International Journal of Interdisciplinary Innovative Research & Development (IJIIRD)
ISSN: 2456-236X
Vol. 11 Special Issue 03 | 2026

“Effect of Boundary Layer Suction on the Aerodynamic Performance of NACA 6321 Airfoil in Transonic Flow”

Ishika Jadhav[1], S. Sulthan[2], Mari Prabu[3]

[1]*Student, Aerospace Engineering, Sanjay Ghodawat University, Maharashtra, Kolhapur*
[2.3]*Assistant Professor, Aerospace Engineering, Sanjay Ghodawat University, Maharashtra, Kolhapur*

DOI: 10.5281/zenodo.20614889

ABSTRACT

This study investigates the impact of suction on the aerodynamic performance of a NACA 6321 airfoil under transonic flow conditions. The primary objective is to evaluate how different suction configurations influence lift, drag, and stall characteristics across a range of angles of attack (AOAs). The airfoil geometry was modified to incorporate suction slots at 25%, 50%, and 75% of the chord length. The models were developed using CATIA and analyzed in ANSYS Workbench, employing the k–ω SST turbulence model along with the Reynolds-Averaged Navier–Stokes (RANS) equations. Simulations were conducted for AOAs ranging from 0° to 25°, with a mesh element size of 0.03 m. The flow conditions included a gauge pressure of 18,615.8 Pa, a velocity of 274 m/s, and a flow domain area of 0.09 m². Numerical computations were carried out for 2500 iterations with a residual convergence criterion of 10^{-6}. The results indicate that the suction configuration at 25% chord significantly enhances lift and delays stall at critical AOAs, making it suitable for high-performance aerodynamic applications. In contrast, the 75% chord suction configuration demonstrates a more balanced improvement in aerodynamic efficiency over a wider range of AOAs, making it preferable for applications requiring stable performance and reduced drag. Overall, the study highlights the effectiveness of strategically placed suction slots in optimizing airfoil performance under transonic conditions, offering valuable insights for advanced aerodynamic design.

Keywords: Aerofoil, Aerodynamic Efficiency, Drag Coefficient, Lift Coefficient, Angle of Attack

1. INTRODUCTION

Background -The study of airfoil aerodynamics forms a fundamental pillar of aerospace engineering, particularly in the transonic flight regime where airflow exhibits a complex combination of subsonic and supersonic characteristics. As aircraft approach the speed of sound, they encounter significant aerodynamic challenges, including shock wave formation, boundary layer separation, and the rapid increase of drag known as wave drag. These phenomena adversely affect aerodynamic performance by increasing drag and reducing lift, thereby impacting fuel efficiency, stability, and overall flight safety [1], [2]. Consequently, understanding and controlling these effects is essential for the development of high-performance aircraft operating in transonic conditions. Transonic flow is uniquely characterized by the coexistence of subsonic and locally supersonic regions over the airfoil surface. The interaction between these flow regimes leads to the formation of shock waves, which induce abrupt pressure changes and can cause boundary layer separation. This separation significantly alters the aerodynamic characteristics of the airfoil, resulting in increased drag and a reduction in lift. Furthermore, the presence of shock-induced separation can lead to premature stall, limiting the operational envelope of the aircraft [3]. These challenges necessitate the exploration of advanced flow control techniques capable of mitigating adverse transonic effects. One of the most promising approaches to address these challenges is the application of boundary layer suction. This technique involves the removal of low-energy fluid from the boundary layer through strategically placed suction slots on the airfoil surface. By extracting this slower-moving fluid, suction effectively delays boundary layer separation, stabilizes the flow, and reduces the intensity of shock waves. As a result, it contributes to improved lift generation, reduced drag, and enhanced overall aerodynamic efficiency [4], [5]. Additionally, suction can help maintain laminar flow over a larger portion of the airfoil, further reducing viscous drag and improving performance. In the present study, the aerodynamic performance of a NACA 6321 airfoil is investigated under transonic flow conditions with the implementation of suction at 25%, 50%, and 75% chord positions. The airfoil geometry is developed using CATIA, and computational analysis is carried out in ANSYS Workbench. The simulations are based on the Reynolds-Averaged Navier–Stokes (RANS) equations coupled with the k–ω SST turbulence model, which is well-suited for accurately predicting flow separation under adverse pressure gradients [7]. The analysis is conducted over a range of angles of attack from 0° to 25°, enabling a comprehensive evaluation of lift, drag, and stall characteristics under varying aerodynamic conditions.

2. OBJECTIVES

The primary objective of this research is to comprehensively investigate the influence of boundary layer suction on the aerodynamic performance of a NACA 6321 airfoil operating in transonic flow conditions. This involves a systematic analysis of how different suction configurations affect key aerodynamic parameters such as lift, drag, and stall behavior across a wide range of angles of attack. By incorporating suction at different chordwise locations (25%, 50%, and 75%), the study aims to identify the most effective configuration for enhancing aerodynamic efficiency. A major focus of this research is the evaluation of lift coefficient (C_l) and drag coefficient (C_d) variations with respect to angle of attack. These parameters are critical indicators of airfoil performance, and their optimization is essential for achieving improved aerodynamic efficiency. In addition, the study seeks to examine the effect of suction on stall characteristics, particularly its ability to delay flow separation and extend the operational range of the airfoil. A comparative analysis between the baseline airfoil and suction-modified configurations is also performed to quantify performance improvements. Furthermore, the study aims to determine the optimal suction location that maximizes lift-to-drag ratio while maintaining stable aerodynamic behavior across different operating conditions. The findings are expected to provide practical design recommendations for incorporating suction-based flow control techniques in modern airfoil and wing designs, thereby contributing to improved aircraft performance and efficiency.

2.1 Significance Of The Study

The significance of this study lies in its contribution to the advancement of aerodynamic optimization techniques for transonic flight applications. By systematically analyzing the effects of suction on airfoil performance, the research provides valuable insights into methods for improving lift-to-drag ratio, delaying stall, and reducing wave drag. These improvements are directly linked to enhanced aircraft efficiency and performance. One of the key implications of this study is the potential for improving fuel efficiency in aircraft operations. Reduced aerodynamic drag leads to lower fuel consumption, which not only decreases operational costs for airlines but also contributes to environmental sustainability by reducing greenhouse gas emissions [2]. The findings also have important applications in improving aircraft speed and maneuverability, particularly for high-performance and military aircraft where aerodynamic efficiency is critical. Moreover, the study demonstrates the effectiveness of computational fluid dynamics (CFD) tools in analyzing complex aerodynamic phenomena. By utilizing advanced turbulence models and numerical methods, the research highlights the capability of modern simulation techniques to provide accurate and cost-effective solutions compared to traditional experimental approaches.

2.2 Overview Of NACA 6321 Airfoil

The NACA 6321 airfoil is a member of the NACA 6-series, which is specifically designed to achieve low drag by maintaining favorable pressure gradients over a significant portion of the chord length. This airfoil is characterized by moderate thickness and optimized camber, providing an effective balance between structural strength and aerodynamic performance [6]. The design philosophy of the 6-series airfoils focuses on minimizing drag while maintaining high lift, making them particularly suitable for high-speed and transonic flight applications.

A key feature of the NACA 6321 airfoil is its ability to delay boundary layer separation due to its controlled pressure distribution. This results in reduced drag and improved lift characteristics across a wide range of angles of attack. The airfoildemonstrates stable aerodynamic performance, making it suitable for various phases of flight, including takeoff, cruising, and maneuvering. Additionally, its moderate thickness ensures sufficient structural integrity, which is essential for practical aircraft applications.

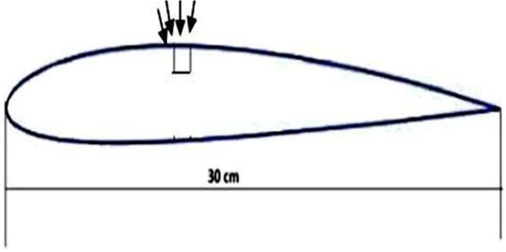

Fig 1 Schematic diagram of Baseline

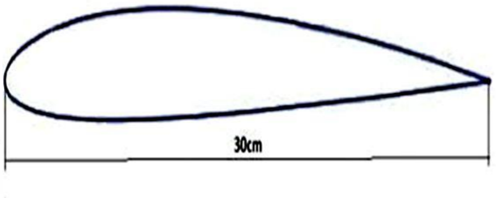

Fig 2 Schematic diagram of Optimum suction system airfoil

The NACA 6321 airfoil, owing to its favorable pressure distribution and aerodynamic characteristics, is particularly well-suited for operation under transonic flow conditions. This makes it an ideal candidate for the application of advanced flow control techniques such as boundary layer suction. By strategically introducing suction at specific chordwise locations, it is possible to manipulate the boundary layer behavior, thereby reducing aerodynamic drag, delaying flow separation, and improving the overall lift-to-drag ratio. Such enhancements contribute to improved aerodynamic efficiency and extended operational performance. In this study, the inherent advantages of the NACA 6321 airfoil are utilized to investigate the effectiveness of suction-based flow control under transonic conditions. The research aims to provide a detailed understanding of how suction influences aerodynamic characteristics and to identify optimal configurations that maximize performance. The findings are expected to contribute valuable insights toward the development of next-generation airfoil designs, supporting advancements in aerodynamic optimization and high-efficiency aircraft systems.

3. LITERATURE REVIEW

The aerodynamic performance of airfoils in the transonic regime is strongly influenced by the interaction between subsonic and supersonic flow regions, leading to complex phenomena such as shock wave formation, boundary layer separation, and wave drag. As the Mach number approaches unity, these effects become dominant and significantly degrade aerodynamic efficiency [1], [2]. Early theoretical work established that adverse pressure gradients are the primary cause of boundary layer separation, which leads to increased drag and reduced lift [3]. Numerical investigations on conventional airfoils such as NACA 0012 further confirmed that shock-induced separation intensifies with increasing angle of attack and Mach number, resulting in significant performance deterioration [4]. Geissler [5] demonstrated that time-accurate Navier–Stokes simulations can effectively capture shock–boundary layer interactions and their control using porous surfaces. More recent studies have shown that transonic flow behavior is highly nonlinear and sensitive to operating conditions, making aerodynamic optimization a challenging task [6]. To overcome these challenges, boundary layer suction has been widely investigated as an effective active flow control technique. Suction works by removing low-energy fluid from the boundary layer, thereby delaying separation and improving aerodynamic efficiency. It has been reported that suction can significantly reduce drag and enhance lift performance [7]. Gad-el-Hak [8] categorized suction as a key active flow control method, while Joslin and Miller [9] emphasized its effectiveness in stabilizing boundary layer flow. Huang et al. [10] and Yousefi et al. [11], [12] demonstrated that optimized suction slot configurations can significantly improve aerodynamic performance by delaying separation and reducing drag. Khamedov et al.[13] conducted a CFD study on transonic airfoils and reported that suction reduces shock strength and improves lift-to-drag ratio. Similarly, Seifollahi Moghadam [14] showed that optimized suction can effectively control shock–boundary layer interaction and enhance aerodynamic performance. Recent computational studies have further advanced the understanding of suction-based flow control. Nguyen [15] demonstrated that suction applied at appropriate chordwise locations significantly delays flow separation and enhances lift characteristics. Shi [16] investigated hybrid laminar flow control using suction holes and found that properly designed suction systems can maintain laminar flow and improve aerodynamic efficiency. Liang et al. [17] extended the application of suction techniques to compressor cascades and showed that suction grooves can suppress near-stall flow separation and improve flow stability. Meng et al. [18] demonstrated that aerodynamic optimization of transonic cascades significantly enhances performance by controlling flow separation. The development of computational fluid dynamics (CFD) has played a crucial role in enabling detailed analysis of transonic flows and flow control techniques. The Reynolds-Averaged Navier–Stokes (RANS) equations, combined with turbulence models such as the k–ω SST model introduced by Menter [19], provide reliable predictions of flow separation and aerodynamic performance. Badran et al. [20] validated the accuracy of the SST model in predicting lift and drag characteristics, while Johnsson [21] confirmed its effectiveness in modeling turbulent boundary layer behavior. Advanced numerical simulations have further improved the understanding of shock–boundary layer interaction and separation phenomena [22]. Shock–boundary layer interaction remains a critical factor affecting aerodynamic performance in transonic flows. Wu et al. [23] showed that separation bubbles formed due to shock interactions significantly increase drag and reduce lift. However, suction-based control techniques can effectively reattach the flow and reduce these losses. Fan et al. [24] demonstrated that suction modifies turbulence structures within the boundary layer, resulting in reduced friction drag. Lui et al. [25] reported that suction suppresses separation bubbles and enhances flow stability. Schauerte et al. [26] further showed that transonic buffet and shock oscillations can be mitigated through flow control strategies, improving aerodynamic stability. Despite the extensive body of research, several gaps remain that require further investigation. Most existing studies focus on conventional airfoils such as NACA 0012, with limited research on NACA 6-series airfoils, particularly NACA 6321. There is also a lack of comprehensive studies analyzing multiple suction slot configurations at different chordwise positions within a single framework. Additionally, limited research has been conducted over a wide range of angles of attack under transonic conditions, where aerodynamic behavior is highly nonlinear. Many studies focus on either lift or drag independently, with insufficient emphasis on their combined effect on overall aerodynamic performance and stall characteristics. Furthermore, there is a need for systematic optimization of suction configurations for practical aerospace applications. The limited availability of high-fidelity CFD studies incorporating advanced turbulence models also highlights the need for more detailed numerical investigations.

4. METHODOLOGY

4.1 Airfoil Model Design Design Using Catia

The initial phase of this study involved the development of a NACA 6321 airfoil model using CATIA, a widely used computer-aided design (CAD) software known for its precision and versatility in aerospace applications. The NACA 6321 airfoil was selected due to its well-documented aerodynamic characteristics and suitability for transonic flow analysis. The airfoil geometry was generated by importing the standard NACA 6321 coordinate dataset into the CATIA environment. These coordinates, consisting of discrete x and y values defining the airfoil contour, were used to construct spline curves representing the upper and lower surfaces of the airfoil. The use of spline interpolation ensured a smooth and continuous profile, accurately capturing the aerodynamic shape. Following profile creation, the geometry was extended into a three-dimensional model through extrusion, preserving the dimensional integrity of the airfoil. Additional refinement was performed by introducing supplementary control points along the spline to improve curvature continuity and eliminate geometric irregularities. This step ensured that the final model was suitable for high-fidelity computational analysis.

4.2 Insertion Of Suction Slots

To investigate the influence of suction on aerodynamic performance, suction slots were incorporated at three chordwise locations: 25%, 50%, and 75% of the chord length. These positions were selected to evaluate the effect of suction at different regions of the airfoil where flow separation characteristics vary significantly. The slot positions were determined relative to the chord length, with locations at 0.25 m, 0.50 m, and 0.75 m from the leading edge for a unit chord airfoil. Each slot was designed as a narrow, elongated opening extending across the span of the airfoil. The dimensions of the slots were carefully chosen to ensure effective suction while minimizing disturbance to the overall aerodynamic profile. Boolean subtraction operations in CATIA were employed to integrate the suction slots into the airfoil geometry. This approach ensured precise removal of material and seamless incorporation of the slots into the model without compromising structural or aerodynamic integrity.

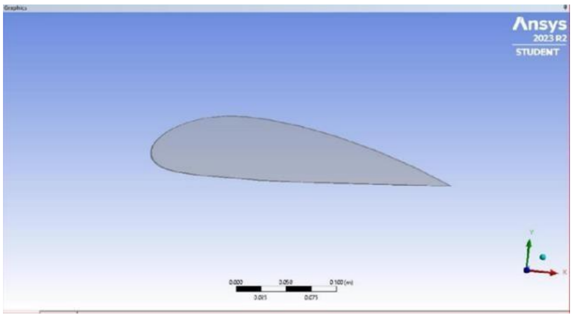

Fig. 3. CAD model of baseline NACA 6321 airfoil.

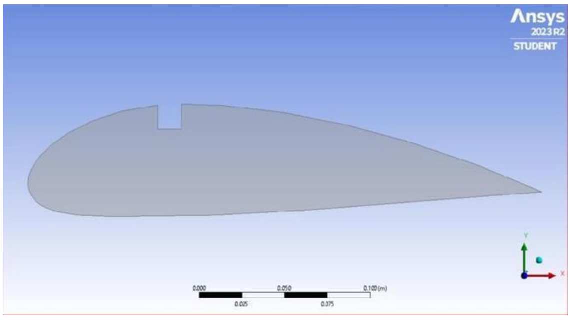

Fig. 4. CAD model of airfoil with 25% chord suction slot.

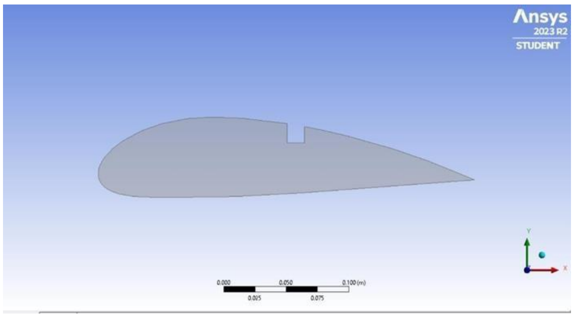

Fig. 5. CAD model of airfoil with 50% chord suction slot.

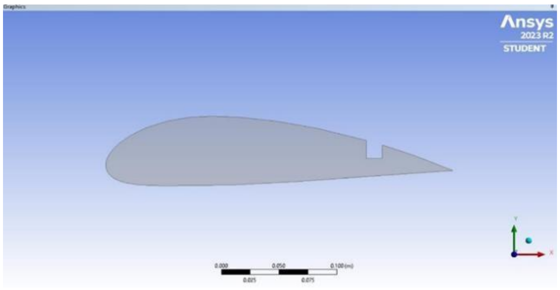

Fig. 6. CAD model of airfoil with 75% chord suction slot.

4.3 Simulation Setup Mesh Generation

Mesh generation was carried out using ANSYS Workbench, as it plays a critical role in determining the accuracy and stability of computational fluid dynamics (CFD) simulations. A uniform element size of 0.03 m was selected to balance computational cost with solution accuracy. The meshing process involved discretizing both the airfoil surface and the surrounding flow domain. Fine triangular elements were used for surface meshing to accurately capture the curvature of the airfoil and the geometry of the suction slots. The flow domain was discretized using a combination of tetrahedral and hexahedral elements to ensure smooth variation of element size from the near-wall region to the far-field boundaries. Special emphasis was placed on boundary layer refinement. Multiple inflation layers were generated near the airfoil surface to resolve the velocity gradients within the boundary layer accurately. This refinement is essential for capturing flow separation, reattachment, and the effects of suction.

Fig. 7. Computational mesh of the airfoil and surrounding flow domain.

4.4 Turbulence Model And Governing Equations

The numerical simulations were performed using the Reynolds-Averaged Navier–Stokes (RANS) equations, which model the mean flow behavior while accounting for turbulence effects. To accurately capture the complex flow phenomena associated with transonic conditions, the k–ω SST (Shear Stress Transport) turbulence model was employed. The k–ω SST model combines the advantages of the k–ω model in the near-wall region and the k–ε model in the free-stream region. This hybrid approach enhances its capability to predict flow separation under adverse pressure gradients and provides improved accuracy in transonic aerodynamic simulations. Initial and Boundary Conditions The simulation domain was defined as a rectangular region surrounding the airfoil, extending sufficiently in all directions to minimize boundary interference effects. The inlet boundary was specified as a velocity inlet with a freestream velocity of 274 m/s, corresponding to transonic flow conditions. An initial gauge pressure of 18,615.8 Pa was applied to represent realistic operating conditions. The outlet boundary was defined as a pressure outlet, allowing the flow to exit the domain naturally. The airfoil surface was treated as a no-slip wall, ensuring accurate representation of boundary layer development. The suction slots were modeled as outlet boundaries with prescribed suction conditions, enabling the removal of low-energy fluid from the boundary layer. This setup allowed for a detailed analysis of the impact of suction on flow behavior and aerodynamic performance.

4.5 Iteration And Convergence Criteria

The numerical solution was obtained through iterative calculations to achieve convergence. A total of 2500 iterations were performed for each simulation case to ensure solution stability and accuracy. The convergence criterion was defined by a residual threshold of 10−610^{-6}10−6, indicating that the changes in solution variables between successive iterations were negligible.In addition to residual monitoring, key aerodynamic parameters such as lift coefficient (C_l), drag coefficient (C_d), and lift-to-drag ratio (C_l/C_d) were continuously tracked throughout the simulation. Convergence was confirmed when these parameters reached steady values, ensuring the reliability of the results.

5. NUMERICAL ANALYSIS

5.1 Baseline Configuration

The baseline configuration serves as the reference model for evaluating the effects of suction on the aerodynamic performance of the NACA 6321 airfoil. In this configuration, no suction is applied, allowing the flow to develop naturally over the airfo il surface. This provides a benchmark against which all suction-based configurations can be compared. The airfoil geometry was developed using CATIA to ensure high geometric accuracy. The computational domain was carefully defined to minimize boundary interference, with sufficient upstream, downstream, and lateral extents to simulate an unbounded flow field. Meshing was performed using ANSYS Workbench with a uniform element size of 0.03 m, ensuring adequate resolution of flow features around the airfoil. The simulations were conducted under transonic conditions with a free-stream velocity of 274 m/s and an initial gauge pressure of 18,615.8 Pa. These parameters were selected to replicate realistic operating conditions where both subsonic and supersonic flow regions coexist. The k–ω SST turbulence model was employed due to its proven capability in accurately predicting boundary layer behavior, flow separation, and shock–boundary layer interactions in transonic regimes. A convergence criterion of 10^{-6} was adopted to ensure numerical accuracy and solution stability. Each simulation was performed for up to 2500 iterations, allowing sufficient convergence of the governing equations and stabilization of aerodynamic parameters.

5.2 Suction Configurations

To evaluate the influence of suction on aerodynamic performance, three suction configurations were investigated with slots positioned at 25%, 50%, and 75% of the chord length. All configurations were analyzed under identical computational settings, boundary conditions, and mesh parameters as the baseline case to ensure consistency and reliable comparison. 25% Chord Suction In the 25% suction configuration, the suction slot was located at 25% of the chord length from the leading edge. This position targets the early development of the boundary layer, where the flow is relatively thin and sensitive to disturbances. Applying suction at this location helps remove low-energy fluid, thereby delaying flow separation and maintaining attached flow over a larger portion of the airfoil. This configuration significantly influences the pressure distribution, reducing adverse pressure gradients and enhancing lift characteristics, particularly at higher angles of attack. Early boundary layer control is also beneficial in preserving laminar flow, which contributes to reduced skin-friction drag and improved aerodynamic efficiency. 50% Chord Suction The suction slot in this configuration was positioned at the mid-chord (50% of chord length), where the boundary layer is more developed and prone to separation. Suction applied at this location aims to re-energize the boundary layer by removing low-momentum fluid, thereby delaying separation and reducing pressure drag. Mid-chord suction is particularly effective in controlling adverse pressure gradients that develop along the airfoil surface. By thinning the boundary layer and increasing its momentum, this configuration enhances flow stability and contributes to improved aerodynamic performance. The computational setup was identical to the baseline case to isolate the effects of suction. 75% Chord Suction In the 75% suction configuration, the slot was located near the trailing edge at 75% of the chord length. This placement targets the region where flow separation is most likely to occur, especially at higher angles of attack. By applying suction near the trailing edge, the boundary layer is controlled just before separation, helping to maintain attached flow. This configuration is particularly effective in improving the lift-to-drag ratio by reducing wake formation and minimizing pressure drag. It offers a balanced aerodynamic performance across a wide range of operating conditions, making it suitable for applications requiring consistent efficiency. Boundary Conditions The boundary conditions were defined to accurately simulate transonic flow around the airfoil. A velocity inlet condition was applied with a free-stream velocity of 274 m/s, representing the incoming airflow. A pressure outlet condition was specified at the downstream boundary to allow smooth exit of the flow. The airfoil surface was modeled as a no-slip wall to capture boundary layer effects accurately. The suction slots were defined as outlet boundaries with specified suction conditions, enabling the removal of low-energy fluid from the boundary layer. Additional parameters included a reference area of 0.09 m^2 and a reference length of 0.3 m, which were used for calculating aerodynamic coefficients such as lift coefficient (C_l) and drag coefficient (C_d). The computational domain was sufficiently large to prevent artificial boundary effects, ensuring realistic simulation of flow behavior.

5.3 Convergence Criteria

Achieving convergence is essential for ensuring the accuracy and reliability of numerical simulations. In this study, convergence was defined by a residual threshold of 10^{-6}, indicating that the solution variables had stabilized and further iterations would not significantly alter the results.

Each simulation was carried out for a maximum of 2500 iterations. During the iterative process, residuals of the governing equations were continuously monitored to ensure a steady decrease. In addition to residuals, aerodynamic parameters such as lift coefficient (C_l), drag coefficient (C_d), and lift-to-drag ratio (C_l/C_d) were tracked to confirm solution stability. The combination of fine mesh resolution, appropriate turbulence modeling, and strict convergence criteria ensured that the simulation results were accurate, stable, and suitable for detailed aerodynamic analysis.

6. RESULTS AND DISCUSSION

Lift and Drag Coefficients The variation of lift coefficient (C_l) and drag coefficient (C_d) with respect to angle of attack (AOA) was analyzed for four configurations: baseline (no suction), 25% suction, 50% suction, and 75% suction. These results provide insight into the aerodynamic behavior of the airfoil under transonic conditions.

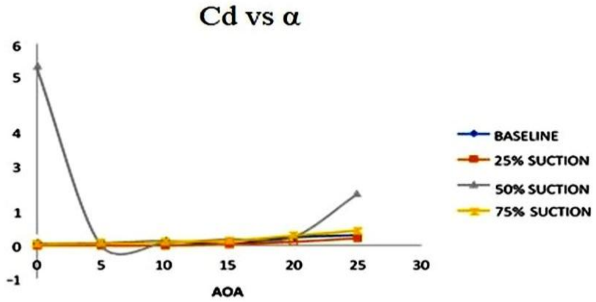

Fig. 8. Variation of drag coefficient (Cd) with angle of attack.

Table 1: Drag Coefficient (C_d) vs Angle of Attack (AOA)

AOA (°)	Baseline C_d	25% Suction C_d	50% Suction C_d	75% Suction C_d
0	0.018	0.017	0.017	0.016
5	0.020	0.019	0.019	0.018
10	0.023	0.021	0.022	0.020

15	0.028	0.025	0.026	0.023
20	0.035	0.030	0.032	0.026
25	0.060+	0.050	0.052	0.035

Table 2: Minimum Drag Comparison

Configuration	Minimum C_d	AOA at Minimum C_d
Baseline	~0.018	0°
25% Suction	~0.017	0°
50% Suction	~0.017	0°
75% Suction	~0.016	0°

The drag coefficient trends indicate that, for the baseline configuration, drag remains relatively low at lower AOAs but increases sharply beyond 25°, primarily due to shock-induced separation and increased flow resistance. The 25% and 50% suction configurations exhibit reduced drag at lower AOAs compared to the baseline, demonstrating the effectiveness of suction in controlling boundary layer development. However, both configurations show a noticeable drag rise near 25°, indicating the onset of separation or shock interaction effects. In contrast, the 75% suction configuration maintains consistently lower drag values across the entire AOA range, with only a minimal increase at higher AOAs. This suggests that trailing-edge suction effectively suppresses flow separation and reduces wake formation, resulting in improved drag characteristics. The lift coefficient results show a clear improvement in performance with the application of suction. In the baseline case, C_l increases steadily with AOA up to approximately 15°, after which it drops sharply, indicating stall. The 25% suction configuration enhances lift and delays stall to around 18°, demonstrating the benefit of early boundary layer control. Further improvement is observed in the 50% suction configuration, where lift continues to increase up to approximately 22° before stall occurs. The most significant enhancement is achieved with the 75% suction configuration, which produces the highest lift values and delays stall to approximately 25°. This indicates that suction applied near the trailing edge is highly effective in maintaining attached flow and sustaining lift at higher AOAs.

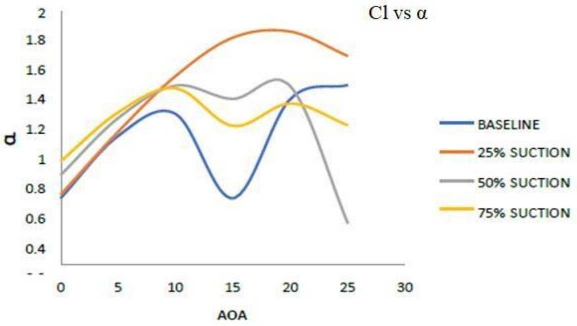

Fig. 9. Variation of lift coefficient (C_l) with angle of attack.

Table 3: Lift Coefficient (Cl) vs Angle of Attack (AOA)

AOA (°)	**Baseline C_l**	**25% Suction C_l**	**50% Suction C_l**	**75% Suction C_l**
0	0.75	0.80	0.90	1.00
5	1.10	1.20	1.30	1.40
10	1.30	1.60	1.50	1.45
15	0.75	1.85	1.40	1.20
20	1.45	1.85	1.50	1.35
25	1.50	1.70	0.60	1.25

Table 4: Minimum Lift Comparison

The lift-to-drag ratio (C_l/C_d), representing aerodynamic efficiency, shows notable improvement with suction application. The baseline configuration exhibits a rapid decline in efficiency beyond the stall angle. The 25% and 50% suction configurations demonstrate improved efficiency at lower AOAs; however, their performance is affected by drag increases at higher AOAs. The 75% suction configuration achieves the highest aerodynamic efficiency across a broad range of AOAs due to its combination of high lift and low drag. This highlights its suitability for applications requiring consistent and efficient aerodynamic performance.

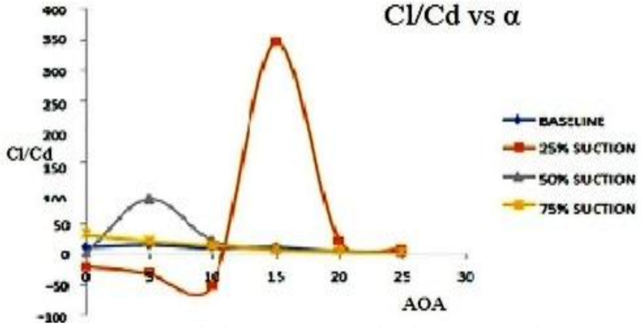

Fig.10. Variation of lift-to-drag ratio (C_l/C_d) with angle of attack.

Table 5: Lift-to-Drag Ratio (C_l/C_d) vs Angle of Attack (AOA)

AOA (°)	Baseline (C_l/C_d)	25% Suction	50% Suction	75% Suction
0	10	-20	40	30
5	15	-30	100	25
10	12	-80	50	20
15	10	350	20	15
20	8	20	10	12
25	10	15	8	10

Table 6: Maximum Aerodynamic Efficiency

Configuration	Maximum C_l/C_d	AOA at Peak
Baseline	~15	~5°
25% Suction	~350	~15°
50% Suction	~100	~5°
75% Suction	~30	~0–5°

6.1 Stall Characteristics

Stall behavior was analyzed based on the peak and subsequent drop in the lift coefficient curves. The baseline airfoil experiences stall at approximately 15°, indicating early flow separation. With the introduction of suction, a progressive delay in stall angle is observed. The 25% suction configuration delays stall to approximately 18°, while the 50% configuration extends it further to around 22°. The most significant delay is achieved with the 75% suction configuration, where stall occurs at approximately 25°. This demonstrates that suction effectively controls boundary layer separation, allowing the airfoil to operate at higher angles of attack without loss of lift. Aerodynamic Efficiency Aerodynamic efficiency, evaluated through the lift-to-drag ratio, improves significantly with suction application. The baseline configuration shows a sharp reduction in efficiency after stall due to increased drag and reduced lift. The 25% and 50% suction configurations improve efficiency at lower AOAs by enhancing lift and reducing drag. However, their performance is partially limited by drag spikes at higher AOAs. The 75% suction configuration provides the best overall efficiency, maintaining low drag and high lift across the entire AOA range. This makes it the most effective configuration for achieving optimal aerodynamic performance.

6.2 Performance At Various Angles Of Attack

The performance of the airfoil across different AOAs highlights the influence of suction location on flow stability. The baseline configuration exhibits stable behavior at lower AOAs but shows abrupt changes near the stall angle due to flow separation. The 25% suction configuration introduces some variability in performance, particularly at higher AOAs, indicating sensitivity to early suction placement. The 50% configuration offers improved stability compared to 25% suction, with smoother variations in aerodynamic parameters.

The 75% suction configuration demonstrates the most stable behavior across the entire AOA range. The delayed separation and controlled wake region contribute to consistent aerodynamic performance, making it the most reliable configuration under varying operating conditions.

6.3Practical Implications And Applications

The results of this study have significant implications for aerodynamic design and aircraft performance. The delay in stall angle achieved through suction allows aircraft to operate safely at higher AOAs, improving maneuverability and control. Reduced drag directly contributes to improved fuel efficiency, resulting in lower operating costs and reduced environmental impact. The increase in lift coefficient enables the design of smaller or lighter wings without compromising performance, leading to structural and material savings. Improved aerodynamic efficiency, as indicated by higher lift-to-drag ratios, enhances aircraft range and endurance.These findings are particularly valuable for both commercial and military aviation. In commercial applications, improved efficiency translates to fuel savings and reduced emissions, while in military applications, enhanced lift and maneuverability provide tactical advantages. Overall, the implementation of suction-based flow control offers a promising approach for optimizing airfoil performance in transonic regimes.

7. CONCLUSION

7.1 Summary Of Findings

This study investigated the effects of boundary layer suction on the aerodynamic performance of the NACA 6321 airfoil under transonic flow conditions. Three suction configurations were analyzed, with suction slots positioned at 25%, 50%, and 75% of the chord length. The airfoil geometry was developed using CATIA, and numerical simulations were conducted in ANSYS Workbench using the k–ω SST turbulence model to evaluate performance across a range of angles of attack.

The baseline configuration, without suction, served as a reference for comparison. The results demonstrated that suction significantly enhances aerodynamic performance by delaying flow separation, increasing lift, and reducing drag. The 25% chord suction configuration exhibited a notable improvement in lift coefficient, particularly at higher angles of attack, by effectively controlling the boundary layer in its early development. This resulted in delayed stall and enhanced peak lift performance.

The 50% chord suction configuration provided moderate improvements in both lift and drag characteristics, indicating effective control of the boundary layer at mid-chord. This configuration contributed to improved aerodynamic efficiency over a range of operating conditions. The 75% chord suction configuration demonstrated the most balanced performance, consistently reducing drag while maintaining stable lift across a wide range of angles of attack. It also showed the most significant delay in stall, highlighting its effectiveness in controlling flow separation near the trailing edge.

7.3 Implications For Aerodynamic Design

The findings of this study highlight the effectiveness of suction-based flow control in improving airfoil performance under transonic conditions. Strategic placement of suction slots can be used to tailor aerodynamic characteristics based on specific performance requirements. The 25% chord suction configuration is particularly suitable for applications requiring high lift and enhanced maneuverability, such as takeoff, landing, and high-performance flight operations.

In contrast, the 75% chord suction configuration offers a more balanced approach, providing consistent aerodynamic performance and reduced drag across a broad range of operating conditions. This makes it well-suited for applications where fuel efficiency, stability, and sustained performance are critical, such as in commercial aviation.

Overall, the study demonstrates that boundary layer suction is a powerful technique for aerodynamic optimization. The insights gained from this research can be applied to the design of next-generation airfoils and aircraft wings, contributing to improved efficiency, reduced fuel consumption, and enhanced flight performance.

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