Benha Journal of Applied Sciences (BJAS) print: ISSN 2356–9751
Vol. (10) Issue (4) (2025), (175- 184) online: ISSN 2356–976x
https://bjas.journals.ekb.eg/
engineering sciences

Aerodynamics Performance Evaluation of S834 Airfoil Using Different Slot Configuration as a Passive Flow Control Method

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Abstract

The global energy crisis has prompted a shift toward renewable energy to reduce emissions and ensure a sustainable future. Wind energy, in particular, has received a lot of attention because it is so widely available. Wind turbines, which convert wind kinetic energy into mechanical energy, are divided into two types: horizontal-axis and vertical-axis turbines. Nevertheless, one of the most significant challenges to wind turbine performance and sustainability is flow separation, which reduces aerodynamic efficiency. This study utilizes a two-dimensional (2D) Computational Fluid Dynamics (CFD) to examine six slot design configurations for the S834 airfoil at a wind speed of 6 m/s. The goal is to assess their effectiveness in reducing flow separation and to compare the performance of the top-performing slot to that of the unslotted airfoil. The findings show that slot performance is heavily influenced by its configuration and dimensions. The appropriate slot design increases the maximum lift-to-drag ratio by 5% while significantly reducing vortex formation on the airfoil's suction side as shown by velocity contour and streamlines. Static pressure coefficient (C_{Ps}) distributions support these findings by demonstrating increased aerodynamic efficiency. These findings highlight the effectiveness of slot implementation in improving wind turbine performance. Slotted airfoils have the potential to advance wind energy technology by reducing flow separation and increasing efficiency, thereby supporting global sustainability initiatives and future renewable energy solutions.

Keywords: passive flow control, slot, S834, Horizontal axis wind turbines, CFD

1. Introduction

Energy from renewable sources is currently seen as an essential solution to rising global energy demand and sustainability issues. Contrasting fossil fuels, which are responsible for greenhouse gas emissions and climate change, sources of renewable energy like solar, wind, hydro, and biomass offers sustainable and environmentally friendly choices. Wind energy has attracted significant interest due to its scalability, efficiency, and small environmental impact. Wind turbines, the main type of technology for harvesting wind energy, convert the kinetic energy of the wind into mechanical power, which is subsequently transformed into electricity. Developments in turbine design, materials, and energy storage have improved wind power's efficiency and dependability, rendering it a viable option for massive electricity generation. Horizontal-axis wind turbines (HAWTs) are the most widely used of all wind turbine configurations due to their high efficiency and well-established technology. The efficiency of HAWT is influenced by blade design, wind speed, and turbine placement. Despite obstacles such as variable wind conditions and land use issues, wind energy remains an essential part of global efforts for a transition to a low-carbon energy future [1]

The efficiency and performance of horizontal-axis wind turbines (HAWTs) are improved employing either passive or active flow control techniques. Active flow control adjusts aerodynamic forces using external mechanisms such as blade pitch control, trailing-edge flaps, and active vortex generator. These systems improve energy capture, structural loads, and stability under fluctuating wind conditions. In contrast, passive flow control employs built-in aerodynamic design features such as slots, micro-cylinder, flexible blades, passive vortex generators, and leading-edge tubercles to adapt to wind fluctuations without the need for external intervention. The combination of the two methods improves turbine efficiency, longevity, and operational reliability in modern wind power installations[2].

Slots are a passive flow control technique that improves the aerodynamic performance of horizontal-axis wind turbine (HAWT) blades by delaying separation of flow and increasing lift. These slots, strategically placed along the blade surface, allow air to flow from the high-pressure to the low-pressure side, energizing the boundary layer and lowering aerodynamic losses. This mechanism improves turbine efficiency by increasing power output while reducing blade stall at high angles of attack. Unlike active control methods, slots do not require any external energy input, making them a low-cost, low-maintenance solution for improving wind turbine efficiency. Further research into slot geometry and placement optimization is helping to improve their effectiveness in modern wind energy applications[3,4].

Recently, there has been a lot of speculation in using slots as a passive flow control method, especially for large-scale wind turbines and compressors. Researchers have conducted extensive research on slot implementation to reduce flow separation, a common aerodynamic issue that can lead to decreased efficiency and performance losses in airfoils and rotating machinery [5]. The incorporation of slots into airfoil designs has demonstrated promising potential for improving aerodynamic efficiency by increasing lift-to-drag ratio and overall power output. M. Moshfeghi et al. [6] conducted a key study in this area by numerically investigating various slot locations and dimensions on the S809 airfoil. Their findings revealed that the aerodynamic performance of the airfoil is highly dependent on both the location and size of the slots. This suggests that optimizing slot configuration is critical for significant performance gains. S. Beyhaghi and R. S. Amano [7] found that optimal slot design conditions can increase the lift-to-drag coefficient by up to 30% at a constant Reynolds number of 1.6×10^6. Their study provided both numerical and experimental validation, highlighting the potential advantages of slot integration in airfoil design. Z. Ni et al. [8] also made significant contributions to this area by investigating a novel slot design for the NACA 634-021 airfoil. This research found a significant improvement in lift-to-drag ratio compared to the unslotted airfoil, using both numerical simulations and experimental testing at a Reynolds number of 105. Their findings demonstrate the effectiveness of slot implementation in reducing aerodynamic losses and increasing overall efficiency. S. Acarer [9] investigated the DU12W262 airfoil and found that slotted blades could significantly improve the lift-to-drag ratio and power coefficient for both horizontal and vertical axis wind turbines. These enhancements are especially useful in the wind energy industry, where optimizing turbine performance has a direct impact on energy generation efficiency and economic feasibility. Akhter et al.[10], [11]expanded on this concept by looking at two-dimensional (2D) and three-dimensional (3D) models of the NREL Phase VI wind turbine blade. Their research looked at the impact of introducing spanwise slots along the blade and discovered that power output could potentially increase by 100%. These findings suggest that incorporating slots into wind turbine blades could result in significant performance improvements, making wind energy systems more effective and sustainable.

Overall, the use of slots in airfoil and wind turbine blade designs has shown great promise for improving aerodynamic efficiency and increasing energy output. While numerous studies have validated the benefits of slot implementation, more research is needed to fine-tune slot configurations and determine their long-term viability in real-world applications. Continued advancements in computational fluid dynamics (CFD) and experimental testing will be critical for optimizing slot designs and realizing their full potential in aerodynamic systems. Hasan et al [12]investigated the performance of a commercial small-scale horizontal-axis wind turbine (HAWT) using mixed blade of airfoils S834, S833 and S835 air through both experimental and numerical methods. Their findings highlighted the importance of airflow behavior and flow separation control in improving the turbine's power coefficient. Furthermore, the study highlighted the difficulties in accurately predicting aerodynamic coefficients under such conditions, emphasizing the need for better modeling techniques and flow control strategies. Elwan et al. [13] introduced a slot on the S834 airfoil and concluded that it improved the airfoil’s performance at moderate angles of attack.

This study evaluates the effect of various slot configurations on the performance of the S834 airfoil using configurations found in the literature. Six different slot designs were investigated to find the most effective design. A computational fluid dynamics (CFD) approach was used to perform an unsteady two dimensional (2D) numerical analysis. The simulations have been performed at a wind speed of 6 m/s and a chord length of 200 mm. This study aims to identify the recommended slot design between these designs that maximizes the airfoil's performance under the given conditions by comparing the aerodynamic performance of the various configurations.

2. Numerical setup

This research focuses on the effect of a slot-based passive flow control strategy on the aerodynamic performance of the S834 airfoil. The study's goal is to evaluate the effect of strategically introducing a slot on airflow behavior and overall efficiency. Based on the findings in Ref. [12], the blade in Figure 1 shows flow separation on the suction side of the S834 airfoil. This separation degrades aerodynamic performance by increasing drag and decreasing lift. Understanding this phenomenon is critical for improving airfoil design and efficiency. The goal of this study is to reduce flow separation and improve overall aerodynamic performance by implementing a slot-based passive flow control strategy two dimensionally (2D). The findings will shed light on how different slot configurations affect separation development behavior, potentially leading to more effective airfoil modifications for increased performance. Figures 2 to 8 depict both the baseline unslotted and the six configuration slots on S834 airfoils. Figure 9 depicts the computational domain and mesh, which was designed according to established literature. Mesh independence has been performed at angle of attack 12° to ensure that the results are independent of the number of cells. The number of cells above 150,000 cells have acceptable accuracy as the results difference is less than 1% as shown in table 1.

The domain extends 10C along the upstream, top, and bottom directions and 15C in the downstream direction. To ensure proper flow development and obtain proper solution conversion, the upstream and bottom boundaries are defined as velocity inlets, while the downstream and top boundaries are defined as pressure outlets. The non-slip boundary conditions are applied on the airfoil surface [14]. To ensure the calculations are performed very close to the surface in the viscous sublayer, the dimensionless wall distance near the wall y+ was kept less than 1. This setup accurately captures the interaction of airflow and airfoil surface, yielding realistic simulation results for SST k-w turbulence model with coupled algorithm. SST k-w combines the advantages of both k-epsilon and k-w standard model [15,16,17]. The governing equation of unsteady incompressible numerical analysis uses computational fluid dynamics (CFD) to determine how different slot configurations affect aerodynamic performance under specific conditions.

Table 1 mesh independency for slotted and unslotted airfoil at angle of attack 12°.

	No of cells	Cl	Cd	Cl/Cd
Unslotted airfoil	90,000	0.95857	0.05633	17.0165
	150,000	0.97615	0.05384	18.13
	314,000	0.98338	0.05363	18.333
	609,000	0.9615	0.05384	17.858
Slotted airfoil	135,350	1.1846	0.0504	23.505
	201,900	1.1853	0.04978	23.809
	266,500	1.1855	0.04961	23.895
	622,00	1.1551	0.04791	24.109

Continuity equation for unsteady incompressible two-dimensional flow

$$\frac{\partial u}{\partial x} + \frac{\partial \upsilon}{\partial y} = 0 \quad (1)$$

momentum equation

$$\frac{\partial \rho \vec{V}}{\partial t} + \vec{V}.\nabla \rho \vec{V} = -\nabla p + \nabla\,[(\mu + \mu_t)\,\nabla \vec{V}] \quad (2)$$

Turbulent kinetic energy (k) equation

$$\frac{\partial \rho k}{\partial t} + \vec{V}.\nabla \rho k = p_k - \beta^* \rho\, k\, \omega + \nabla\,[(\sigma_k \mu + \mu_t)\,\nabla \vec{V}] \quad (3)$$

Specific dissipation rate (ω) equation

$$\frac{\partial \rho \omega}{\partial t} + \vec{V}.\nabla \rho \omega = \alpha \frac{\omega}{k} p_k - \beta^* \rho\, \omega^2 + \nabla\,[(\mu + \sigma_\omega \mu_t)\,\nabla \vec{V}] + 2(1 - F_1)\rho \sigma_{\omega 2} \frac{1}{\omega}\, \nabla k\, \nabla \omega \quad (4)$$

u is the velocity component in the x-direction,
υ is the velocity component in the y-direction,
$\vec{V}$ is (u,υ) velocity vector (components in x, y),
∇ is vector differential operator,
x and y are the spatial coordinates,
ρ is fluid density,
p is the pressure,
μ is dynamic viscosity.
μt is turbulent eddy viscosity, and
β^*, σ_k, σ_ω, and $\sigma_{\omega 2}$ are constants

The six models are evaluated based on lift coefficient, drag coefficient, and lift-to-drag ratio. The flow physics are assessed through velocity contours, streamlines, and static pressure coefficient distributions. The solution is performed for wind speed 6m/s and cord length 200mm using unsteady second order under coupled algorithm. These criteria assist in assessing aerodynamic performance through examination of airflow behavior, pressure variations, and efficiency.

$$C_L = \frac{L}{0.5\, \rho\, C\, U_\infty^2} \quad (5)$$

$$C_d = \frac{D}{0.5\, \rho\, C\, U_\infty^2} \quad (6)$$

$$CP_s = \frac{p - p_\infty}{0.5\, \rho\, U_\infty^2} \quad (7)$$

L: lift force
D: drag force
C: chord length
ρ: density
U_∞: free stream velocity
CPs Static pressure coefficient
p: static pressure
p_∞: static pressure at the inlet

This study seeks to identify the most effective configuration between the six designs that improve aerodynamic efficiency by systematically investigating the effect of slot-based passive flow control. The findings will help to improve our understanding of flow control techniques, potentially leading to better airfoil designs for a variety of aerodynamic applications.

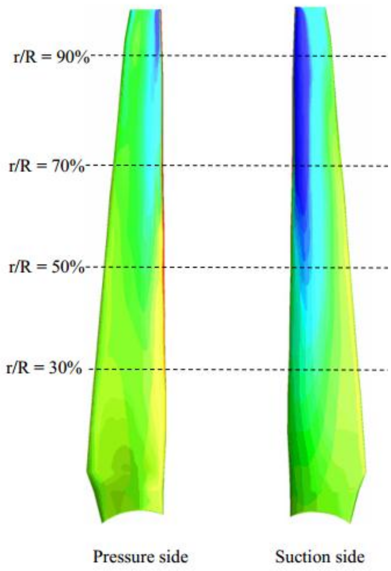


Fig. 1. The static pressure coefficient for pressure and suction side [12].

Fig. 2 Unslotted S834 airfoil.

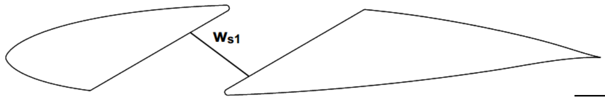


Fig. 3 Slot 1 Configuration.

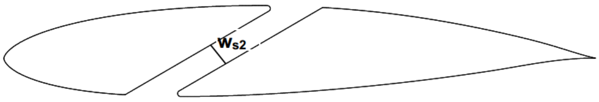


Fig. 4 Slot 2 Configuration.

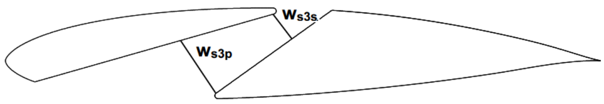


Fig. 5 Slot 3 Configuration.

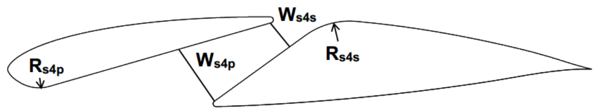


Fig. 6 Slot 4Configuration.

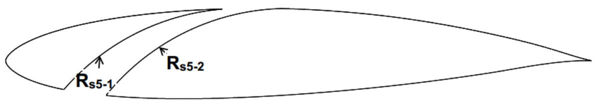


Fig. 7 Slot 5 Configuration.

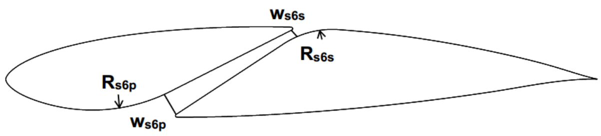
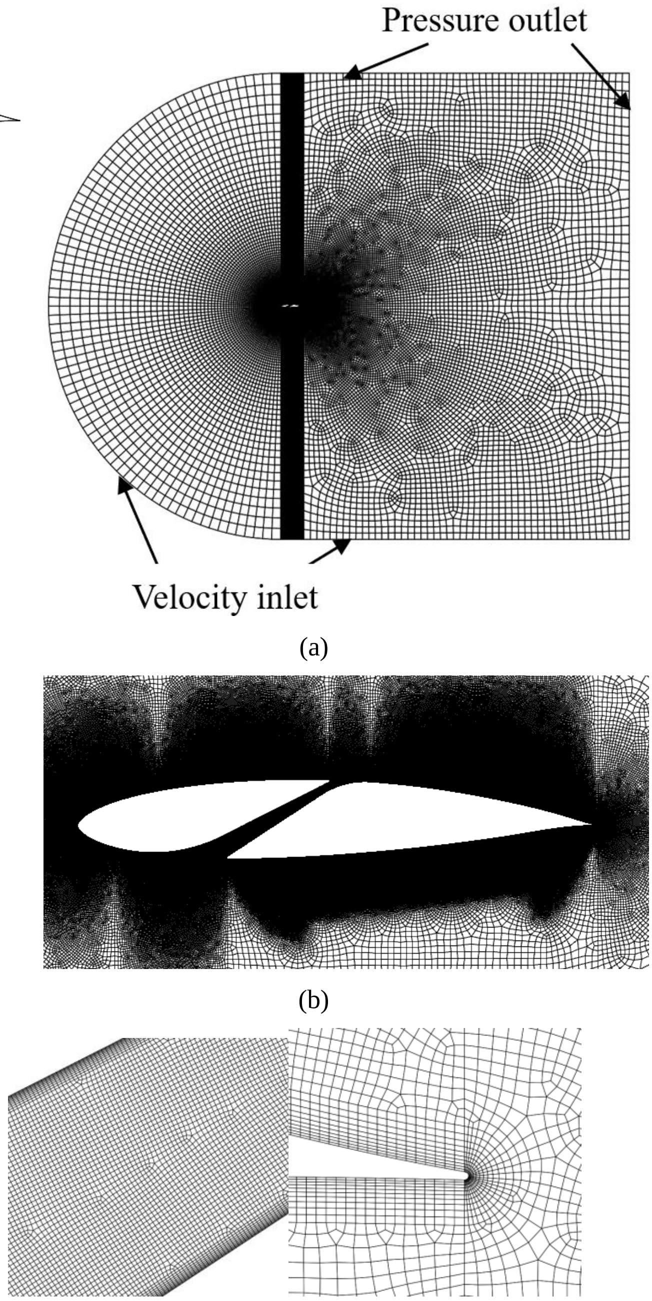


Fig. 8 Slot 6 Configuration.

Table 2 slot designs parameter and their dimensions with respect to chord length.

Slot no	Parameter	% Chord
Slot 1	W_{s1}	11
Slot 2	W_{s2}	4
Slot 3	W_{s3s}	4
	W_{s3p}	11
Slot 4	W_{s4s}	4
	W_{s4p}	11
	R_{s4s}	13
	R_{s4p}	6.5
Slot 5	R_{s5-1}	40
	R_{s5-2}	40
Slot 6	W_{s6s}	1.5
	W_{s6p}	4
	R_{s6s}	15
	R_{s6p}	15



(a) (b) (c) (d)

Fig. 9 (a) Computational domain. **(b)** mesh around airfoil. **(c)** mesh inside slot. **(d)** mesh around trailing edge.

3. Results and Discussions

The S834 airfoil behaves efficiently at lower to moderate angles of attack; however, at higher angles, flow separation grows, leading to poor aerodynamic performance. To address this, six slot configurations

(Slots 1-6) were tested. Slot 1 greatly diminished lift and increased drag, lowering the peak lift-to-drag ratio by about 75%. This configuration performed poorly for all angles of attack, except for angles of attack above 16°, where slight enhancements were noted. This occurs due to the lower lift and higher drag caused by the slot compared to the unslotted airfoil. The constant area slot behaves poorly due to pressure accumulating inside it, which leads to high vortex generation. Slot 2 exhibited a similar development, but with a 67.5% reduction in the peak lift-to-drag ratio. Unlike Slot 1, performance improvements started at angles of attack higher than 15°. Slot 3 performed intermediately between Slots 1 and 2, with a 71% reduction in peak lift-to-drag ratio and improvements beginning at angles of attack higher than 15.5°. At lower angles of attack, Slot 3 performance is considered the worst due to the formation of an enormous vortex on the slot wall caused by the flow's entrance angle, resulting in high drag and low lift. Slot 4 demonstrated a significant improvement over the previous three designs, drastically reducing the peak lift-to-drag ratio by only 19% then the performance stalled rapidly at angle of attack 10° while improving performance starting again at angles of attack above 14.5° with respect to unslotted airfoil. The advanced performance of slot 4 at low angles of attack results from the smooth entrance of flow from the pressure side, which allows perfect attachment of flow and slot wall. The rapid decline of slot 4 results when the angle of attack increases; the detachment of flow occurs at the left edge of the slot, leading to a high drop in lift and a sudden increase in drag. Despite this progress, all four slot configurations reduced the lift coefficient while increasing the drag coefficient. This resulted in a reduction in overall aerodynamic efficiency, as shown in Figures 10-12. In contrast, slot designs 5 and 6 performed more effectively at higher angles of attack. Slot 6 outperformed the unslotted airfoil's maximum lift-to-drag ratio by about 5%. While slot 5 did well at higher angles of attack, its maximum lift-to-drag ratio was 8% lower than unslotted airfoil. The performance of slot 5 is positive with respect to the previous slot's designs but still needs optimization for more improvement. We evaluate the recommended slot designs on the S834 airfoil in this study, but we will further enhance this slot in our future work. According to this analysis, the most meaningful comparative is between the unslotted airfoil and the slot 6 design, which provides greater aerodynamic efficiency. The results suggest that slot 6 can improve airfoil performance, especially in conditions were maintaining a high lift-to-drag ratio is vital.

Slot 6 has less effectiveness than the unslotted airfoil at angles of attack ranging from 2° to 10°. Within this range, slot 6 has a lower lift coefficient with a higher drag coefficient than the unslotted airfoil, resulting in a lower lift-to-drag ratio. However, for angles of attack greater than 10°, both the lift and drag coefficients increase, resulting in an overall improvement in the lift-to-drag ratio, as shown in Figures 10-12 which align with the results of reference [18].

The velocity contours and streamlines in Figure 13 show that the unslotted airfoil has minor flow separation, that separation occurring only at the trailing edge for angles of attack ranging from 2° to 8°. Conversely, the slotted airfoil shows flow separation within the slot, which is consistent with the static pressure coefficient distributions shown in Figures 14-17. While the static pressure coefficient on the pressure side is nearly identical for both configurations, the suction side of the slotted airfoil has a higher static pressure than the unslotted airfoil. As a result, the slotted airfoil has a considerably lesser lift-to-drag ratio than the unslotted airfoil, with decreases of 84%, 64%, 35%, and 12.5% at angles of attack of 2°, 4°, 6°, and 8°, respectively. The main reason for the low performance is the increasing pressure on the suction side of the airfoil resulting from the high vortex generated at the trailing edge.

On the unslotted airfoil, significant flow separation appears at angles of attack ranging from 10° to 18°. However, as shown in Figure 13, the slot helps to mitigate separation. Figures 18-22 further support these findings, demonstrating that the static pressure coefficient remains nearly constant on the pressure side but decreases on the suction side. A decline in suction-side pressure improves aerodynamic efficiency, as evidenced by an increase in the lift-to-drag ratio. The lift-to-drag ratio rises by 9%, 33%, 3%, 22%, and 20% for angles of attack of 10°, 12°, 14°, 16°, and 18°, respectively, as shown in Figure 12.

For an angle of attack of 10, the vortex at the suction side starts to diminish the performance of the unslotted airfoil, while the slotted airfoil begins to praise the performance by migrating the flow separation. The low pressure at the suction side, close to the trailing edge, reflects this. For an attack angle of 12, the separation grows more than before, affecting performance, as shown in Figure 12. The slotted airfoil intervened to eliminate these vortices, resulting in an enhancement of the static pressure coefficient for both the suction side and the pressure side, as indicated in Figure 19. The best flow elimination of the slot is achieved at an angle of attack of 14, which presents a final disappearance of the vortex and enhancement of the static pressure coefficient for both sides of the airfoil. At higher angles of attack, specifically 16 and 18, the slot continued to provide a noticeable improvement, but it was unable to completely control the enormous vortex.

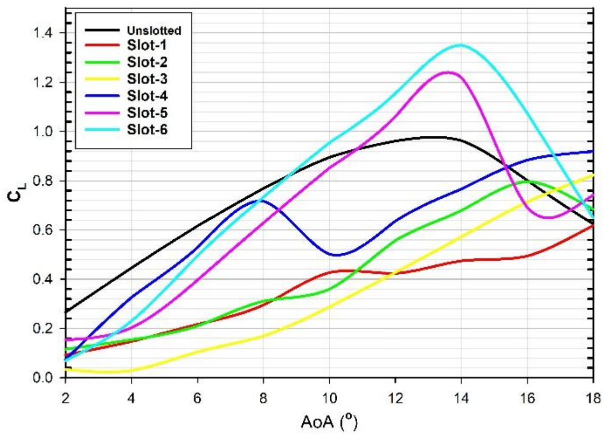


Fig. 10 Lift coefficient for unslotted airfoil and the six designs.

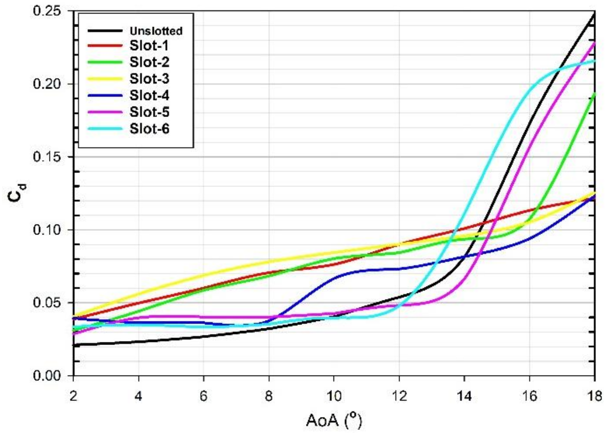


Fig. 11 Drag coefficient for unslotted airfoil and the six designs.

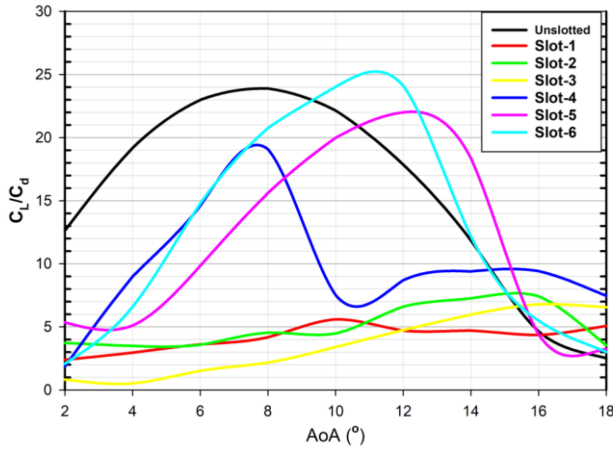


Fig. 12 Lift to drag coefficient for unslotted airfoil and the six designs.

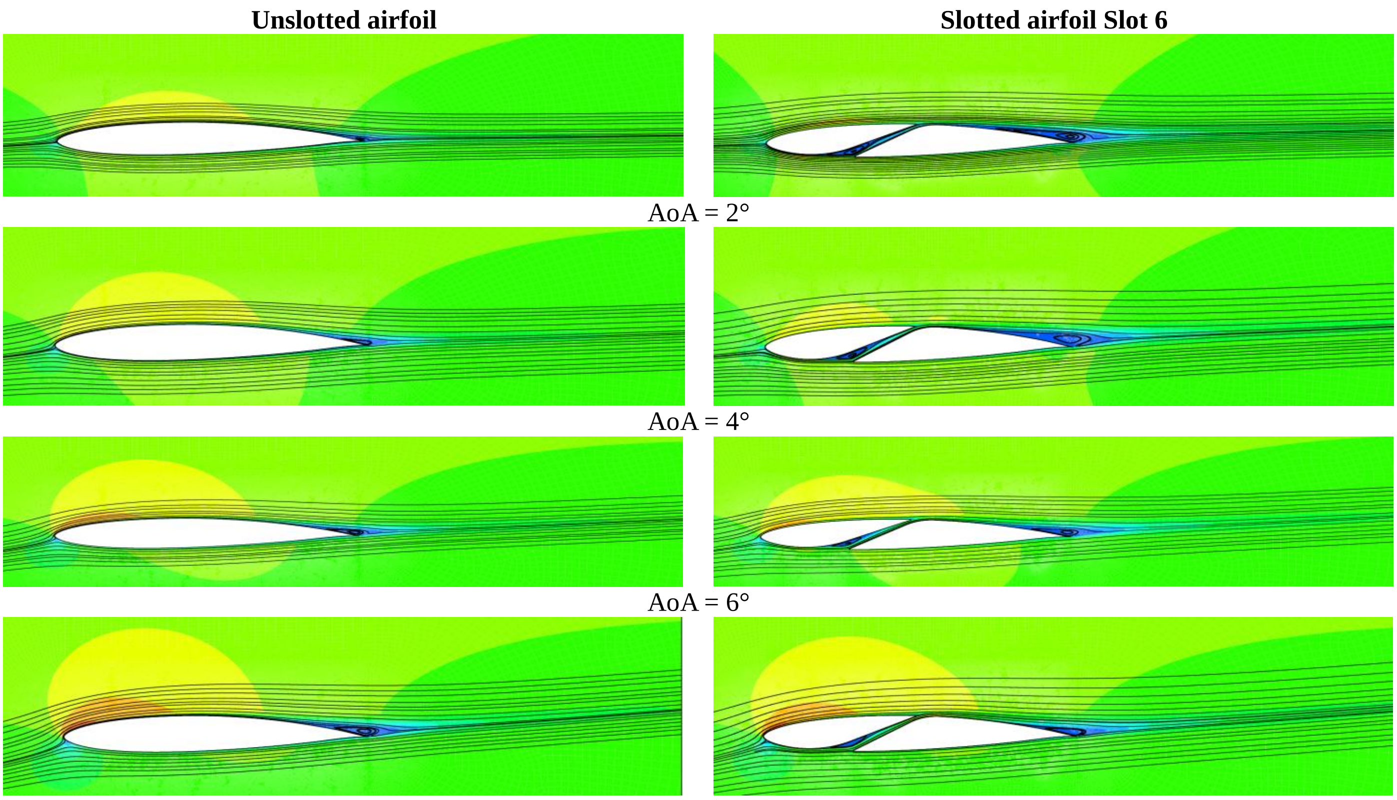


Fig. 13 Velocity contour and streamlines for unslotted and slot 6 design airfoil

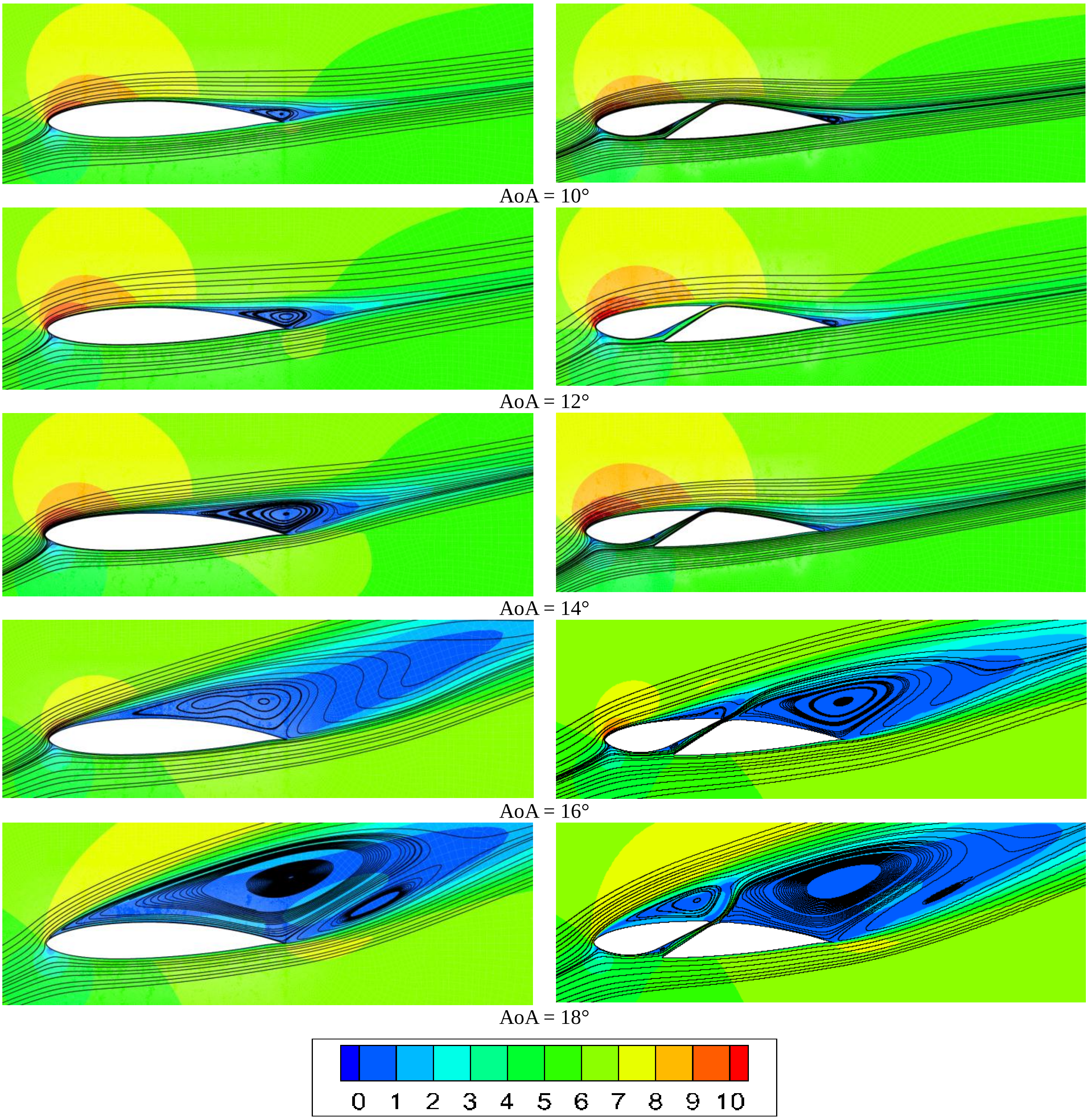


Fig. 14 Velocity contour and streamlines for unslotted and slot 6 design airfoil(continued)

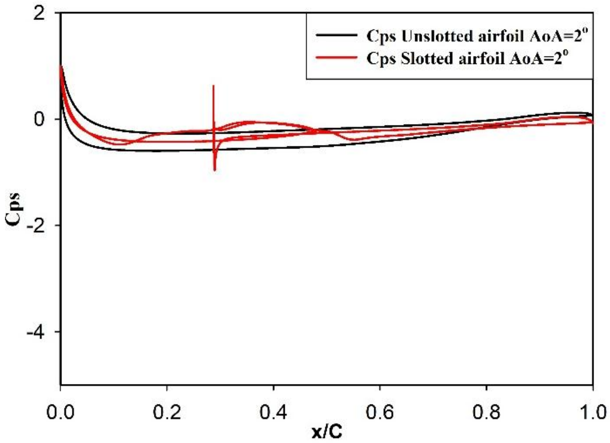


Fig. 15 Static pressure coefficient at AoA=2 for unslotted and slot 6 design airfoil.

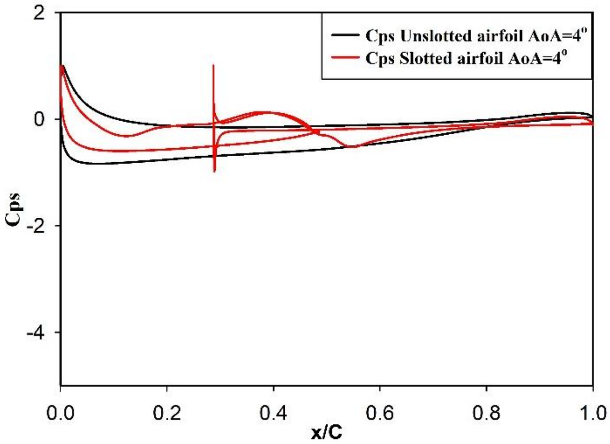


Fig. 16 Static pressure coefficient at AoA=4 for unslotted and slot 6 design airfoil.

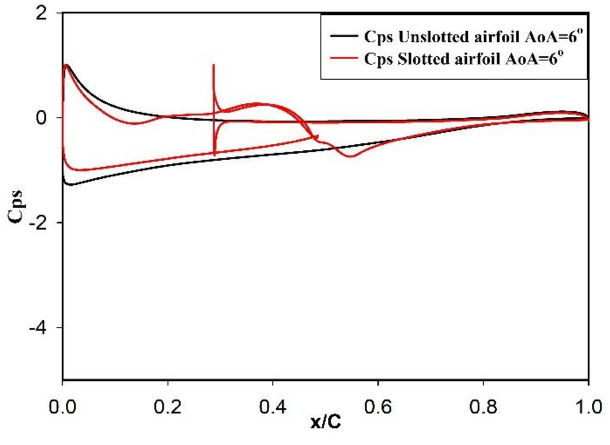


Fig. 17 Static pressure coefficient at AoA=6 for unslotted and slot 6 design airfoil.

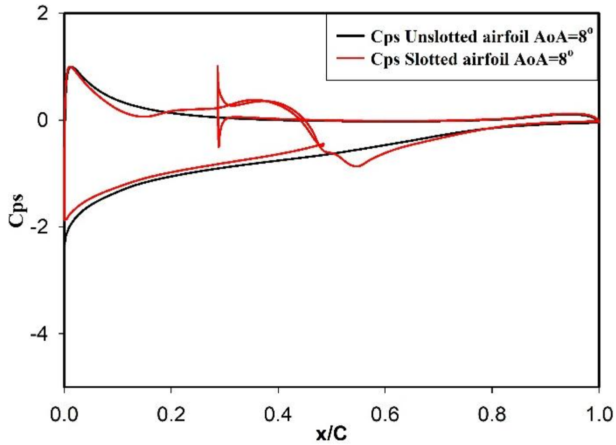


Fig. 18 Static pressure coefficient at AoA=8 for unslotted and slot 6 design airfoil.

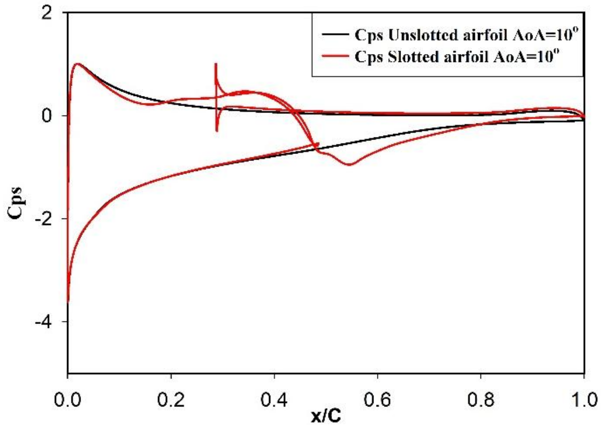


Fig. 19 Static pressure coefficient at AoA=10 for unslotted and slot 6 design airfoil.

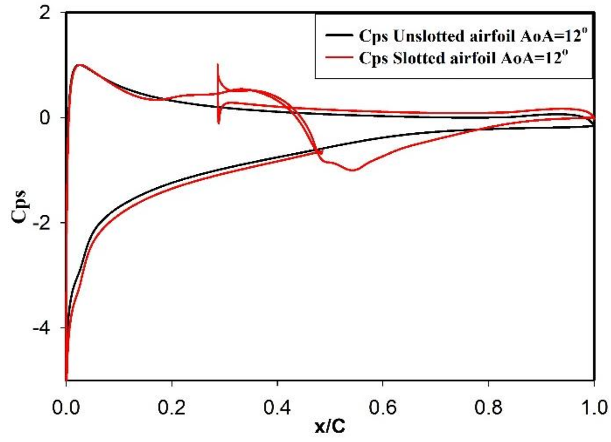


Fig. 20 Static pressure coefficient at AoA=12 for unslotted and slot 6 design airfoil.

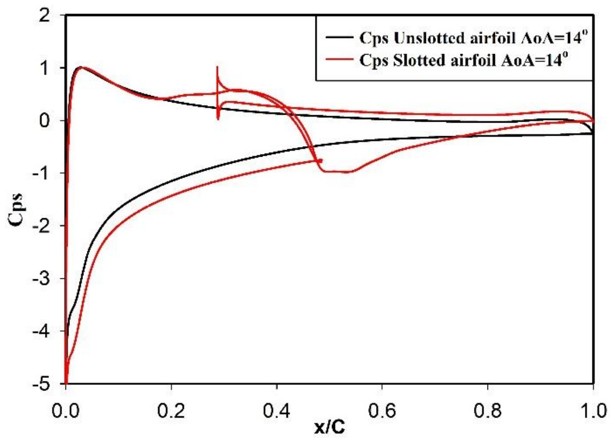


Fig. 21 Static pressure coefficient at AoA=14 for unslotted and slot 6 design airfoil.

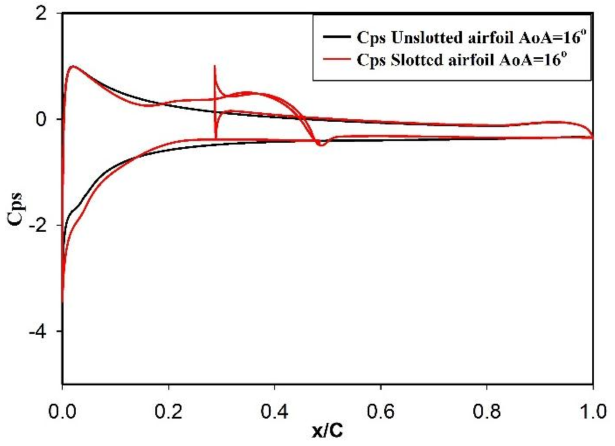


Fig. 22 Static pressure coefficient at AoA=16 for unslotted and slot 6 design airfoil.

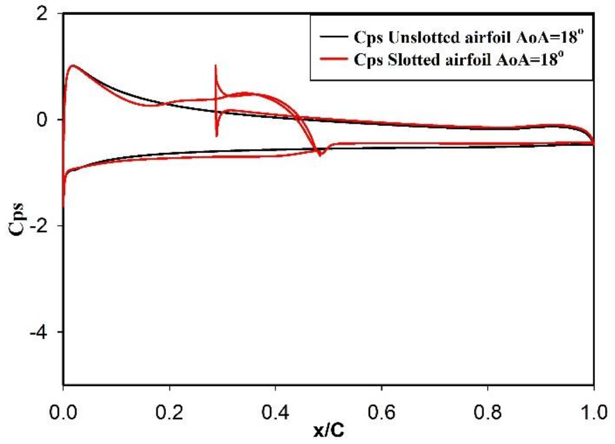


Fig. 23 Static pressure coefficient at AoA=18 for unslotted and slot 6 design airfoil.

4. Conclusion

The research was carried out on six slot design configurations to determine the variables that affect slot performance at a wind speed of 6 m/s and a Reynolds number of 85,000. The analysis was done numerically with unsteady two-dimensional (2D) Computational Fluid Dynamics (CFD) simulations. Results showed that slot configuration and dimensions have a significant impact on slot performance, and that slot designs for different airfoils must be tailored. Additionally, a variable cross-sectional area was found to be more effective than a uniform one. The best performing slot design efficiently decreased flow separation at greater angles of attack. Although the slotted airfoil performed worse than the unslotted airfoil at low angles of attack (2° to 8°), it showed significant aerodynamic improvements at higher angles (10° to 16°). The slot is considered an appropriate solution for flow separation for thick airfoils and may moderately perform for thin airfoils. The slot parameter needs to be studied carefully for each airfoil individually. Velocity contours and static pressure coefficient distributions revealed significant changes in vortex formation, indicating that the slotted airfoil design may improve wind energy efficiency. These enhancements contribute to more efficient energy utilization, aligning with global sustainability efforts.

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