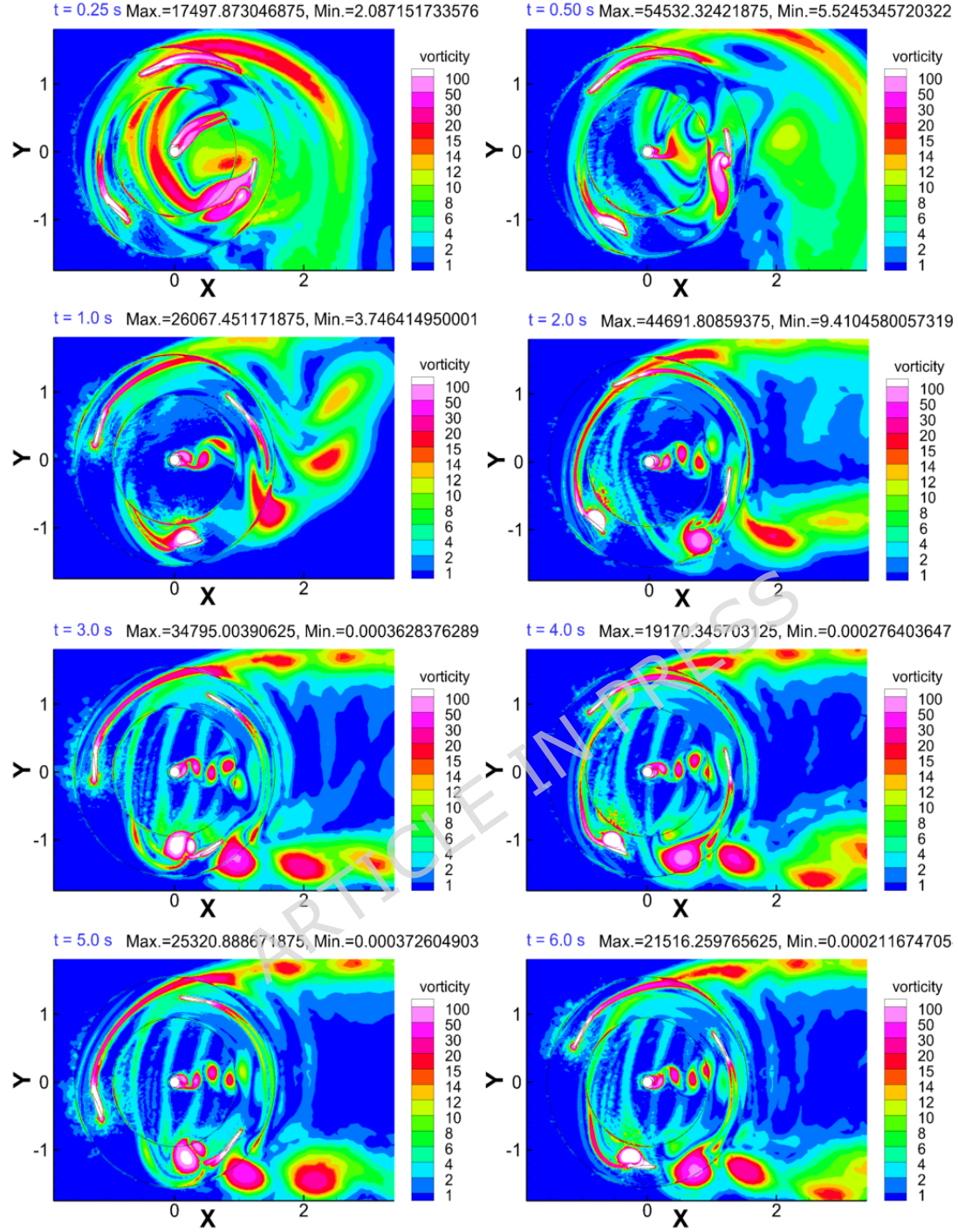


Figure 17: ω -contours for NACA 0012 at different times, $V = 6\text{m/s}$, $\text{TSR} = 2$.

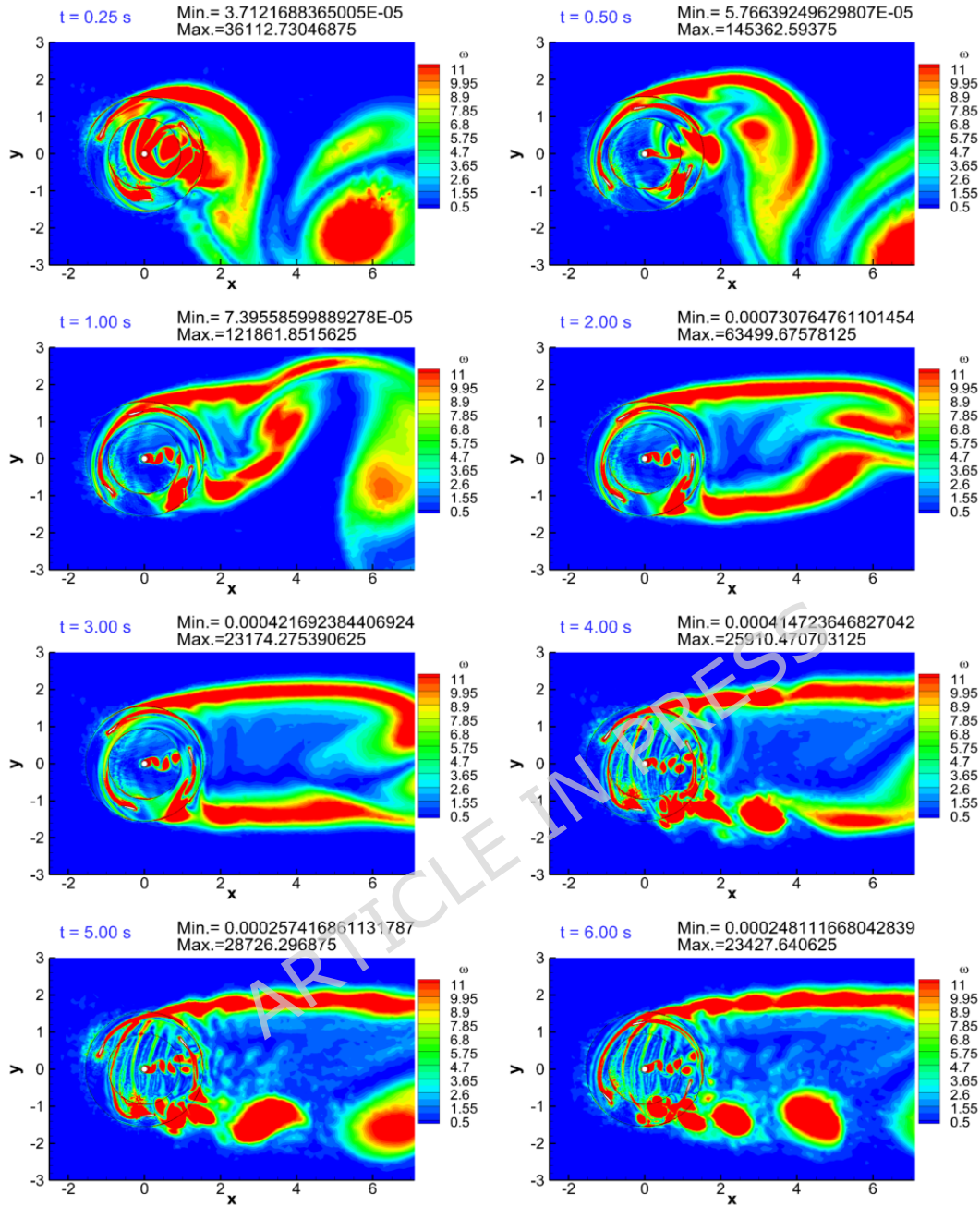


Figure 18: ω -contours for NACA 0012 at different times, $V = 8\text{m/s}$, $\text{TSR} = 2$

Figures 17 and 18 present the instantaneous vorticity contours for the NACA0012-based three-bladed VAWT at freestream velocities of 6 m/s and 8 m/s, respectively, illustrating the influence of inflow velocity on unsteady aerodynamic behaviour.

At 6 m/s (Figure 17), the flow is characterized by periodic two-dimensional vortex shedding from the blade surfaces, with moderately intense vortical structures forming in the near wake. The vortices remain relatively compact and exhibit mild asymmetry, indicating limited flow separation and moderate unsteady loading associated with cyclic blade-wake interaction. At 8 m/s (Figure 18), the vorticity magnitude increases significantly and the shed vortices become more spatially extended. Stronger leading-edge vortex (LEV) formation and shear-layer roll-up are observed, accompanied by enhanced wake turbulence

and increased flow unsteadiness. These features reflect the intensified unsteady aerodynamics at higher inflow velocity and are consistent with the increased torque fluctuations observed in the transient performance results. It is noted that the present simulations are two-dimensional, and therefore the observed vortical structures represent planar vortex shedding and LEV dynamics, rather than three-dimensional blade-tip vortices. Nonetheless, the comparison highlights the clear influence of freestream velocity on vortex strength, wake development, and unsteady aerodynamic loading in the VAWT.

Figures 19 and 20 shows aerodynamic characteristics (C_l , C_d), and Torque Variation for 3-bladed VAWT at Different Freestream Velocities and TSR = 3 with NACA0012 and NACA0015 blade profiles respectively.

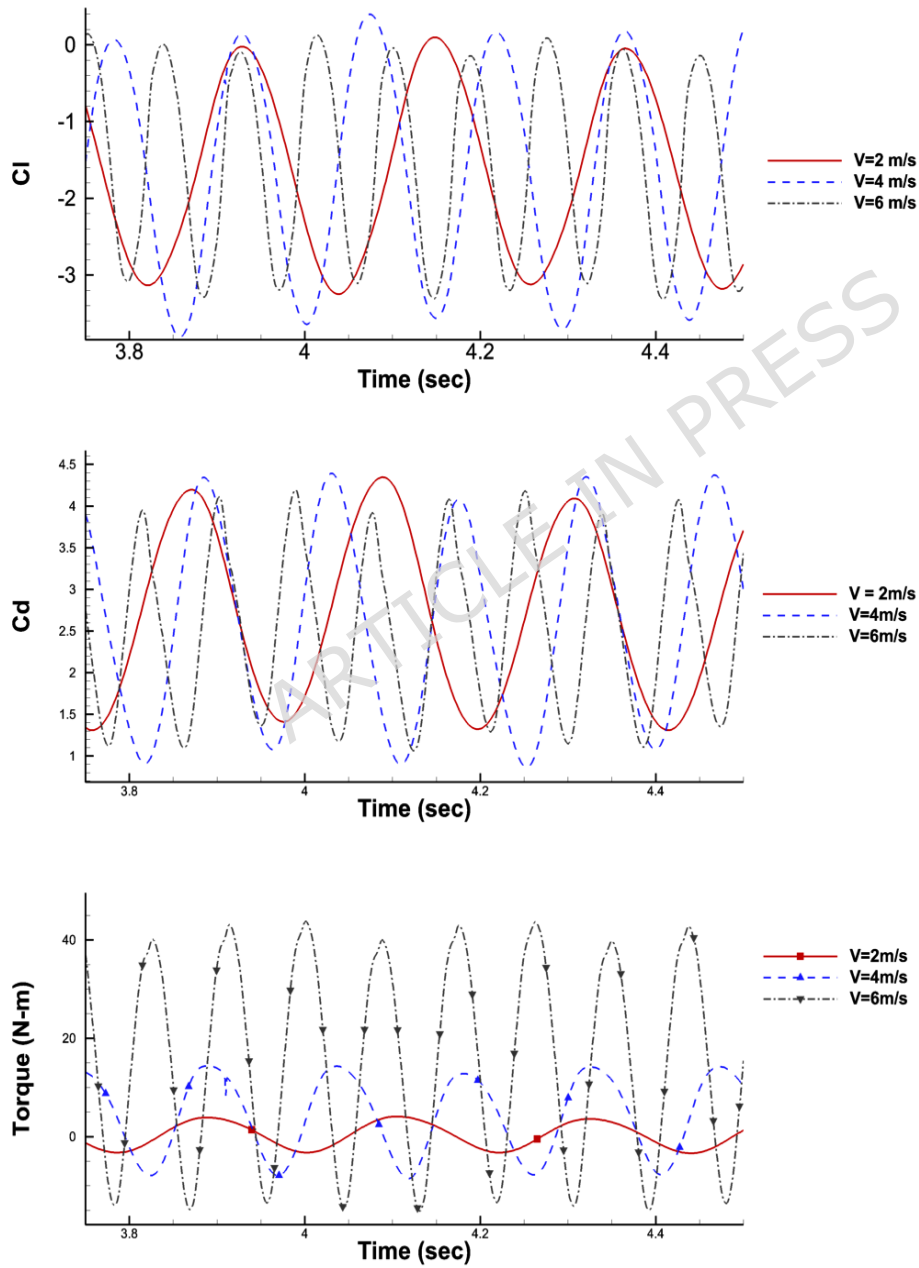


Figure 19: C_l , C_d , and Torque Variation for NACA0012 3-bladed VAWT at different freestream velocities and TSR = 3.

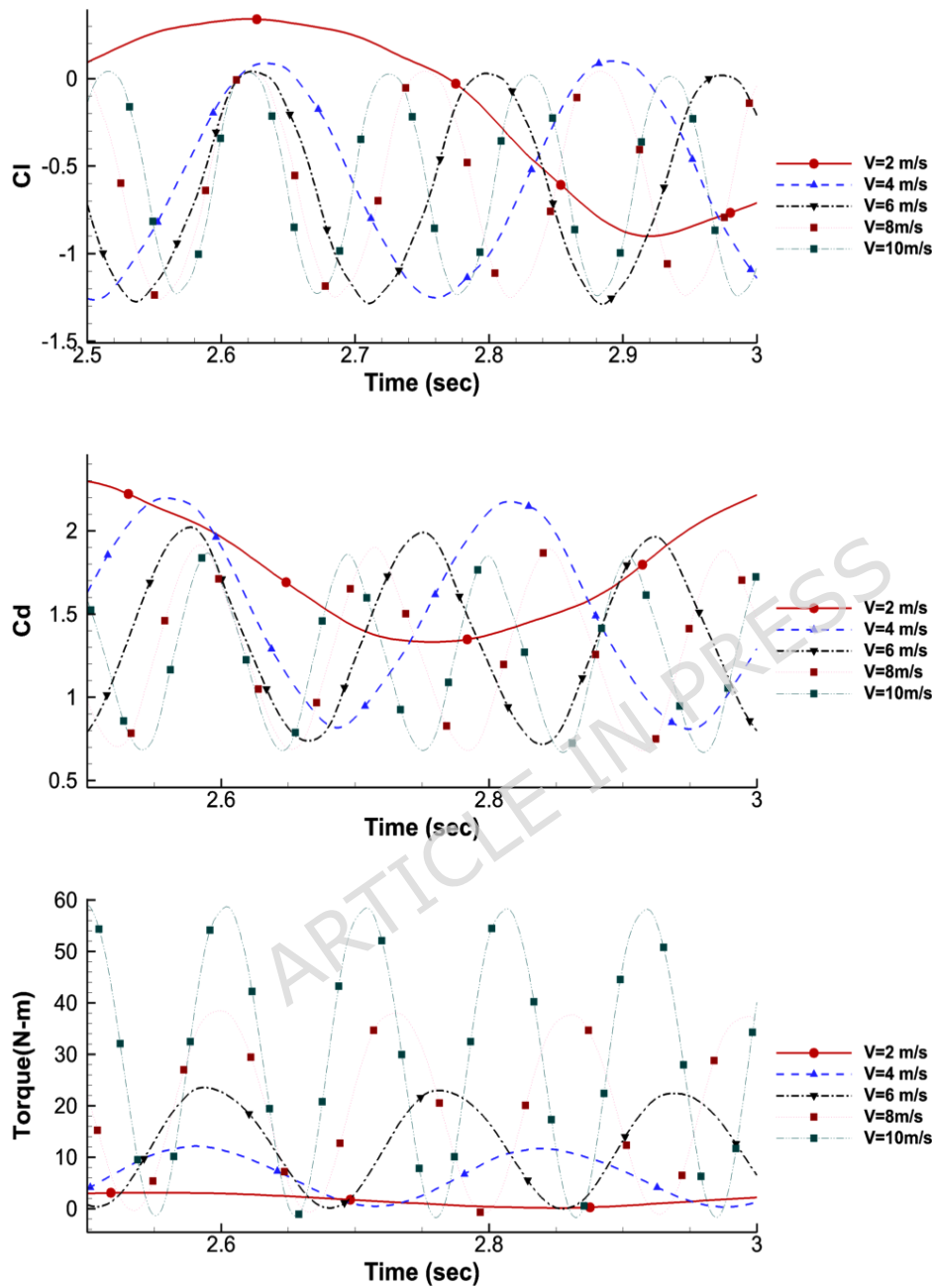


Figure 20: C_l , C_d , and Torque Variation for NACA0015 3-bladed VAWT at different freestream velocities and TSR = 3.

The performance comparison between NACA0012 and NACA0015 airfoils at TSR = 3 across varying freestream velocities (2, 4, 6, 8, and 10 m/s) reveals distinct aerodynamic characteristics and flow physics influencing wind turbine performance.

From these figures, NACA0015 exhibits smoother and more sinusoidal variations in lift coefficient (C_l), drag coefficient (C_d), and torque compared to NACA0012. As the freestream velocity increases,

NACA0015 consistently generates higher and more stable torque outputs, particularly evident at 8 m/s and 10 m/s. This is attributed to its increased relative thickness, enhancing flow attachment and delaying dynamic stall effects during blade rotation.

NACA0012 exhibits more unpredictable variations in aerodynamic forces, particularly in C_l and C_d , which indicates a higher vulnerability to vortex shedding and unstable flow separation at higher velocities. At higher wind speeds, NACA0015 performs noticeably better than NACA0012, according to torque charts, which display a wider and more potent torque profile. This implies higher energy harvesting efficiency when TSR is high. Lift and overall performance are improved by the improved pressure differential between the blade surfaces caused by the higher relative thickness in NACA0015. Because TSR stabilizes aerodynamic forces throughout the rotational cycle, its effects are also more advantageous for NACA0015. On the other hand, the performance of NACA0012 is still susceptible to flow instabilities, which could result in mechanical stress and ineffective torque generation. Overall, NACA0015 is a better option for high-speed wind environments and stable power generation applications due to its superior aerodynamic stability, higher lift-to-drag ratios, and improved adaptability to freestream velocity variations for high-performance VAWTs operating at $TSR = 3$.

Quantitative comparison at $TSR = 3$ within the common velocity range of 2-6 m/s confirms that the NACA0015 rotor provides measurably improved aerodynamic stability over NACA0012. The maximum observed drag level for NACA0015 (≈ 2.2) is nearly 50% lower than that of NACA0012 (≈ 4.5), while the magnitude of the negative lift excursion is reduced from about -3.5 to -1.3, corresponding to an approximately 60% decrease in stall severity. Furthermore, NACA0015 maintains consistently positive torque ($\approx 2-4$ N·m at 2 m/s), whereas NACA0012 exhibits torque reversal with values oscillating between negative and positive limits, indicating loss of useful work during part of the rotation cycle. These quantitative differences demonstrate that the thicker NACA0015 airfoil mitigates dynamic stall effects and yields more stable energy extraction, thereby making it more suitable for VAWT operation at medium to high tip-speed ratios.

Table -8 presents the cycle-averaged aerodynamic characteristics of the NACA0012 and NACA0015 airfoils at a constant tip-speed ratio of 2.5. The results indicate that the NACA0015 airfoil consistently outperforms the NACA0012 airfoil in terms of aerodynamic torque generation throughout the investigated wind-speed range. The mean aerodynamic torque increases from 1.289 N·m at 2 m/s to 32.185 N·m at 10 m/s for the NACA0015 airfoil, whereas the corresponding values for the NACA0012 airfoil range from 0.335 N·m to 17.466 N·m. In addition, the NACA0015 profile exhibits consistently lower Moment Fluctuation Index (MFI) values (102–109%) compared with NACA0012 (122–165%), indicating a smoother temporal variation of aerodynamic loading. The reduced fluctuation, together with the higher cycle-averaged aerodynamic torque, demonstrates that the NACA0015 airfoil provides improved aerodynamic performance under the investigated operating conditions at $TSR = 2.5$. Furthermore, the lower mean drag coefficient observed for NACA0015 suggests more efficient aerodynamic loading, while the comparatively larger magnitude of the mean lift coefficient for NACA0012 does not translate into superior torque generation.

Table 8: Comparison of cycle-averaged aerodynamic characteristics of NACA0012 and NACA0015 airfoils operating at a tip-speed ratio (TSR) of 2.5. The statistical quantities were computed after excluding the initial 500 time steps to eliminate start-up transients, and the remaining periodic solution was used for averaging.

Wind Speed, V_∞ (m/s)	Airfoil	Mean (C_l)	Mean (C_d)	Mean Torque (N·m)	Moment Fluctuation Index (MFI, %)
---------------------------------	---------	-------------------	-------------------	----------------------	--------------------------------------

2	NACA0012	-1.482	2.827	0.335	164.77
	NACA0015	-0.640	1.473	1.289	109.38
4	NACA0012	-1.561	2.730	2.381	143.37
	NACA0015	-0.601	1.394	5.403	105.63
6	NACA0012	-1.423	2.605	8.649	126.59
	NACA0015	-0.589	1.259	10.545	105.55
8	NACA0012	-1.396	2.579	15.919	122.24
	NACA0015	-0.594	1.277	19.709	104.06
10	NACA0012	-1.545	2.539	17.466	132.45*
	NACA0015	-0.586	1.293	32.185	102.50

The cycle-averaged lift coefficient, drag coefficient and aerodynamic moment were computed as

$$\bar{\phi} = \frac{1}{N} \sum_{i=1}^N \phi_i, \text{ where } \phi \text{ represents } C_l, C_d \text{ or aerodynamic moment, } N \text{ is the total number of samples}$$

considered after removing the initial transient, and ϕ_i denotes the instantaneous value at the i^{th} time step. The normalized moment fluctuation index is defined as $MFI = 100 * (M_{\max} - M_{\min}) / |M_{\max}|$, where, $M_{\max}$ = maximum aerodynamic moment and $M_{\min}$ = minimum aerodynamic moment. The MFI quantifies the cyclic variation of the rotor moment during periodic operation. Lower MFI values indicate smoother torque production and reduced cyclic aerodynamic loading.

5. Conclusion

The aerodynamic performance of the investigated VAWT configurations was evaluated over the simulated in 2D configuration and experimentally tested TSR range of 0.5-3.0. The results indicate that stable and repeatable torque and power output are obtained primarily within the TSR range of 2.0-3.0, which corresponds to the operating conditions for which both CFD and experimental data were available. Within this range, the NACA0015-based configuration consistently demonstrates higher mean power coefficient and reduced torque fluctuations compared to the NACA0012-based configuration, attributable to thickness-related aerodynamic effects rather than camber. At TSR values below 1.5, the turbine operates in a highly unsteady regime dominated by large torque oscillations, whereas TSR= 3.0 represent the upper operational limit investigated in the present study.

The geometry of NACA0015 contributed to superior lift generation, delayed dynamic stall onset, and more stable torque output, making it more suitable for decentralized, urban, and semi-urban applications common in India. At medium to high tip speed ratios, the NACA0015-based rotor exhibits consistently higher torque and power coefficients compared to NACA0012. Within the investigated operating range, the improvement is observed as a measurable increase in the cycle-averaged aerodynamic performance, highlighting the practical significance of the thicker airfoil under low-Reynolds-number VAWT operation.

The current work explores the intricate aerodynamic processes that control VAWTs, paying special attention to unstable effects such torque variation, flow separation, dynamic stall, and vorticity distribution. A VAWT's blade rotation introduces constantly shifting angles of attack, which causes cyclic fluctuations in lift and drag that have a major effect on turbine performance. Transient CFD models were used to capture these effects, demonstrating how sensitive the flow field is to variations in freestream velocity and TSRs. Torque generation and stability were found to be influenced by vortex shedding,

asymmetric pressure distribution, and the interaction between upstream and downstream blades. The more coherent wake structures and delayed stall produced smoother torque characteristics, especially for profiles like NACA0015. In order to optimize blade shape and achieve better energy extraction efficiency in real-world wind conditions, the study also highlights the significance of capturing azimuthal flow behavior, pressure coefficients, and transient lift-drag interactions.

In order to enhance self-start characteristics and power production in low-speed regimes, future research should investigate the creation of tailored or hybrid airfoil profiles, maybe including passive flow control features or adaptive materials. Performance adaptability will also be improved by looking at bio-inspired geometries and data-driven design optimization (for example, using AI or genetic algorithms)^{38,50}. These developments are necessary to provide efficient, locally based wind energy harvesting systems that can satisfy India's increasing need for renewable energy.

6. Limitations

The numerical simulations in this study are conducted using a two-dimensional (2D) approach. While this framework effectively captures the primary unsteady aerodynamic features and enables a consistent comparative assessment of blade profiles at low Re , it inherently neglects three-dimensional effects such as tip vortices, spanwise flow, and end losses. It was noted by Howell et al.⁴⁹ that compared to the experimental and 3D CFD models, the 2D computational model predicts a higher performance coefficient and are caused by the existence of over tip vortices. These effects can influence absolute torque and power predictions in real VAWT configurations. Accordingly, the present results should be interpreted in terms of relative performance trends rather than exact turbine output. Extension to fully three-dimensional CFD analysis is identified as an important direction for future work. Further, Fluid-structure interaction (FSI) effects are not considered in the present study, and the blades are assumed to be rigid. Although PLA blades were designed for low-speed wind tunnel testing with minimal deformation, the inclusion of coupled FSI analysis could provide more accurate insights into deformation-induced aerodynamic performance variations and is recommended for future investigations.

7. Future Scope

The present work does not include a comprehensive sensitivity or parametric analysis of Re or blade geometric variations. A comprehensive statistical analysis and uncertainty quantification of unsteady aerodynamic loads is beyond the scope of the present work and is recommended for future investigations. Apart from variation in tip speed ratio, key parameters are intentionally kept constant to enable a focused comparative evaluation of blade profiles under low wind speed conditions. Consequently, the conclusions should be interpreted within the defined operating range, and extended parametric studies are recommended for future work to assess broader robustness. Also, direct experimental validation of NACA-based VAWTs is identified as an important direction for future work. The inference regarding the suitability of the NACA0015 profile for low-wind regions is based on comparative aerodynamic behavior under low-Reynolds-number conditions and is not supported by site-specific operational modeling or field data.

Acknowledgement:

This research was supported by the “University of Debrecen Program for Scientific Publication.” This work has been supported by Department of Science and Technology. - Science and Engineering Research Board (SERB), Govt. of India (Grant No. EEQ/2019/000450). The authors sincerely acknowledge the financial support received for this work. The authors also sincerely thank Padmabhooshan Vasantdada Patil Institute of Technology, Pune, India and University of Debrecen, Hungary, for the infrastructural support and the testing facilities.

Data availability:

Additional data supporting the findings of this study are available from the corresponding author upon reasonable request.

Funding:

This research is carried out with the financial support from Department of Science and Technology. - Science and Engineering Research Board (SERB), Govt. of India (Grant No. EEQ/2019/000450).

Competing interests:

The authors declare no conflict of interest.

Authors' contributions:

Ashish Chaudhari: Conceptualization, Resources, Writing - original draft, Investigation, Methodology, Visualization. **Pramodkumar Bagade:** Conceptualization, Software, Data curation, Methodology, Visualization, Writing - review & editing, Supervision, Funding acquisition. **Avinash Somatkar:** Conceptualization, Validation, Investigation, Data curation, Writing - review & editing. **Masuk Abdullah:** Visualization, Data curation, Writing - review & editing, Project administration. **Preeti Gaikwad:** Software, Data curation, Visualization, Methodology, Writing - review & editing. **Atul Kulkarni:** Validation, Writing - review & editing, and Supervision. **József Menyhárt:** Visualization, Writing - review & editing, Supervision.

References

1. Ben Backwell, GLOBAL WIND REPORT-2023, Global Wind Energy Council, 2023. p. 3, <https://www.enertech.com/wp-content/uploads/2023/12/GWEC-2023-Report.pdf>
2. Davis, N. N., Badger, J., Hahmann, A. N., Hansen, B. O., Mortensen, N. G., Kelly, M., Larsén, X. G., Olsen, B. T., Floors, R., Lizcano, G., Casso, P., Lacave, O., Bosch, A., Bauwens, I., Knight, O. J., Van Loon, A. P., Fox, R., Parvanyan, T., Hansen, S. B. K., . . . Drummond, R. (2023). The Global Wind Atlas: a High-Resolution Dataset of Climatologies and Associated Web-Based application. Bulletin of the American Meteorological Society, 104(8), E1507–E1525. <https://doi.org/10.1175/bams-d-21-0075.1>
3. NIWE- National Institute Of Wind Energy, Chennai, India's Wind Potential Atlas at 150m agl , pp. 8-12, 2023, <https://maps.niwe.res.in/media/150m-report.pdf>
4. NIWE. (2022). Wind Resource Assessment Report. National Institute of Wind Energy, Government of India.p. 26, 2022, https://niwe.res.in/media/annual-reports/Annual_Report_2021-22_english_xAHGlZt.pdf
5. Lee, S. L., & Shin, S. J. (2022). Structural design optimization of a wind turbine blade using the genetic algorithm. Engineering Optimization, 54(12), 2053–2070. <https://doi.org/10.1080/0305215X.2021.1973450>
6. Kumar, R., Stallard, T., & Stansby, P. K. (2020). Large-scale offshore wind energy installation in northwest India: Assessment of wind resource using Weather Research and Forecasting and leveled cost of energy. Wind Energy, 24(2), 174–192. <https://doi.org/10.1002/we.2566>
7. Abul-Ela, M. S., ElRefaie, M. E., & Sayed, A. I. (2025). Enhancing vertical-axis wind turbine self-starting with distinctive blade airfoil designs. Journal of Engineering and Applied Science, 72(1). <https://doi.org/10.1186/s44147-025-00660-6>
8. Howell, R., Qin, N., Edwards, J., & Durrani, N. (2009). Wind tunnel and numerical study of a small vertical axis wind turbine. Renewable Energy, 35(2), 412–422. <https://doi.org/10.1016/j.renene.2009.07.025>

9. Balduzzi, F., Bianchini, A., Maleci, R., Ferrara, G., & Ferrari, L. (2015). Critical issues in the CFD simulation of Darrieus wind turbines. *Renewable Energy*, 85, 419–435. <https://doi.org/10.1016/j.renene.2015.06.048>
10. Rezaeiha, A., Montazeri, H., & Blocken, B. (2018). Towards optimal aerodynamic design of vertical axis wind turbines: Impact of solidity and number of blades. *Energy*, 165, 1129–1148. <https://doi.org/10.1016/j.energy.2018.09.192>
11. Wang, L., Kolios, A., Nishino, T., Delafin, P., & Bird, T. (2016). Structural optimisation of vertical-axis wind turbine composite blades based on finite element analysis and genetic algorithm. *Composite Structures*, 153, 123–138. <https://doi.org/10.1016/j.compstruct.2016.06.003>
12. Bausas, M. D., & Danao, L. a. M. (2015). The aerodynamics of a camber-bladed vertical axis wind turbine in unsteady wind. *Energy*, 93, 1155–1164. <https://doi.org/10.1016/j.energy.2015.09.120>
13. Davari, H. S., Botez, R. M., Davari, M. S., Chowdhury, H., & Hosseinzadeh, H. (2024). Numerical and experimental investigation of Darrieus vertical axis wind turbines to enhance self-starting at low wind speeds. *Results in Engineering*, 24, 103240. <https://doi.org/10.1016/j.rineng.2024.103240>
14. Davari, H. S., Botez, R. M., Davari, M. S., Chowdhury, H., & Hosseinzadeh, H. (2024a). Blade height impact on self-starting torque for Darrieus vertical axis wind turbines. *Energy Conversion and Management X*, 24, 100814. <https://doi.org/10.1016/j.ecmx.2024.100814>
15. Rainbird, J., Peiro, J., & Graham, J. M. (2017). Poststall Airfoil performance and Vertical-Axis wind turbines. *Journal of Propulsion and Power*, 33(5), 1053–1062. <https://doi.org/10.2514/1.b35896>
16. Cao, H., Wu, X., Ye, H., Hu, S., Lu, L., & Peng, J. (2018). Optimization Research on Lift-Type Vertical Axis Wind Turbine Airfoil by CFD. *Journal of Physics Conference Series*, 1064, 012072. <https://doi.org/10.1088/1742-6596/1064/1/012072>
17. Rocha, P. a. C., Rocha, H. H. B., Carneiro, F. O. M., Da Silva, M. E. V., & De Andrade, C. F. (2016). A case study on the calibration of the $k-\omega$ SST (shear stress transport) turbulence model for small scale wind turbines designed with cambered and symmetrical airfoils. *Energy*, 97, 144–150. <https://doi.org/10.1016/j.energy.2015.12.081>
18. Barnes, A., Marshall-Cross, D., & Hughes, B. R. (2021). Validation and comparison of turbulence models for predicting wakes of vertical axis wind turbines. *Journal of Ocean Engineering and Marine Energy*, 7(4), 339–362. <https://doi.org/10.1007/s40722-021-00204-z>
19. Hao, W., Li, C., & Wu, F. (2024). Adaptive blade pitch control method based on an aerodynamic blade oscillator model for vertical axis wind turbines. *Renewable Energy*, 223, 120114. <https://doi.org/10.1016/j.renene.2024.120114>
20. Shen, Z., Gong, S., Zu, H., & Guo, W. (2024). Multi-objective optimization study on the performance of double Darrieus hybrid vertical axis wind turbine based on DOE-RSM and MOPSO-MODM. *Energy*, 299, 131406. <https://doi.org/10.1016/j.energy.2024.131406>
21. Dutta, S., Basack, S., Podder, S., Sarkar, B., & Lucchi, E. (2025). Numerical analysis and optimization of airfoil modeling related to vertical axis wind turbine. *Discover Mechanical Engineering*, 4(1). <https://doi.org/10.1007/s44245-025-00153-z>
22. Dennis, D., Ganesh, P., Joy, J., Amjith, L., & Bavanish, B. (2022). Computational design & analysis of vertical axis wind turbine. *Materials Today Proceedings*, 66, 1501–1508. <https://doi.org/10.1016/j.matpr.2022.06.407>

23. Riley, D., Chen, Y., Lu, C., Mohagheghian, I., Hassanin, H., & Sareh, P. (2025). Morphing structural materials used in wind turbine blades. *Renewable and Sustainable Energy Reviews*, 216, 115618. <https://doi.org/10.1016/j.rser.2025.115618>.
24. Zhang, L., Gu, J., Zhu, H., Hu, K., Li, X., Jiao, L., Miao, J., Liu, J., & Wang, Z. (2020). Rationality research of the adjustment law for the blade pitch angle of H-type vertical-axis wind turbines. *Renewable Energy*, 167, 484–496. <https://doi.org/10.1016/j.renene.2020.11.104>.
25. Athkuri, S. S. C., Nived, M. R., Aswin, R., & Eswaran, V. (2025). Static-stall prediction of airfoils at high Reynolds numbers using hybrid RANS–LES models. *The European Physical Journal Special Topics*. <https://doi.org/10.1140/epjs/s11734-025-01771-0>
26. De Tavernier, D., Ferreira, C., Viré, A., LeBlanc, B., & Bernardy, S. (2021). Controlling dynamic stall using vortex generators on a wind turbine airfoil. *Renewable Energy*, 172, 1194–1211. <https://doi.org/10.1016/j.renene.2021.03.019>.
27. Guo, H., Li, G., & Zou, Z. (2022). Numerical Simulation of the Flow around NACA0018 Airfoil at High Incidences by Using RANS and DES Methods. *Journal of Marine Science and Engineering*, 10(7), 847. <https://doi.org/10.3390/jmse10070847>
28. Rogowski, K., Kubacki, S., & Michna, J. (2025). DNS Dataset of a Thick Symmetric Airfoil at Low Reynolds Number: NACA 0018 with LES Comparison. *Journal of Applied Fluid Mechanics*, 19(2). <https://doi.org/10.47176/jafm.19.2.3738>
29. Berger, M., Raffener, P., Senfter, T., & Pillei, M. (2024). A comparison between 2D DeepCFD, 2D CFD simulations and 2D/2C PIV measurements of NACA 0012 and NACA 6412 airfoils. *Engineering Science and Technology an International Journal*, 57, 101794. <https://doi.org/10.1016/j.jestch.2024.101794>
30. Umar, D. A., Yaw, C. T., Koh, S. P., Tiong, S. K., Alkahtani, A. A., & Yusaf, T. (2022). Design and optimization of a Small-Scale horizontal Axis wind turbine blade for energy harvesting at low wind profile areas. *Energies*, 15(9), 3033. <https://doi.org/10.3390/en15093033>
31. Sharma, D., & Goyal, R. (2023). Methodologies to improve the performance of vertical axis wind turbine: A review on stall formation and mitigation. *Sustainable Energy Technologies and Assessments*, 60, 103561. <https://doi.org/10.1016/j.seta.2023.103561>
32. Zhang, L., Gu, J., Zhu, H., Hu, K., Li, X., Jiao, L., Miao, J., Liu, J., & Wang, Z. (2020). Rationality research of the adjustment law for the blade pitch angle of H-type vertical-axis wind turbines. *Renewable Energy*, 167, 484–496. <https://doi.org/10.1016/j.renene.2020.11.104>.
33. Gosselin, R., Dumas, G., & Boudreau, M. (2016). Parametric study of H-Darrieus vertical-axis turbines using CFD simulations. *Journal of Renewable and Sustainable Energy*, 8(5). <https://doi.org/10.1063/1.4963240>.
34. Kong, Z., & Sun, X. (2025). Numerical Study on Aerodynamic Characteristics of H-Darrieus Wind Turbine with Blunt Trailing-edge Airfoil. *Journal of Applied Fluid Mechanics*, 18(4). <https://doi.org/10.47176/jafm.18.4.3019>
35. Bianchini, A., Ferrara, G., & Ferrari, L. (2014). Design guidelines for H-Darrieus wind turbines: Optimization of the annual energy yield. *Energy Conversion and Management*, 89, 690–707. <https://doi.org/10.1016/j.enconman.2014.10.038>
36. Moon, H., Jeong, J., Jeong, J., Park, S., Ha, K., Jeong, J., & Jeong, J. (2023). Numerical and experimental validation of vortex generator effect on power performance improvement in MW-class wind turbine blade. *Renewable Energy*, 212, 443–454. <https://doi.org/10.1016/j.renene.2023.04.104>.

37. Saad, A. S., El-Sharkawy, I. I., Ookawara, S., & Ahmed, M. (2020). Performance enhancement of twisted-bladed Savonius vertical axis wind turbines. *Energy Conversion and Management*, 209, 112673. <https://doi.org/10.1016/j.enconman.2020.112673>.
38. Chen, Z., Shi, Z., Chen, S., & Yao, Z. (2021). Stall flutter suppression of NACA 0012 airfoil based on steady blowing. *Journal of Fluids and Structures*, 109, 103472. <https://doi.org/10.1016/j.jfluidstructs.2021.103472>
39. Chang, J., Zhang, Q., He, L., & Zhou, Y. (2022). Shedding vortex characteristics analysis of NACA 0012 airfoil at low Reynolds numbers. *Energy Reports*, 8, 156–174. <https://doi.org/10.1016/j.egyr.2022.01.149>
40. Von Krauland, A., & Jacobson, M. Z. (2024). India onshore wind energy atlas accounting for altitude and land use restrictions and co-located solar. *Cell Reports Sustainability*, 1(5), 100083. <https://doi.org/10.1016/j.crsus.2024.100083>
41. Bagade, P. M., Bagade, P. P., Chaudhari, A., Ranjan, P., Shirke, S., & Sedani, C. (2023). Numerical investigation on aerodynamic performance of helical Savonius rotor inspired by natural shapes. *Journal of Mines Metals and Fuels*, 1697–1705. <https://doi.org/10.18311/jmmf/2023/35859>
42. Pramodkumar M. Bagade, Preeti P. Bagade, Prabhat Ranjan, Amit Chakravorty, Eeshan Kamath and Omkar Mogare. (2023). Numerical Analysis of Vertical Axis Wind Turbine with Different Profiles. *Journal of Mines, Metals and Fuels*, 71(11): 2176-2184. DOI: <https://doi.org/10.18311/jmmf/2023/36046>.
43. Saha, U., Thotla, S., & Maity, D. (2008). Optimum design configuration of Savonius rotor through wind tunnel experiments. *Journal of Wind Engineering and Industrial Aerodynamics*, 96(8–9), 1359–1375. <https://doi.org/10.1016/j.jweia.2008.03.005>.
44. Ndindayino, O., Puel, A., & Meyers, J. (2025). Effect of blockage on wind turbine power and wake development. *Wind Energy Science*, 10(9), 2079–2098. <https://doi.org/10.5194/wes-10-2079-2025>
45. Suryanarayana, G. K., & Yanamashetti, G. (2021). Effect of wind tunnel model blockage on aerodynamic characteristics at transonic speeds. *Journal of Spacecraft and Rockets*, 59(1), 353–357. <https://doi.org/10.2514/1.a35222>
46. Lagos, F., Menacer, B., Salas, A., Narayan, S., Medina, C., Valle, R., Garrido, C., Pincheira, G., Oñate, A., Hunter-Alarcón, R., & Tuninetti, V. (2025). Recent advances in the analysis of functional and structural polymer composites for wind turbines. *Polymers*, 17(17), 2339. <https://doi.org/10.3390/polym17172339>
47. Younoussi, S., & Ettaouil, A. (2024). Calibration method of the k- ω SST turbulence model for wind turbine performance prediction near stall condition. *Heliyon*, 10(1), e24048. <https://doi.org/10.1016/j.heliyon.2024.e24048>
48. S. Martínez-Aranda, A. L. García-González, L. Parras, J. F. Velázquez-Navarro, C. del Pino, Comparison of the Aerodynamic Characteristics of the NACA0012 Airfoil at Low-to-Moderate Reynolds Numbers for any Aspect Ratio, *International Journal of Aerospace Sciences* 2016, 4(1): 1-8, DOI: <https://doi.org/10.5923/j.aerospace.20160401.01>
49. Howell, R., Qin, N., Edwards, J., & Durrani, N. (2009). Wind tunnel and numerical study of a small vertical axis wind turbine. *Renewable Energy*, 35(2), 412–422. <https://doi.org/10.1016/j.renene.2009.07.025>

50. Pourrajabian, A., Dehghan, M., & Rahgozar, S. (2021). Genetic algorithms for the design and optimization of horizontal axis wind turbine (HAWT) blades: A continuous approach or a binary one? *Sustainable Energy Technologies and Assessments*, 44, 101022. <https://doi.org/10.1016/j.seta.2021.101022>
51. Ioana-Octavia Bucur, Daniel-Eugeniu Crunt ,eanu and Mădălin-Constantin Dombrovschi, Aerodynamic Performance Improvement of a Straight-Bladed Vertical Axis Wind Turbine Through a Modified NACA0012 Profile with Inclined Orifices, *Inventions* 2026, 11, 37. <https://doi.org/10.3390/inventions11020037>