QBlade-based aerodynamic investigation of NREL S823 and S815 airfoils under different Reynolds regimes

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Abstract. The efficiency of lift-based wind turbines mainly depends on the selection of airfoils and its performance under various operating flow conditions. So, it is very important to study the airfoil performance, nothing but aerodynamic behaviour, under different flow conditions. Such kind of study is attempted in this work. For that, two airfoils viz., NREL S823 and NREL S815 were selected and analysed using the open source QBlade software, which built on XFOIL. The simulation is carried out under various Reynolds numbers (Re) fluctuating between 0.13×10^5 to 0.26×10^5. From the results, the various aerodynamic characteristics such as lift coefficient (C_L), Sliding ratio also called as Lift to Drag ratio (C_L/C_D), along with Coefficient of Pressure (C_P) were analysed over a range of AoA (angle of attack) i.e., -5° to 20°. The simulation results revealed that, the NREL S823 airfoil demonstrates greater C_L value at lower Re numbers, making it appropriate choice for small-scale wind turbines, while S815 displays smoother stall characteristics and higher C_L/C_D values at higher Re, which is more required for medium scale wind turbines. Moreover, distribution in C_P is a significant factor in deciding which airfoil to apply to the wind turbine designs, whether the design focus is upon the greatest possible operating stability or the ratio of lift to drag performance at variable aerodynamic load. The presented QBlade-based study helps to identify the impact of the Reynolds number on aerodynamic behaviour and offers comparative information on the suitability of the airfoils S823 and S815 in various applications in wind turbines.

1 Introduction

Aerodynamic properties of the wind turbine blade profiles including airfoils are also significant in determining the total efficiency, stability, and energy output of the contemporary wind power systems. The dependence on Reynolds number (Re) is one of the most important aspects of aerodynamic factors that define the laminar-turbulent transition processes, separations, and lift-to-drag ratio in the different regimes of operation. As the collective desire to design turbines on a site-specific basis and in particular areas with low to

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medium wind speed, airfoil selection and performance evaluation in different Reynolds regimes have become essential in maximizing turbine performance [1]. The National Renewable Energy Laboratory (NREL) has created various classes of airfoils specifically used in wind turbines, one of which is the family of S-series airfoils which was commonly used in medium and small-scale wind turbines. The most commonly considered among them were NREL S823 and NREL S815 airfoils that were appropriate in various conditions of operation [2-5]. NREL S823 is made to achieve greater lift characteristics with reduced Re, therefore it is beneficial when working with small wind turbines, where the blade sections tend to have low relative velocities. The S815 on the other hand does provide a balance between lift and drag with the stall behaviour being smoother at higher Reynolds number and thus appealing to medium-large turbines [2].

Re is a very powerful determinant of aerodynamic performance of an airfoil and it determines the relative importance of inertial and viscous forces in fluid flow. In small-scale wind turbines (at low Re) the separation caused by the boundary layer, laminar separation bubbles and premature stall greatly impact efficiency. With larger turbines, with higher Re, the flow will be attached longer, leading to delayed stall and better aerodynamic efficiency. Therefore, the study of the airfoil behaviour over a series of Reynolds number is vital to determining their applicability in the practical in terms of turbines. Low-fidelity analysis tools, including XFOIL, and its built-in platform QBlade, are traditionally popular in making predictions about the aerodynamic polars of airfoils because they are computationally efficient. Although various studies have examined the aerodynamic properties of NREL S-series airfoil, most of them use experimental configurations or high fidelity CFD simulations, which are laborious and time consuming to compute. For instance, Kadrowski et al. [6] focuses on the design and performance analysis of a new blade geometry for small wind turbines using QBlade, incorporating NREL S826 and S834 airfoils. The study emphasizes the importance of Re in rotor performance and validates the blade design through numerical and experimental approaches, demonstrating significant improvements in power coefficient. Seifi Davari et al. [7] focuses on six different airfoil profiles, analyzing modifications to the thickness-to-camber ratio (t/c) to enhance aerodynamic efficiency within a Reynolds number range of 50k to 500k. The study highlights significant improvements in the maximum power coefficient ($C_{p,max}$) for the modified BW-3 airfoil, achieving a 40.5% increase at Re 500k, emphasizing the importance of aerodynamic design for small wind turbines. Tarhan & Yilmaz[8] wroks on14 different small wind turbine airfoils, such as S823, and uses both numerical methods with Ansys Fluent and experimental methods in a wind tunnel to figure out their lift, drag, and lift/drag coefficients. The research investigates these airfoils at Reynolds numbers of 50,000, 100,000, and 200,000. Significant studies on the aerodynamics of the S823 and S815 airfoils are presented in Table 1.

Table 1. Key studies on S823 and S815 airfoil aerodynamics.

Authors	Focus	Methodology	Key Insight
Reddy et al. [[5]	S823 with auxiliary airfoil	Experimental & CFD	10%+ lift increase, better stall
Supreeth et al. [9]	S823 with tubercles	Experimental & CFD	Up to 26% lift increase, soft stall
Reddy et al. [10]	S823 at various Re	QBlade simulation	Higher lift at low Re, validated
Somers [2]	S815 design	Theoretical	High lift, low drag, roughness-insensitive

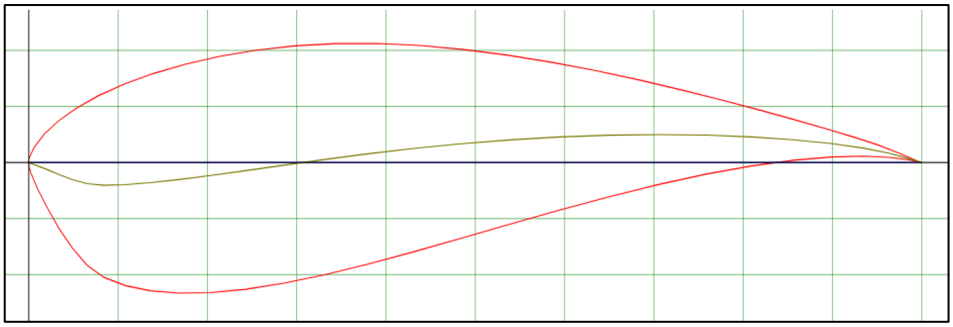
However, limited work has been reported using QBlade, an open-source aerodynamic analysis tool that integrates XFOIL for rapid generation of airfoil polars and wind turbine performance prediction. In particular, comparative studies on NREL S823 and S815 airfoils

across different Reynolds numbers using QBlade alone are scarce in the literature. The novelty of this work lies in employing QBlade as a standalone tool to systematically investigate and compare the lift, drag, and lift-to-drag characteristics of the two airfoils at varying Reynolds regimes, thereby providing valuable preliminary insights for small- and medium-scale wind turbine blade design without the need for resource-intensive simulations.

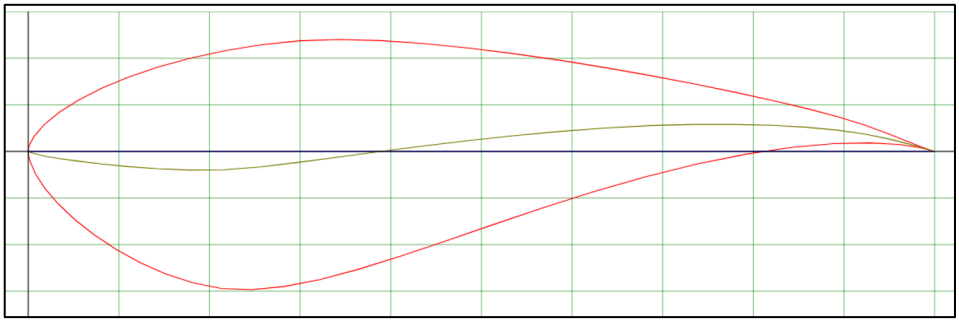
2 Methodology

2.1 Airfoil selection and Re range

The present study focuses on two members of the NREL S-series airfoil family: S823 and S815. These airfoils are specifically designed for wind turbine applications, with S823 being optimized for higher lift performance at lower Re, while S815 poses a balance between ldrag and lift with softer stall behaviour. The geometry coordinates of the airfoils were gotten from the airfoil database and imported into QBlade software for aerodynamic analysis. To capture aerodynamic behaviour under changing flow regimes, analyses were performed at Re 0.13 x 10^5 to 0.26 x 10^5. Figure 1 shows the geometry of selected airfoils - NREL S823 and NREL S815.



(a)



(b)

Fig. 1. Selected airfoil a) NREL S823, and b) NREL S815.

2.2 QBlade setup

QBlade, an open-source wind turbine simulation environment, is used for the aerodynamic analysis. The software integrates the XFOIL solver, which generates airfoil polars by solving coupled inviscid and boundary-layer equations. The aerodynamic simulations in QBlade

were carried out over an angle of attack range from -5° to 20°. A two-dimensional polar computation based on the integrated XFOIL solver is employed to generate the aerodynamic coefficients. The transition model is used the e^n method with a default amplification factor of Ncrit = 9, which represents typical free-turbulence atmospheric conditions. Viscosity effects were included by specifying the corresponding Reynolds numbers for each case. The iterative solver is allowed to run until the default convergence criteria of QBlade were satisfied, ensuring accuracy in the computed polars. The details of Computational setup and airfoil specification specified in Table 2.

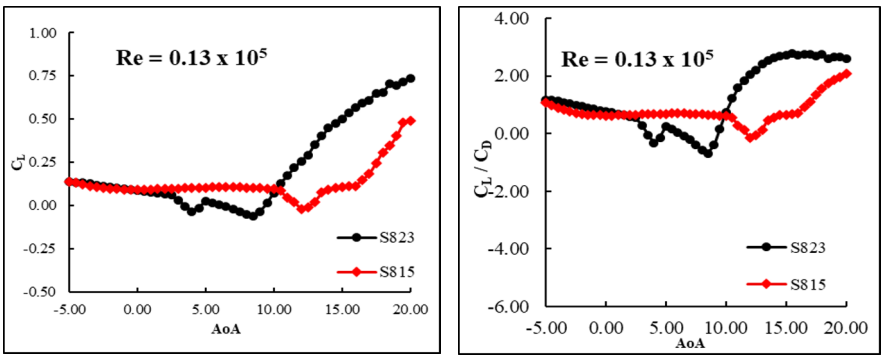
Table 2. Key computational and geometric parameters.

Parameter	Description/value
Re Range	0.13 x 10^5 to 0.26 x 10^5.
Tested AoA Range	-5° to 20°
Transition Model	e^n model with Ncrit = 9
Convergence Criteria	Iterative residual tolerance of 1 × 10^{-6}
Panel Density	200 panels for airfoil
XFOIL Iteration Limit	250
Stall Model Setting	Default XFOIL viscous/inviscid coupling with boundary-layer separation tracking
Maximum Camber	For NREL S823 ; 2.4% at 70.5% chord For NREL S815 ; 2.9% at 77.9% chord
Maximum Thickness	For NREL S823 ; 21.2% at 24.3% chord For NREL S815 ; 26.2% at 25.7% chord

3 Results and discussion

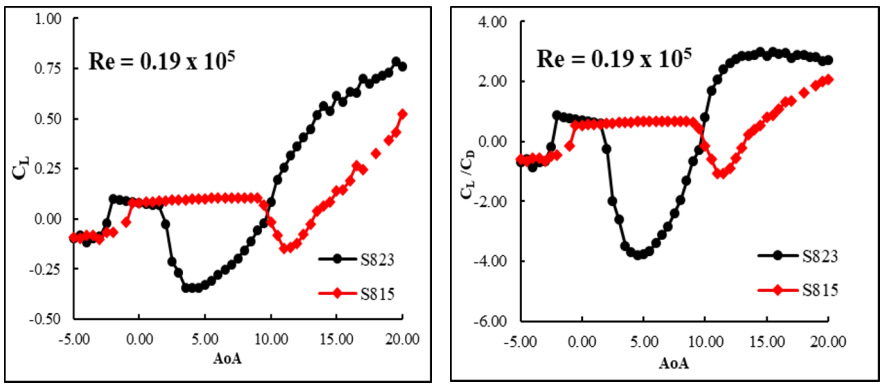
3.1 Aerodynamic analysis

The NREL S823 and S815 airfoils' relative aerodynamic performance at three distinct Reynolds numbers is displayed in Figure 2-4. C_L vs. AoA and C_L/C_D vs. AoA are the two subplots in each figure. which shows notable variations in lift properties and effectiveness. Both of the chosen airfoils produced low C_l values at low lift at Small AoA, as shown in Figure 2(a). However, the S823's C_l rises more sharply beyond 10° AoA, whereas the S815's Cl increases more gradually and has lower peak values. The NREL S823 airfoil is more effective at extracting lift under Re conditions, as shown by the efficacy (C_l/C_d) curves, which show that it performs better than the S815, which stays between 1.5 and 2.0. Both airfoils exhibit improved aerodynamic behaviour as the Reynolds number rises to 0.19×10^5; S823 continuously generates more lift and reaches efficiency values above 3.0, while S815 performs smoother but less efficiently. The trend continues at $Re=0.26\times10^5$, where both airfoils achieve higher C_L and efficiency than at lower Re. However, S823 continues to lead, peaking close to 3.5 in C_l/C_d, while S815 trails slightly.



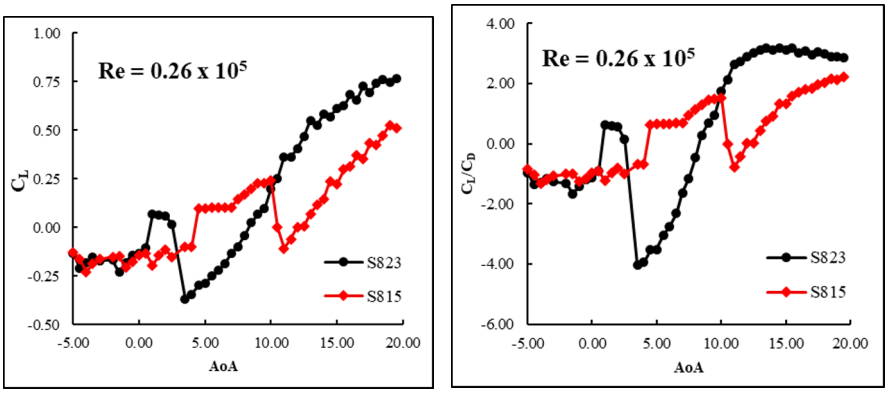
(a) (b)

Fig. 2. Assessment of NREL S823 and S815 airfoils C_L Vs AoA, C_L/C_D Vs AoA at Re = 0.13 x 10^5 (a) C_L Vs AoA, and (b) C_L/C_D Vs AoA.



(a) (b)

Fig. 3. Assessment of NREL S823 and S815 airfoils C_L Vs AoA, C_L/C_D Vs AoA at Re = 0.19 x 10^5 a) C_L Vs AoA, and b) C_L/C_D Vs AoA.



a) b)

Fig. 4. Assessment of NREL S823 and S815 airfoils C_L Vs AoA, C_L/C_D Vs AoA at Re = 0.26 x 10^5 a) C_L Vs AoA, and b) C_L/C_D Vs AoA.

The S823 is more suitable for low Re applications, like small-scale wind turbines, since it displays better lift generation, stronger stall recovery, and higher aerodynamic efficiency overall across the tested Reynolds regimes. The S815, on the other hand, has less efficient but more stable characteristics, which might be advantageous in situations requiring a smoother aerodynamic response at lower AoA.

3.2 Pressure distribution analysis

C_p distribution on the chord gives important information about the aerodynamic loading of an airfoil. The comparison between the viscous predictions and inviscid predictions of the NREL S823 and S815 airfoils is presented in Figures 5 and 6 respectively. The idealized field of flow through the inviscid solutions approximates the flow without viscous losses whereas the viscous solutions are used to take into consideration the effects of the boundary layers and separation of flows.

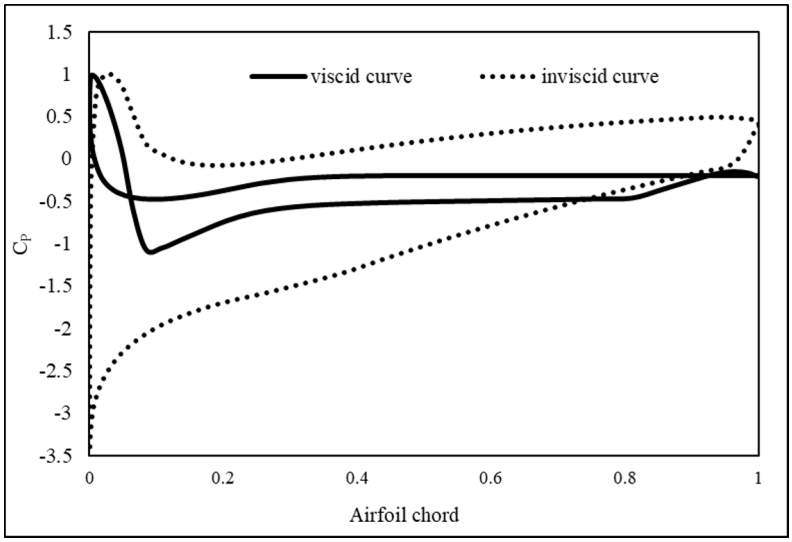


Fig. 5. Coefficient of pressure displays at Re =0.26 x 10^5 and AoA = 7° for NREL S823 airfoil.

In the case of S823 airfoil, (Figure 5), the inviscid curve exhibits high peak of suction at the leading edge then a smooth recovery at the trailing edge. When viscosity is taken into consideration, the peak of suction decreases greatly and the pressure recovery is slower. It means that the viscous effects have a potent impact on the aerodynamic characteristics of the S823 airfoil, especially at the beginning of the edge. The steep suction peak in the inviscid case indicates a possible highly high lift generation, but in reality viscous flow, the suction peak is very small, and the flow separation may occur at a very early stage. This makes the S823 both more prone to sudden stalling behavior, and also able to generate high lift at lower Reynolds numbers. This abrupt stall reaction may reduce its stability of operation and thus its performance will greatly rely on the flow conditions and angle of attack.

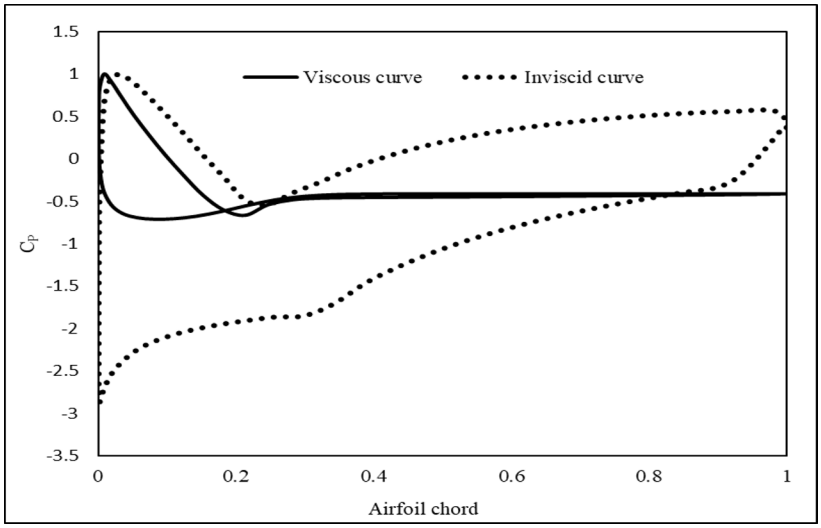


Fig. 6. Coefficient of pressure displays at Re =0.26 x 10^5 and AoA = 7° for NREL S815 airfoil.

As compared to that, S815 airfoil (Figure 6) displays a more balanced aerodynamic response. In spite of the fact that the inviscid solution to S815 also indicates a suction peak at the leading edge, the disparity between viscous and inviscid prediction is much less noticeable than in S823. The distribution of viscous forces in S815 (Figure 6) exhibits a less jagged curve across the chord with a comparatively smaller suction peak and a slow recovery towards the trailing end which is nearly uniform. This behaviour signifies lower-level of sensitivity to viscous effects, which is converted to delayed stall initiation and slower loss of lift. The S815 is therefore better with regard to stall resistance and aerodynamic performance at a broader range of flow conditions. All these observations put together the trade-off between high lift potential and stall stability: S823 provides enhanced aerodynamic performance at the expense of sharp stall tendencies, and S815 compromises some peak efficiency at the expense of smoother and more reliable operation. This difference is fundamental in the choice of the suitable airfoil to use in the wind turbine application, whether the design focus is on the optimal operational stability or the lift to drag efficiency of the airfoil under varying aerodynamic loads.

3.3 Validation

In order to deal with the validity of the current simulation outcomes using QBlade software, an airfoil with known performance properties has been modelled to make a comparison between the theoretical and experimental input. To this end, the NREL S823 airfoil is chosen and a simulation performed at a Re = 2×10^5 to compare with those of the experiment as given in Uma reddy et al. [10]. The Comparison in Figure 7. exhibits the good compliance between the simulation data and experimental data.

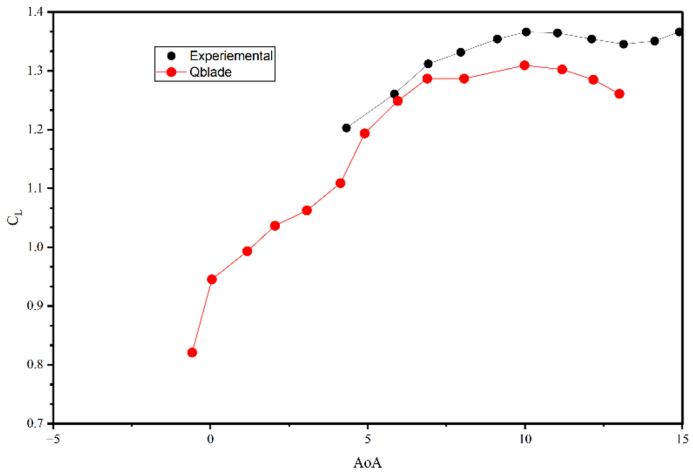


Fig. 7. Validation Plot between present QBlade procedure results vs Experimental results reported in Uma reddy et al [10]. at Re= 2×10^5.

4 Conclusions

Different aerodynamic behaviors that directly affect the NREL S823 and S815 airfoils' suitability for wind energy applications are highlighted in this comparison study of these airfoils under low Re conditions. The NREL S823 has always shown superior performance to the S815 in all operation regimes whereas the two airfoils show higher lift and efficiency as the Re rises. Its robustness for low Re environments is demonstrated by its capacity to produce greater lift, attain superior lift-to-drag ratios, and recover from stall efficiently, especially at medium to high angles of attack. Significantly, the efficiency of the S823 exceeds 3.0 at Re=0.19 x10^5 and approaches 3.5 at Re=0.26 x 10^5 which goes to confirm that it has a high aerodynamic advantage in small-scale wind turbines and other low-speed devices with high energy capture. Conversly, the S815, although less efficient in peak performance, provides smoother aerodynamic response and more gradual stall behaviour at lower angles of attack. These properties render it an attractive option when using it in applications where the stability of operation and predictable load to aerodynamic performance are of importance rather than peak efficiency.

All in all, the results strongly serve to confirm the S823 as a better choice among small-scale wind turbines that would be used in the conditions of a low Reynolds number, with the S815 providing its countermeasures in cases of the need to use it in the context of stability and smoother operation. Besides directing the choice of airfoils in a custom-designed turbine design, these insights also highlight the greater significance of an aerodynamic assessment that is Reynolds-number-dependent in the optimization of wind energy systems. It should be noted, though, that XFOIL and QBlade have certain intrinsic limitations in their applicability to low-Reynolds-number aerodynamic analysis. At Re < 2×10^5, these tools may exhibit reduced predictive accuracy due to simplified transition modeling and the inability to fully capture laminar separation bubble formation and reattachment behavior. The e^n transition model implemented in XFOIL assumes quasi-steady boundary layer development, which can lead to discrepancies in lift, drag, and moment predictions, particularly near stall and in post-stall regimes. Similarly, QBlade's built-in panel and blade-element momentum (BEM) approaches may not fully resolve complex three-dimensional flow effects and dynamic stall phenomena under such flow conditions.

To address these confines and reinforce the assurance in the present numerical findings, upcoming future studies should focus on experimental investigation and validation through controlled subsonic wind-tunnel testing of the selected airfoils and high-fidelity numerical simulations using RANS or LES-based CFD techniques at demonstrative Res and AoA. Such efforts would help quantify model deviations, refine transition predictions, and provide a more comprehensive understanding of aerodynamic behavior under low-Reynolds-number operating conditions.

References

1. Mazarbhuiya, H.M.S.M., Biswas, A., Sharma, K.K.: Blade thickness effect on the aerodynamic performance of an asymmetric NACA six series blade vertical axis wind turbine in low wind speed. Int J Green Energy. 17, 171–179 (2020). https://doi.org/10.1080/15435075.2020.1712214
2. Somers, D.M.: S814 and S815 Airfoils: October 1991--July 1992. National Renewable Energy Lab.(NREL), Golden, CO (United States) (2004)
3. Tenango-Pirin, O., Davalos Ramirez, J.O., Caldiño, U., Martinez, R., Castro, L., García Castrejón, J.C., Rodriguez, J.A.: Shape effect of thickness of the NREL S815 profile on the performance of the H-rotor Darrieus turbine. Instituto de Ingeniería y Tecnología. (2021)
4. Somers, D.M.: S822 and S823 Airfoils: October 1992--December 1993. National Renewable Energy Lab.(NREL), Golden, CO (United States) (2005)
5. Uma Reddy, K., Deb, B., Roy, B., Majumder, P.: Experimental and numerical analysis of NREL S823 airfoil with auxiliary airfoil integration. Energy Sources, Part A: Recovery, Utilization and Environmental Effects. 46, 13633–13653 (2024). https://doi.org/10.1080/15567036.2024.2407470
6. Kądrowski, D., Kulak, M., Lipian, M., Stępień, M., Baszczyński, P., Zawadzki, K., Karczewski, M.: Challenging low Reynolds-SWT blade aerodynamics. 10.1051/matecconf/201823401004
7. Seifi Davari, H., Mihaela Botez, R., Seify Davari, M., Chowdhury, H.: Enhancing aerodynamic efficiency: shape modification of airfoils. International Journal of Ambient Energy. 45, (2024). https://doi.org/10.1080/01430750.2024.2439441
8. Tarhan, C., Yilmaz, I.: Numerical and experimental investigations of 14 different small wind turbine airfoils for 3 different reynolds number conditions. Wind and Structures. 141–153 (2022)
9. Supreeth, R., Arokkiaswamy, A., Anirudh, K., Pradyumna, R.K., Pramod, P.K., Sanarahamat, A.K.: Experimental and numerical investigation of the influence of leading edge tubercles on S823 airfoil behavior. Journal of Applied Fluid Mechanics. 13, 1885–1899 (2020)
10. Reddy, K.U., Deb, B., Roy, B.: Analysis of the aerodynamic characteristics of nrel s823 and du 06-w-200 airfoils at various reynolds numbers using qblade. In: Emerging Trends in Mechanical Engineering: Select Proceedings of ICETMIE 2019. pp. 279–286. Springer (2020)