

CFD Validation and Comparative Performance Analysis of a Micro Vertical-Axis Wind Turbine Using NACA 0018 and S822 Airfoils

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ABSTRACT

This study investigates the aerodynamic performance of a micro vertical-axis wind turbine (VAWT) by comparing the baseline NACA 0018 airfoil with the S822 airfoil using computational fluid dynamics (CFD). The novelty of the study lies in validating a transient two-dimensional sliding-mesh CFD framework and using it to compare a conventional VAWT airfoil with a dedicated small-wind airfoil while identifying the shift in the effective operating tip-speed ratio (TSR) range. A comparison with published CFD data showed good agreement, with a root mean square error (RMSE) value of 0.0176 and R^2 of 0.48 for the compared power-coefficient points. The NACA 0018 airfoil and the S822 airfoil achieved a peak power coefficient of 0.2635 and 0.2077, with a TSR of 2.3477 and 2.6147, and peak average torque of 6.358 N · m and 4.500 N · m, respectively. Further, for the S822 airfoil, the comparison showed that the effective operating range shifted toward higher TSR values. These findings confirm the importance of airfoil selection for micro VAWT applications and verify its suitability for future optimization in urban and low-wind-speed environments.

Keywords: vertical-axis wind turbine, micro wind turbine, CFD validation, NACA 0018, S822 airfoil, tip-speed ratio

1. INTRODUCTION

Vertical-axis wind turbines (VAWTs) have attracted increased attention for small-scale and urban wind energy applications owing to their ability to operate under multidirectional and turbulent wind conditions and their small installation footprint. Their aerodynamic performance depends largely on the blade design, especially the airfoil shape, which affects the lift, drag, torque generation, and dynamic stall during rotation. In urban and low-speed wind conditions, these aerodynamic effects are particularly important for achieving a useful turbine performance^{1,2}.

Previous studies have examined the influence of airfoil geometry on the performance of Darrieus-type VAWTs using both computational and experimental approaches. Earlier work has shown that the blade thickness and camber can significantly affect the turbine performance for different values of tip-speed ratio (TSR)³. Computational fluid dynamics (CFD)-based prediction models have been developed to estimate the performance and blade aerodynamic forces of straight-bladed Darrieus turbines, and the results were validated with experimental data⁴. Subsequent studies have demonstrated that reliable VAWT prediction requires consideration of the validation strategy, mesh resolution, time step, and fully unsteady modeling^{5,6}. Rezaeiha et al.⁷ demonstrated that domain size and azimuthal increment can significantly affect the predicted performance of a VAWT, while Bianchini et al.⁸ showed that accurately configured two-dimensional (2D) CFD simulations can reproduce both the

performance curve and the wake behavior with reasonable accuracy. Further, Franchina et al. showed that three-dimensional (3D) effects and boundary condition treatment become increasingly important when the full VAWT flow field is examined in detail. More recent research comparing NACA 0018 with positively and negatively cambered airfoils has shown that airfoil performance can vary over a wide operating range, and that a negative camber does not necessarily improve overall turbine efficiency¹⁰.

However, most of these studies focused on conventional NACA or similar airfoils, and there has been relatively little attention on replacing NACA 0018 with a dedicated small-wind airfoil. The present study addresses this gap by assessing the aerodynamic performance of the S822 airfoil in comparison with the NACA 0018 for a micro VAWT under the identical flow and operating conditions. Although S822 was originally developed for small wind turbines, it was designed for low-Reynolds-number operations with limited maximum lift, low profile drag, and reduced sensitivity to surface roughness, making it a strong candidate for small-wind applications¹¹. The present work aims to validate a transient 2D sliding-mesh CFD framework and use it to compare a conventional VAWT airfoil (NACA 0018) with a dedicated small-wind airfoil (S822), highlighting both the difference in peak performance as well as the shift in the effective operating TSR range. Accordingly, the first objective of this study is to validate the CFD model using reference data to determine the reliability of numerical predictions. Second, this study

compares the performances of NACA 0018 and S822 in terms of their power coefficient, average torque, and TSR.

The remainder of this paper is organized as follows: Section 2 presents the methodology, including the CFD model, computational domain, mesh generation, boundary conditions, and solver settings. Section 3 presents the aerodynamic performance analysis and the main performance indicators used in this study. Section 4 presents the results and discussion, focusing on numerical validation and an aerodynamic comparison between NACA 0018 and S822. Finally, Section 5 summarizes the main conclusions of this study.

2. METHODOLOGY

This section describes the numerical procedure used to evaluate the aerodynamic performance of baseline NACA 0018 and S822 airfoils for a micro-straight-bladed VAWT. A 2D unsteady CFD model was adopted to capture the main aerodynamic behavior of the turbine while maintaining low computational cost. To ensure a consistent comparison, both airfoils were analyzed using the same turbine geometry, inlet wind speed, selected rotational speed, and performance indicators.

2.1. Numerical Model and Computational Domain.

The turbine was modeled as a micro H-Darrieus rotor with three straight blades spaced 120° apart. The aerodynamic performance of the micro VAWT was investigated using a 2D transient CFD model [Figure 1](#) and [Table 1](#). The baseline turbine geometry consisted of a blade chord with a length of 0.246 m and a rotor with

a diameter of 1.7 m. In the present study, the same turbine geometry and operating conditions were maintained, while the blade profile was changed from NACA 0018 to S822 to evaluate the influence of the airfoil selection on the turbine performance. A 2D approach was adopted because it can provide reliable aerodynamic predictions for Darrieus VAWTs when the computational domain is sufficiently large and the unsteady blade–wake interaction is accurately captured^{5,8,9}.

The computational domain is divided into two main regions, namely a fixed outer domain and a rotating inner domain. The outer domain is rectangular, representing the surrounding flow field, whereas the inner domain is circular and encloses the rotating blades. The diameter of the rotating region is 2.2 m. The outer domain dimensions were set to $L1 = 40D$, $L2 = 100D$, and $W = 60D$, where D is the turbine diameter. This large domain size was used to reduce the blockage effects and enable the wake to develop without strong interference from the domain boundaries. The interface between the fixed and rotating regions is defined as a sliding interface that allows transient blade motion relative to the stationary flow field⁷.

A uniform inlet velocity of 8 m/s was applied at the upstream boundary of the fixed domain. The outlet boundary was defined as a pressure outlet at atmospheric pressure, and symmetric boundary conditions were imposed on the lateral boundaries. The rotating inner domain contained three S822 blades and was rotated at the prescribed angular velocity corresponding to the selected turbine speed. This configuration was chosen because the sliding-mesh method provides a more realistic representation of the unsteady flow around the blades and wake interaction than

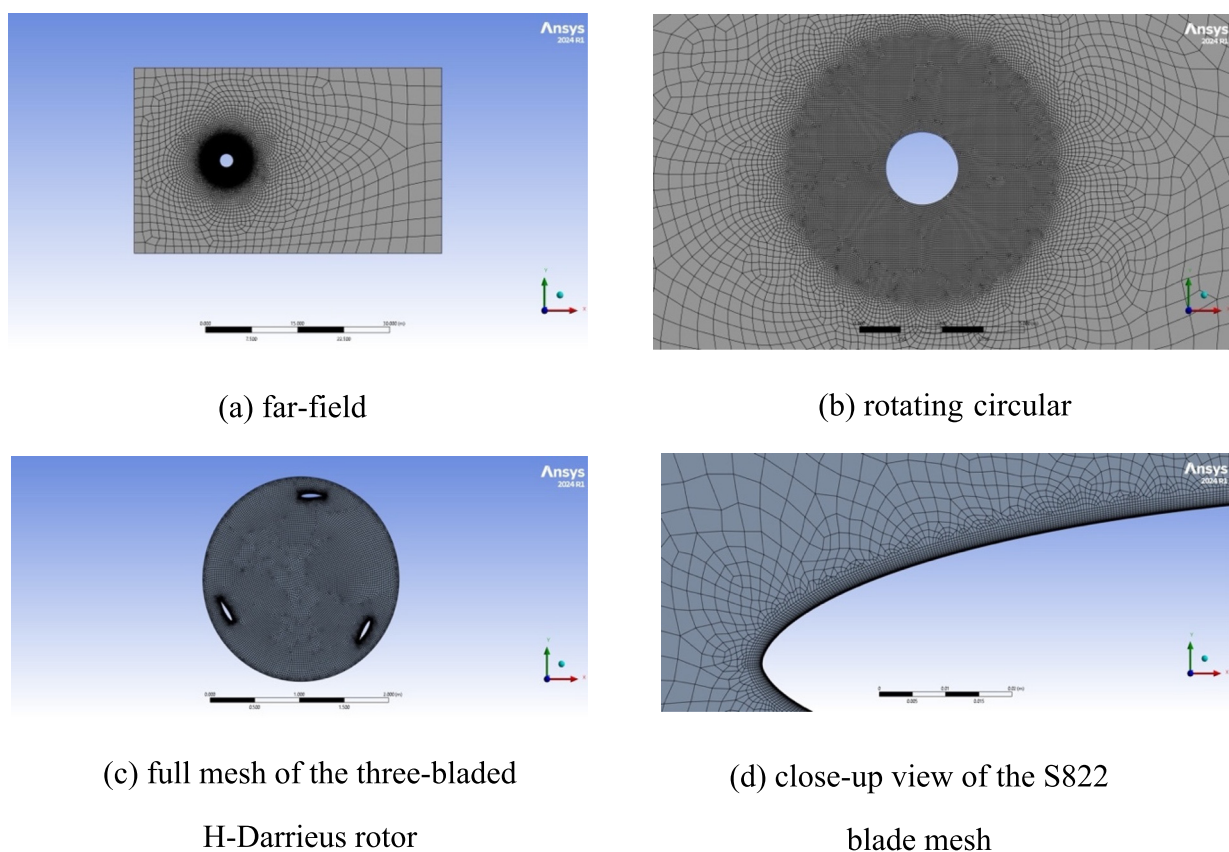


Figure 1. Numerical model and computational domain used in the CFD simulation

Table 1. Main geometric and operating parameters of the CFD model

Parameter	Value
Turbine type	Straight-bladed H-Darrieus VAWT
Airfoils	NACA 0018 and S822
Number of blades	3
Blade spacing	120°
Blade chord length	0.246 m
Rotor diameter	1.7 m
Rotating domain diameter	2.2 m
Free-stream wind speed	8 m/s
Selected rotational speeds	180, 211, 235, 249 rpm
Corresponding TSR values	2.003, 2.348, 2.615, 2.770
Mesh type	Refined hybrid 2D CFD mesh
Number of mesh elements	240,637
Simulation approach	2D transient sliding mesh

steady or moving reference-frame approaches^{5,7}. Accordingly, this computational domain and boundary condition arrangement served as the basis for the CFD analysis of the S822 airfoil in this study.

2.2. Mesh Generation and Boundary Conditions. A 2D computational mesh was generated for both the stationary and rotating domains of the micro VAWT. The stationary outer domain represented the surrounding flow field, while the rotating inner circular domain contained the three turbine blades. A refined mesh was applied in the rotating region and near the blade surfaces to improve the prediction of the boundary-layer flow and wake development. Then, additional local refinement was introduced near the leading and trailing edges of the S822 airfoil, where strong pressure and velocity gradients were expected. Figure 2 shows the mesh distribution used in the present CFD model, including the full mesh of the rotating domain and a close-up view of the blade mesh.

The mesh density was gradually reduced with increasing distance from the blade surfaces to maintain computational efficiency while preserving solution accuracy near the rotor. The interface between the stationary and rotating regions was defined using a sliding-mesh approach, which enabled the transient movement of the blades relative to the surrounding flow field. This method was selected because it provides a more realistic description of the unsteady blade–wake interaction in Darrieus-type VAWTs compared with steady-state approaches^{4,5}. In the present study, the reported simulations were performed using Mesh1, which consisted of 240,637 elements.

A uniform inlet velocity of 8 m/s was applied at the upstream boundary of the stationary domain. The downstream boundary was defined as the pressure outlet, and symmetry boundary conditions were applied to the upper and lower boundaries of the far-field domain. For a fair aerodynamic comparison, the same boundary conditions were used for both the NACA 0018 and S822 airfoils. Transient simulations were performed at rotational

speeds of 180, 211, 235, and 249 rpm, corresponding to TSR values of 2.003, 2.348, 2.615, and 2.770, respectively. These cases were selected because they provided the most reliable results for the present mesh configuration.

For both airfoils, the selected simulation cases considered in this study correspond to rotational speeds of 180, 211, 235, and 249 rpm. The same turbine geometry, inlet velocity, and mesh configuration were used in both cases, and the observed performance differences were attributed mainly to the effect of the airfoil shape. This setup provides a reliable basis for validating the numerical model and for conducting a subsequent comparison between NACA 0018 and S822.

3. AERODYNAMIC PERFORMANCE ANALYSIS

The aerodynamic performance of the micro VAWT was evaluated using the main numerical outputs obtained from the CFD simulations, namely the power coefficient and average torque. These parameters were used to assess the effect of airfoil selection on the turbine behavior for selected rotational speeds. The analysis was first performed for the baseline NACA 0018 airfoil and then extended to the S822 airfoil under the same inlet wind speed and selected rotational speeds. This approach provides a consistent basis for evaluating the influence of the airfoil geometry on the aerodynamic response of the turbine.

3.1. Performance Indicators. The aerodynamic behavior of the turbine was assessed using two main indicators, namely the power coefficient and average torque. These quantities were selected because they provide a clear measure of the turbine efficiency and aerodynamic loading under simulated operating conditions.

3.1.1. Power coefficient evaluation. The power coefficient was used as the primary indicator of the aerodynamic efficiency. It describes the ability of a turbine to convert the available wind power into useful mechanical power. In the present study,

Table 2. Key aerodynamic quantities used in the present analysis

Quantity	Symbol	Purpose in this study
Power coefficient	C_p	Used to evaluate aerodynamic efficiency and compare the overall turbine performance of NACA 0018 and S822
Average torque	T_{avg}	Used to represent the aerodynamic loading generated by the turbine at each simulated RPM
Tip-speed ratio	TSR or λ	Used to compare turbine behavior under different operating conditions
Rotational speed	RPM	Used to define the simulated operating points for each airfoil

the variation in the power coefficient with the TSR was analyzed to identify the operating range in which the turbine achieves maximum efficiency and to compare the aerodynamic behavior of the NACA 0018 and S822 airfoils under identical conditions.

3.1.2. Average torque evaluation. The second performance indicator considered in this study was the average torque generated by the turbine at each simulated rotational speed. Average torque was used instead of the instantaneous oscillating torque history, as it provides a clearer and more representative measure of the aerodynamic loading of the turbine. This makes it more suitable for comparing the two airfoils and for relating the torque response to the corresponding power-coefficient behavior.

The key aerodynamic quantities used in the present analysis are summarized in Table 2.

3.2. Solver Settings and Result Extraction. CFD simulations were performed using a 2D transient sliding-mesh approach to capture the unsteady blade–wake interaction of a micro vertical-axis wind turbine. The sliding-mesh method was selected because it provides a more realistic representation of the rotor motion and wake development when compared with moving-reference-frame approaches for Darrieus-type turbines^{5,7}. The same numerical framework was applied to both NACA 0018 and S822 airfoils to ensure a fair comparison under identical operating conditions. The Shear Stress Transport (SST) $k-\omega$ turbulence model was adopted in the present study.

Transient simulations were performed using a time step of 0.00013 s, and the physical time was obtained by multiplying the number of time steps by the selected time step. The selected operating points were 180, 211, 235, and 249 rpm. In the reference study used for validation, the solution was advanced for a sufficient number of revolutions until the aerodynamic response approached a stable periodic behavior, and the average torque was extracted only after the initial transient stage decayed⁵. In

the present work, the same approach was followed to improve the reliability of the comparison between the two airfoils.

To determine the stable periodic region of the transient response, a representative instantaneous torque-time history of the S822 airfoil was examined at 211 rpm. As shown in Figure 3, the torque signal initially exhibits transient behavior and then approaches a nearly periodic oscillation. Therefore, the average torque reported in this study was calculated from the stable periodic region rather than from the initial transient stage. This procedure enables a more representative measure of the aerodynamic loading generated by the turbine under each operating condition.

4. RESULTS AND DISCUSSION

The CFD results show that the aerodynamic performance of the micro VAWT was significantly affected by the airfoil selection. In general, the baseline NACA 0018 airfoil provided a better overall performance than the S822 airfoil under most operating conditions considered for the comparison. This behavior was reflected in both the power coefficient and average torque results. As the turbine power is related to the torque and angular velocity, the generated power can be expressed as

$$P = T\omega \quad (1)$$

where P is the turbine power, T is the aerodynamic torque, and ω is the angular velocity. The power coefficient is given by:

$$C_p = P/(0.5\rho AU^3) \quad (2)$$

where ρ is the air density, A is the frontal area of the turbine, and U is the free-stream wind speed.

4.1. Validation and Power-Coefficient Analysis. The power-coefficient results indicate that the numerical model is

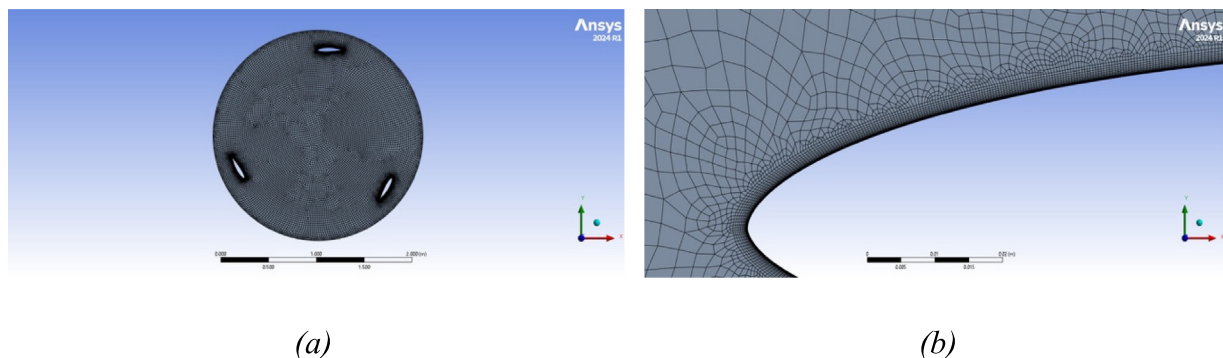


Figure 2. Mesh generation used in the CFD model: (a) full mesh of the rotating turbine domain and (b) close-up view of the refined mesh around the S822 airfoil

suitable for evaluating the aerodynamic behavior of turbines and comparing both airfoils under the same operating conditions. First, this section discusses the validation of the baseline model, and it then examines the effect of airfoil replacement on the C_p response.

4.1.1. Validation of numerical model. The baseline NACA 0018 model was first validated against the published CFD and experimental results. Figure 4 compares the present power coefficient trend with reference literature data¹⁰ and shows that the current CFD model reproduces the general shape of the performance curve with reasonable agreement, particularly in the mid-range operating region. The peak power coefficient predicted by the present model differs from the reference CFD value by approximately 5.2%. The present model predicts an increase in the power coefficient up to the optimum TSR region and captures the subsequent decrease at higher TSR values. This agreement confirms the reliability of the adopted numerical framework and indicates the suitability of the present CFD setup for comparative analysis of different airfoils^{5,8}.

To quantify the agreement between the present CFD results and the reference CFD curve, literature values were interpolated at the present CFD TSR points, and the root mean square error (RMSE) and coefficient of determination (R^2) were calculated. The comparison yielded $RMSE = 0.0176$ and $R^2 = 0.48$ for the power-coefficient values. Although local differences remain near the upper part of the curve, these metrics confirm that the proposed model captures the overall variation and magnitude of the reference performance curve with acceptable accuracy for comparative airfoil assessment.

Owing to the high computational cost of the unsteady sliding-mesh approach and the limited amount of available parallel-processing resources, the present validation focused on four operating points that bracket the peak of the C_p -TSR curve, which represents a region of primary practical interest. The selected TSR values cover the rising branch, peak operating region, and descending branch of the performance curve. In future work, the validation will be extended to a wider TSR range.

4.1.2. Comparison of power coefficient between NACA 0018 and S822. Figure 5 presents a comparison of the variation in the power coefficient with the TSR for the NACA 0018 and S822 airfoils. The results indicate that airfoil selection has a clear influence on the turbine performance. The NACA 0018 airfoil reaches its peak performance at $C_p = 0.2635$ and $TSR = 2.3477$, whereas the S822 airfoil reaches its peak performance at $C_p = 0.2077$ and $TSR = 2.6147$. These results show that the peak operating point of the S822 turbine is shifted to a higher TSR than that of the NACA 0018. For the NACA 0018 airfoil, the effective operating range is approximately $TSR = 1.8$ to 3.0 , while for the S822 airfoil, this range is shifted toward higher TSR values. Under the present simulation conditions, the NACA 0018 airfoil provided higher C_p values than most compared conditions, whereas the S822 airfoil achieved its best performance at a different operating point. Specifically, the S822 airfoil exhibited negative power-coefficient values at $TSR = 2.003$ and 2.348 , indicating unfavorable aerodynamic performance at lower operating conditions, but its performance improved considerably at higher TSR values, reaching a maximum C_p of 0.2077 at $TSR = 2.6147$ and maintaining a similar value at $TSR = 2.770$. In contrast, the NACA 0018 airfoil achieved a higher peak C_p of 0.2635 at $TSR = 2.3477$ and maintained positive power-coefficient values throughout the investigated TSR range. These results indicate that the effective operating range of the S822 airfoil is shifted toward higher TSR values, although its maximum aerodynamic efficiency remains lower than that of the NACA 0018 airfoil under the present operating conditions.

4.2. Average Torque Analysis. The average torque results support the same overall trend observed in the power-coefficient comparison. According to Eq. (1), the turbine power depends directly on the torque, and the average torque response thus provides an additional basis for evaluating the aerodynamic effectiveness of the two airfoils. In this study, the average torque was calculated for each simulated RPM to provide a clearer representation of the turbine performance than the instantaneous oscillating torque history.

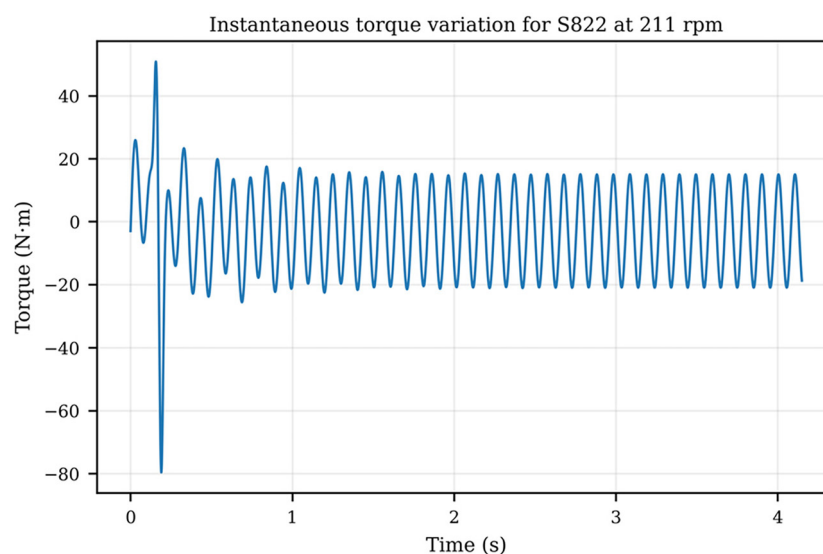


Figure 3. Instantaneous torque variation with time for the S822 airfoil at 211 rpm, showing the periodic response used to determine the average torque extraction

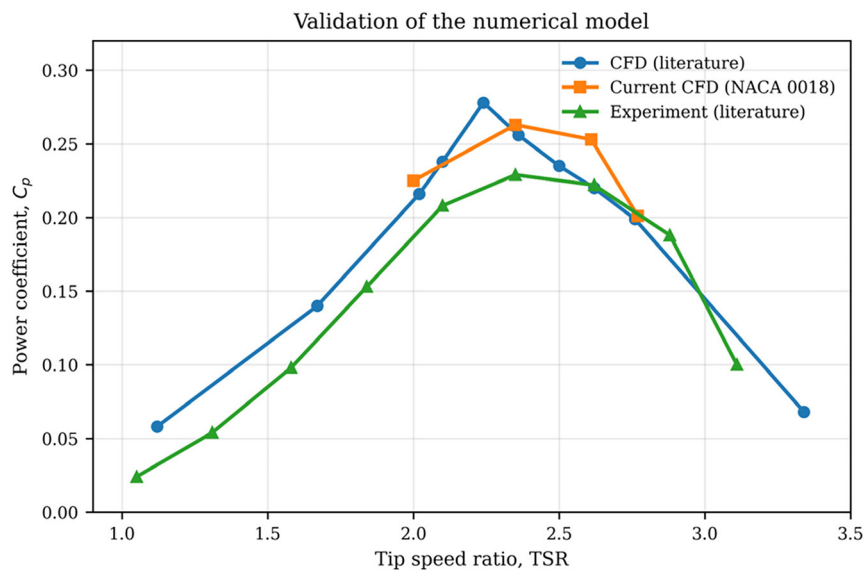


Figure 4. Validation of the numerical model based on the variation of power coefficient with TSR compared with published CFD and experimental results

4.2.1. Comparison of average torque between NACA 0018 and S822. Figure 6 compares the average torque responses of the NACA 0018 and S822 airfoils under the selected operating conditions. The results show differences in the torque-producing behavior of the two airfoils. The NACA 0018 airfoil achieved a maximum average torque of $6.358 \text{ N} \cdot \text{m}$ at $\text{TSR} = 2.3477$, whereas the S822 airfoil achieved a maximum average torque of $4.500 \text{ N} \cdot \text{m}$ at $\text{TSR} = 2.6147$, indicating that the S822 turbine reaches its best response at a higher operating point. In general, the NACA 0018 airfoil produces higher average torque values under most of the compared conditions, whereas the S822 airfoil exhibits a weaker torque response and negative average torque under lower operating conditions.

This difference in the average torque response is consistent with the power-coefficient trends and indicates that the effective

operating range changes when the airfoil is changed from NACA 0018 to S822. Accordingly, the suitability of an airfoil for micro wind-turbine applications should be determined based on its own performance curve rather than by assuming the same optimum operating behavior for different blade profiles.

The main comparison outcomes, including the peak performance and effective operating range of the two airfoils, are summarized in Table 3.

4.3. Study Limitations. The present study has some limitations. First, the numerical analysis was limited to a 2D transient CFD model that did not capture the 3D blade tip effects. Second, a comparison was made for a selected set of operating conditions rather than the full operating range of the turbine. Third, the conclusions were based on numerical results and require additional

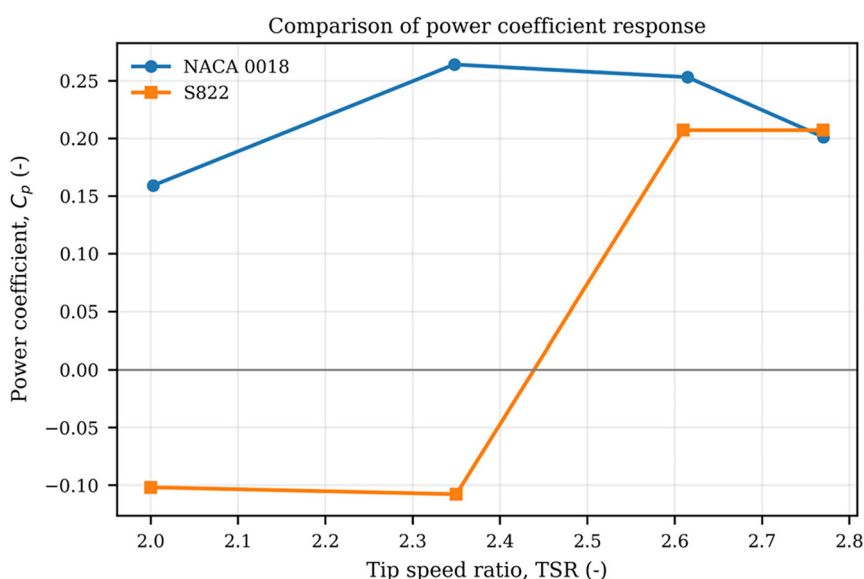


Figure 5. Comparison of power coefficient (C_p) versus TSR for the micro VAWT using NACA 0018 and S822 airfoils

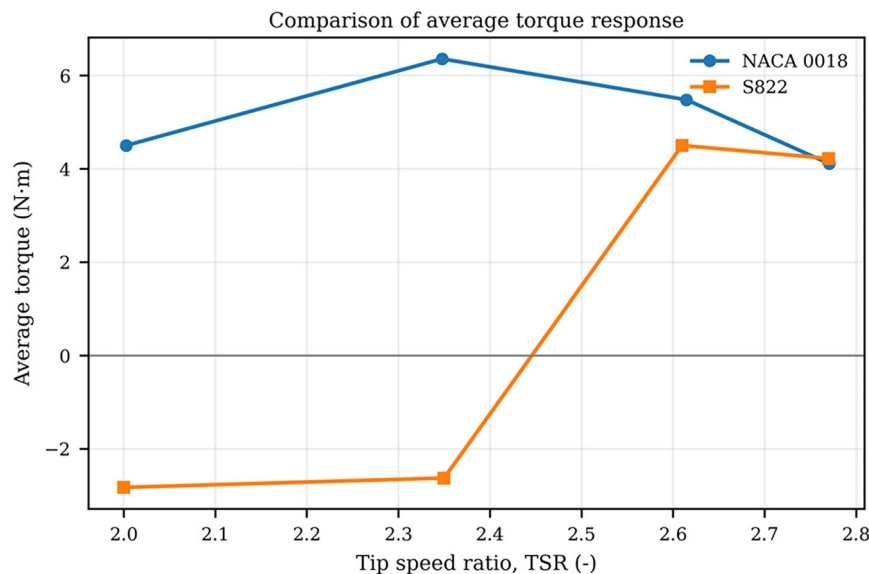


Figure 6. Comparison of average torque versus TSR for micro VAWT using NACA 0018 and S822 airfoils at selected operating points

Table 3. Summary of peak performance and effective operating range of the two airfoils

Airfoil	Peak C_p	TSR at peak C_p	Peak average torque	TSR at peak average torque	Effective TSR range
NACA 0018	0.2635	2.3477	6.358	2.3477	1.8–3.0
S822	0.2077	2.6147	4.500	2.6147	2.5–3.4 (shifted to higher TSR)

experimental validation under the same operating conditions. However, despite these limitations, this study provided useful insights into the influence of airfoil selection on the aerodynamic performance of micro VAWTs.

5. CONCLUSIONS

This study investigated the aerodynamic performance of a micro VAWT using NACA 0018 and S822 airfoils by employing a 2D transient CFD approach. The numerical model was validated, and the aerodynamic behavior of the two airfoils was compared under the same operating conditions. Based on the numerical results, the following conclusions were made:

1. The baseline NACA 0018 model showed acceptable agreement with published CFD and experimental results, supporting the reliability of the adopted numerical framework.
2. The validated model reproduced the expected variation in the power coefficient with the TSR, including an increase toward the optimum operating region and a decrease at higher TSR values.
3. The comparison between the two airfoils showed that airfoil selection had a clear effect on the aerodynamic performance of the micro VAWT.
4. Under the present simulation conditions, NACA 0018 provided a better overall aerodynamic performance than S822 under most of the operating conditions considered for comparison.
5. The average torque results support the same conclusion, as NACA 0018 generally produces higher average torque values

than S822 under most of the operating conditions considered for comparison.

6. Although S822 was originally developed for small wind turbines, the present results indicate that it does not outperform NACA 0018 in the current vertical-axis turbine configurations.
7. Future work should focus on three-dimensional CFD analysis, experimental validation, and further airfoil optimization.

Overall, the present study contributes to the understanding of airfoil selection for small wind turbines and provides a useful basis for future work on airfoil optimization, including increased operating ranges, improved numerical modeling of micro VAWT performance, and experimental validation.

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