

Numerical Analysis of Modified Supersonic Airfoils to Investigate Aerodynamic Performance

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Abstract - This study presents a Computational Fluid Dynamics (CFD) investigation into the aerodynamic performance of modified supersonic airfoils, focusing on two novel configurations: a Modified double wedge and a Wedge-convex airfoil. Traditional supersonic airfoils such as the double wedge and biconvex perform effectively at high Mach numbers but often experience increased drag and reduced efficiency at moderate angles of attack. To address these issues, geometric modifications were introduced to improve shock control and pressure distribution. The aerodynamic performance of the modified airfoils was assessed using steady, compressible, two-dimensional CFD simulations. Simulations were conducted across Mach numbers ranging from 1.5 to 4.0 and angles of attack (AOA) of 0°, 2°, 4°, 6°, 10°, and 15°. Key aerodynamic parameters including lift coefficient (CL), drag coefficient (CD), moment coefficient (CM), and lift-to-drag ratio (CL/CD) were evaluated to understand the performance across various flow conditions. Results indicate that the wedge-convex airfoil outperforms the traditional biconvex airfoil, particularly in terms of CL/CD and stability. Among the tested geometries, the wedge-convex airfoil consistently exhibited superior performance, suggesting strong potential for applications in supersonic aircraft wings and missile nose designs.

Keywords - Supersonic airfoil, Computational Fluid Dynamics, Wedge-convex airfoil, Shock control, Compressible flow, Lift-to-drag ratio.

I. INTRODUCTION

Supersonic flight has long been a cornerstone of advanced aerospace engineering, enabling rapid global reach for military platforms and emerging high-speed commercial applications. The aerodynamic performance of vehicles operating in the supersonic regime is strongly influenced by airfoil geometry, as shock-wave formation, pressure distribution, and wave drag dominate the flow physics at high Mach numbers. Consequently, the selection and optimization of airfoil profiles play a critical role in determining overall efficiency, maneuverability, and mission capability.

Conventional supersonic airfoil geometries such as double-wedge and biconvex profiles have been widely adopted due to their geometric simplicity and reliable performance in high-speed flows.

Double-wedge airfoils, characterized by sharp leading edges, are known for their ability to reduce wave drag at higher Mach numbers, while biconvex airfoils provide smoother pressure distributions and comparatively better aerodynamic performance at moderate supersonic speeds. Despite these advantages, both profiles exhibit inherent limitations, including increased wave drag, inefficient pressure recovery, and degraded aerodynamic performance at moderate angles of attack. These shortcomings become more pronounced in applications requiring wide operational envelopes, high maneuverability, and improved fuel efficiency.

To overcome these challenges, recent research has increasingly focused on modified and non-conventional supersonic airfoil configurations that offer improved shock control and enhanced flow behaviour. By introducing tailored geometric features such as modified wedge angles or curved surfaces, these advanced airfoils aim to mitigate shock strength, delay flow separation, and achieve better lift-to-drag characteristics across a broad

range of Mach numbers and angles of attack. Among such configurations, the Modified Double Wedge and Wedge-Convex airfoils have emerged as promising alternatives to traditional designs.

The present study investigates the aerodynamic performance of these two non-conventional supersonic airfoils using Computational Fluid Dynamics (CFD). Their performance is systematically compared with that of a conventional biconvex airfoil under varying Mach numbers and angles of attack. Special emphasis is placed on evaluating lift, drag, pressure distribution, and shock-wave behaviour to assess the effectiveness of geometric modifications in improving overall aerodynamic efficiency. The outcomes of this research are intended to contribute valuable insights toward the development of optimized airfoil designs for next-generation supersonic vehicles operating across diverse flight conditions.

II. OBJECTIVES

The primary goal of this study is to investigate the aerodynamic performance of nonconventional supersonic airfoils, specifically focusing on Modified Double Wedge and Wedge-Convex configurations. To explore potential performance enhancements, geometric modifications were introduced to the conventional Double Wedge and Biconvex airfoils, and a novel Wedge-Convex airfoil was designed to promote favorable pressure distribution and improved shock control. A key aspect of this study is that all three airfoils were designed with the same chord length (1 m) and maximum thickness (8.75 cm) to ensure that the impact of profile geometry on aerodynamic performance could be evaluated independently of size-related effects.

CFD simulations were conducted under steady, viscous, compressible flow conditions across a wide range of freestream Mach numbers: 1.5, 2.0, 2.5, 3.0, 3.5, and 4.0. For each Mach number, analyses were performed at various angles of attack (AOA): 0°, 2°, 4°, 6°, 10°, and 15°, to study lift and drag behavior under different flow incidence conditions. The lift-to-drag ratio was used as the primary metric for aerodynamic efficiency, with higher values indicating

superior performance. This study demonstrates that strategic geometric modifications, particularly the inclusion of convex curvature, can yield significant improvements in supersonic aerodynamic characteristics, offering valuable insights for future high-speed airfoil design.

III. NUMERICAL METHODOLOGY

The CFD simulations in this study were carried out using the density-based solver embedded within ANSYS Fluent, which is well-suited for compressible, high-speed aerodynamic flows. The grand solver architecture solves the coupled system of Continuity, Navier-Stokes, and Energy equations simultaneously using a Finite Volume Method (FVM). This tightly coupled framework ensures accurate capture of flow gradients, particularly in shock-dominated regions, which are critical in supersonic airfoil analyses.

For turbulence modeling, the Reynolds-Averaged Navier-Stokes (RANS) equations are solved using the SST $k-\omega$ model, which offers superior accuracy in capturing shock-boundary layer interactions and adverse pressure gradients typical in high-speed aerodynamic flows. The energy equation was activated to account for compressibility and thermal effects in supersonic flow. The solution methodology incorporated a fully coupled solver, with implicit formulation, and second-order upwind schemes for momentum, energy, and turbulence equations. Convergence was monitored via residuals and physical variable stabilization, with under-relaxation factors finely tuned to maintain solver stability in shock-dominated zones.

Geometries

The modified double wedge, the novel wedge convex and the biconvex are the three different airfoil geometry configurations that are designed using SOLIDWORKS for this study. The first two specified airfoil configurations are the airfoils of interest for this numerical analysis, and the latter is designed as a baseline model comparison. Initially, domain study is carried out to find the right domain configuration. It was decided to choose C-domain, within which the geometry is bound.

Modified Double wedge:

This airfoil features two wedge segments on both upper and lower surfaces, with a noticeable flat section at mid-chord. The design includes 8.29° leading and trailing wedge angles and a maximum thickness of 8.75 cm at 40% chord. It generates strong oblique shocks at the leading edge and expansion waves at breaks. The flat center helps stabilize shock interactions and pressure recovery, improving supersonic performance over a traditional double wedge.

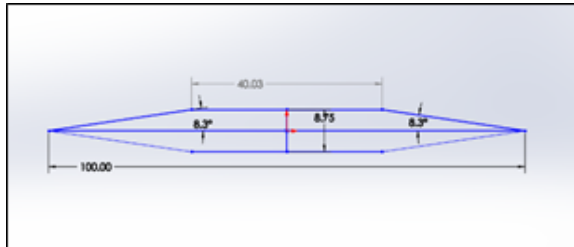


Figure 1. Modified Double Wedge

Dimensions:
Chord length: 100 cm
Half wedge angle: 8.296 deg
Max thickness: 8.7488 cm
Flat surface: 0.4 C

Wedge Convex :

This airfoil combines a flat lower surface with a convex curved upper surface. The 5° wedge angles create sharp leading edges ideal for supersonic flows. The flat bottom promotes strong expansion waves, while the curved top maintains smoother pressure gradients. This design delays shock detachment on the upper surface, generating better lift performance with reduced drag compared to symmetric wedges.

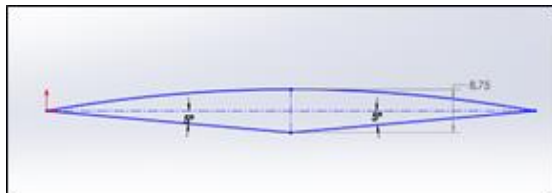


Figure 2. Wedge Convex

Dimensions:
Chord length: 100 cm

Half wedge angle of lower surface: 5 deg
Max thickness: 8.7488 cm

Biconvex:

This airfoil has a symmetric, smooth curvature on both upper and lower surfaces, reaching a thickness of 8.75 mm at mid-chord. It promotes attached oblique shock formation and minimizes wave drag. The gradual curvature reduces flow separation and enhances pressure recovery, making it highly efficient in supersonic regimes. Biconvex profiles are known for high lift-to-drag ratios and smooth flow control at moderate angles of attack.

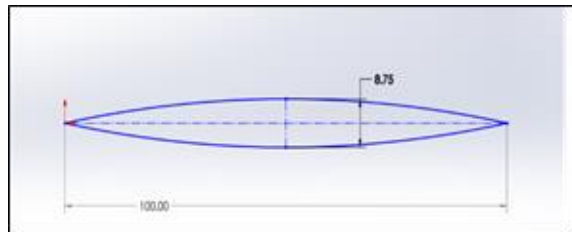


Figure 3. Biconvex

Dimensions:
Chord length: 100cm
Max thickness: 8.7488cm

Formula Used: $y_t(x) = \frac{t_{max}}{2} \left[1 - \left(\frac{2x}{c} - 1 \right)^2 \right]$

Where M_∞ represents the Free Stream Mach Number, α is the Angle of Attack, C is the chord length, set equal to 1 meter, and t represents the maximum thickness. The top and bottom surfaces of the biconvex airfoil are generated using two sets of equations.

Computational Domain

For this study, the geometry is enclosed within a C-domain with definite boundary dimensions as follows:

Upstream: 15C
Downstream: 20C
Top/Bottom: 15C.

To ensure accurate shockwave resolution and prevent numerical reflections, the computational domain was extended to 15 times the chord length (1500 cm) in all directions. This large domain allows

shockwave capturing, minimization of boundary effects, better flow development.

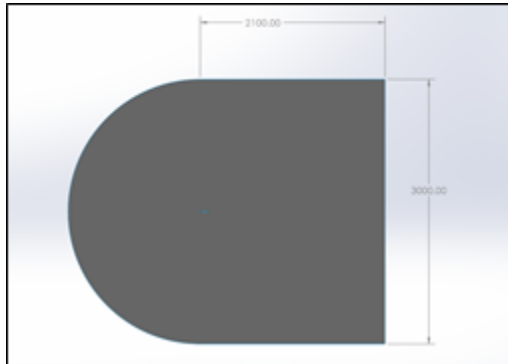


Figure 4. C- Domain

The extended inlet and outlet distances allow the supersonic flow to stabilize before and after interacting with the airfoil, improving the reliability of the results. Simulations were performed under sea-level atmospheric conditions, with standard air properties applied for all cases. The boundary conditions were set as Pressure Farfield for the domain inlet and outlet, allowing the specification of freestream Mach number, static pressure, and temperature to simulate external compressible flow accurately. The airfoil surface was defined with a no-slip adiabatic wall condition, assuming zero heat transfer and viscous effects confined to the boundary layer.

Meshing

To ensure numerical accuracy and computational efficiency, a structured mesh was generated around the computational domain using ANSYS ICEM. The mesh was refined near the solid boundaries and regions of expected high gradients (i.e., shock zones, boundary layers, separation regions). Inflation layers were applied near the wall to resolve viscous effects.

A fine mesh was used near the wall with a first cell height corresponding to $y^+ < 1$ to accurately capture the laminar/turbulent boundary layer.



Figure 5. Structured Mesh of Wedge Convex Airfoil

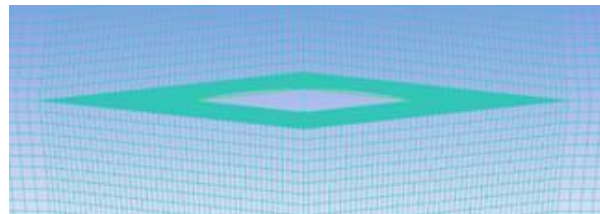


Figure 6. Fine Mesh near boundary layer

The Shear Stress Transport (SST) $k-\omega$ turbulence model is selected due to its effectiveness in accurately predicting flow separation and shock-induced boundary layer interactions, which are crucial in the divergent section of the nozzle. This model combines the advantages of the $k-\omega$ model near walls and the $k-\epsilon$ model in free-stream regions, providing a balanced approach to modelling turbulence in highly dynamic flow regimes.

Mesh Independence Study

A mesh independence study was conducted to ensure the accuracy of numerical results without incurring excessive computational cost. The primary objective was to identify the optimal mesh density that yields stable and reliable values of aerodynamic coefficients such as lift (CL), drag (CD), and pressure distributions, with minimal change across successive refinements. Simulations were run under identical boundary conditions and solver settings. The variation in the results (especially CD) between the medium and fine meshes was found to be within [1–2%], indicating that the solution had become effectively mesh-independent. Key mesh quality indicators such as skewness, orthogonal quality, and aspect ratio were monitored throughout the refinement process to ensure numerical stability.

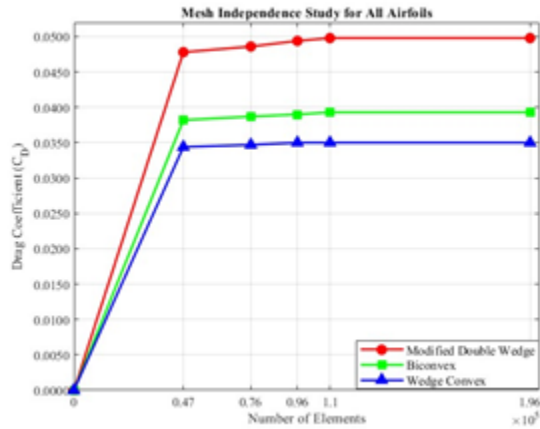


Figure 7. Mesh Independence graph

CFD Validation with Linear Theory:

To validate the CFD model, linearized supersonic theory was used for a biconvex airfoil at Mach 1.5. The theoretical lift coefficient is given by:

$$C_L = \frac{4\alpha}{\sqrt{M_\infty^2 - 1}}$$

where α is in radians and M_∞ is the freestream Mach number. The theoretical predictions were found to be in good agreement with the CFD results, particularly at lower angles, where linear assumptions hold well. This consistency confirms that the CFD model reliably captures the aerodynamic behaviour in the supersonic regime.

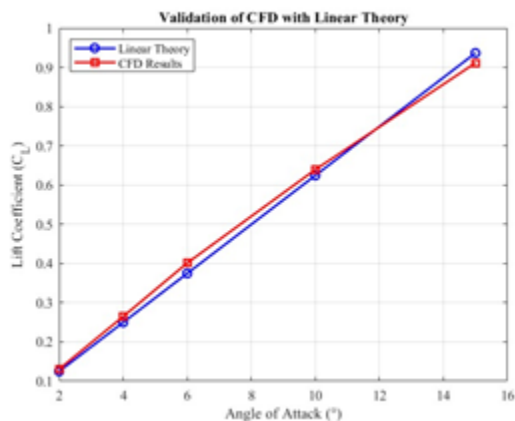


Figure 8. Linear theory vs Numerical study for Biconvex at Mach 1.5

Results and Discussions

The numerical simulations for the modified double-wedge, wedge-convex, and biconvex airfoils were performed across various Mach numbers (1.5, 2.0, 2.5, 3.0, 3.5, and 4.0) and angles of attack (0°, 2°, 4°, 6°, 10°, and 15°). The primary focus was on understanding the influence of geometric modifications on the aerodynamic performance of the three airfoils was evaluated in terms of CL, CD, and CL/CD ratio across the entire Mach range.

To ensure the accuracy of the CFD approach, the results for the biconvex and modified double-wedge airfoils were compared with the available experimental and theoretical data from literature.

Lift and Drag Characteristics

Lift Coefficient (CL)

In supersonic flows, lift typically increases linearly with angle of attack due to pressure differentials enhanced by oblique shocks. Among the three airfoils, the wedge-convex consistently delivered the highest lift across all Mach numbers and angles of attack, owing to its combination of a sharp leading edge and a curved upper surface that enhances expansion effects. The modified double wedge also showed strong lift performance, closely trailing the wedge-convex. In contrast, the biconvex airfoil, though aerodynamically smooth, generated comparatively lower lift, particularly at higher AOA, due to reduced surface pressure gradients. Overall, the wedge-convex airfoil proved superior in lift generation, making it optimal for applications requiring higher lifting capability under supersonic conditions. For all configurations, CL increased almost linearly with AOA at lower incidences (0°–4°), consistent with linear theory predictions.

- Modified Double Wedge: CL increased rapidly with AOA at all Mach numbers but plateaued beyond 10° due to shock-induced flow separation.
- Wedge-Convex: The lift curve exhibited a smoother gradient, and the delayed stall characteristics were evident, especially at Mach 2.5 and 3.0.

- Biconvex: The highest CL was observed at moderate Mach numbers (2.0–2.5), confirming its suitability for efficient cruise at these speeds.

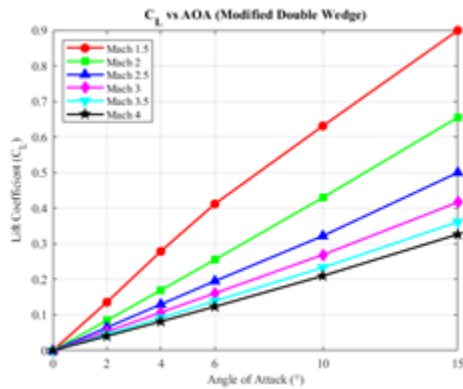


Figure 9. CL vs AOA - Modified double wedge

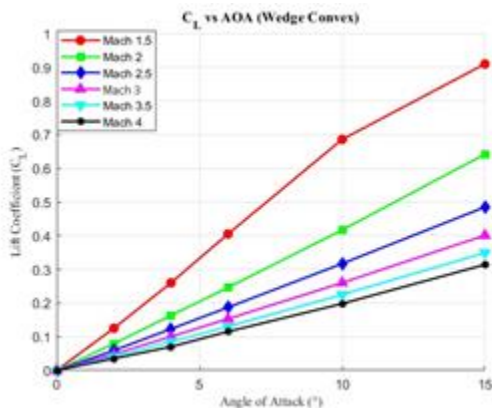


Figure 10. CL vs AOA – Wedge Convex

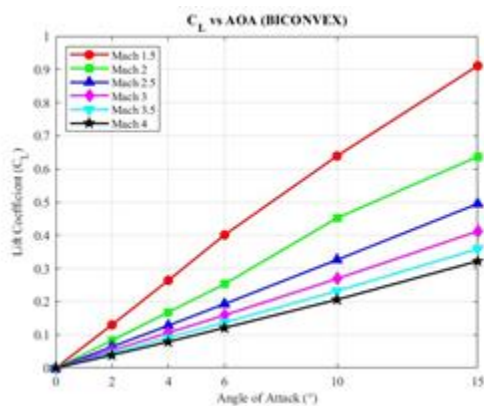


Figure 11. CL vs AOA – Biconvex

Drag Coefficient (CD)

Drag in supersonic regimes is dominated by wave drag and boundary layer interactions. The biconvex airfoil displayed the lowest drag

among the three configurations at most conditions, benefiting from its symmetric and smooth contour that minimizes shock intensity and pressure drag. The wedge convex showed moderate drag, performing better than modified double wedge at higher Mach numbers due to its convex geometry that delays shock detachment. The modified double wedge airfoil, while average in lift, experienced higher drag, especially at lower Mach numbers and high AOA, due to stronger shock formation near its sharp edges. From a drag perspective, the biconvex airfoil is the most efficient, making it ideal where drag minimization is critical.

- Modified Double Wedge: Exhibited the highest CD at higher Mach numbers, primarily due to strong shock reflections and pressure drag.
- Wedge-Convex: The convex upper surface helped in reducing wave drag, with CD values consistently lower than the modified double wedge at all Mach numbers.
- Biconvex: Showed the lowest CD at Mach 2.0 and 2.5, aligning with the findings of Athul Krishna et al. [2].

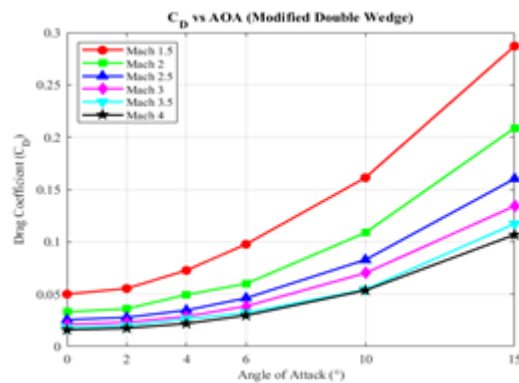


Figure 12. CD vs AOA - Modified double wedge

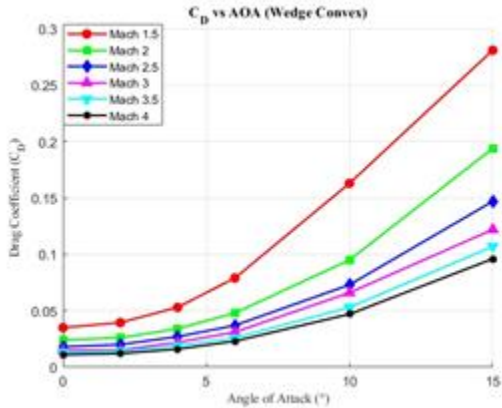


Figure 13. CD vs AOA – Wedge Convex

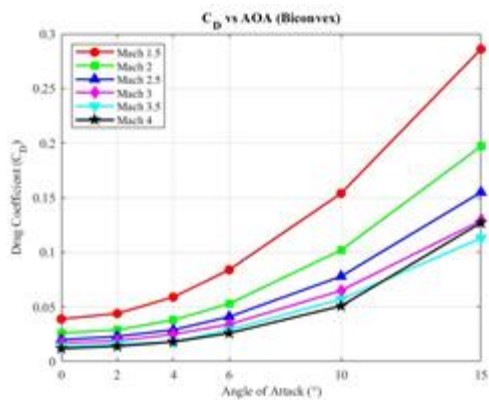


Figure 14. CD vs AOA - Biconvex

Lift-to-Drag Ratio (CL/CD)

The lift-to-drag ratio is a key metric of aerodynamic efficiency, especially under supersonic conditions where trade-offs between lift and wave drag are prominent. Among the three airfoils, the wedge-convex airfoil demonstrated excellent CL/CD performance, particularly in the Mach 1.5–2.5 range and at moderate angles of attack (4°–6°). Its superior lift capabilities outweighed the drag rise, resulting in high efficiency. The modified double wedge also exhibited good CL/CD especially at Mach 3, offering a balanced performance due to its sharper geometry. The biconvex airfoil, while efficient in minimizing drag, produced relatively lower lift, which led to poorer lift-to-drag ratios overall. Therefore, in terms of aerodynamic efficiency, the wedge-convex airfoil outperforms across most Mach conditions, especially in regimes where high lift and moderate drag are desired.

- Modified Double Wedge: CL/CD peaked at Mach 2.5–3.0, showing a good balance between sharp-edge lift generation and moderate drag levels, particularly effective at 4°–6° AOA.
- Wedge-Convex: Delivered consistently high CL/CD across all Mach numbers, with exceptional performance at Mach 1.5–2.5 due to high lift and controlled drag making it efficient across a broad supersonic envelope.
- Biconvex: Showed moderate CL/CD ratios; while drag was minimal, limited lift production reduced aerodynamic efficiency best suited for steady cruise where drag minimization is the priority.

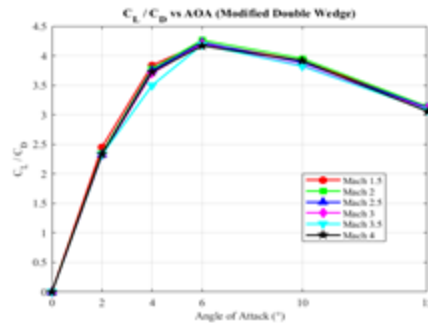


Figure 15. CL/CD vs AOA - Modified double wedge

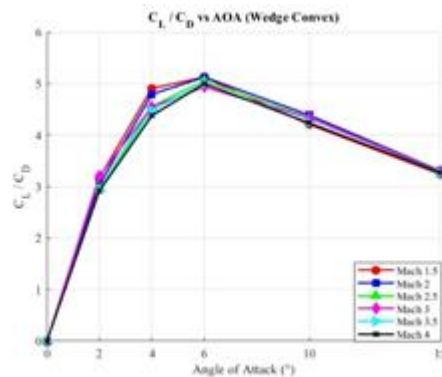


Figure 16. CL/CD vs AOA – Wedge Convex

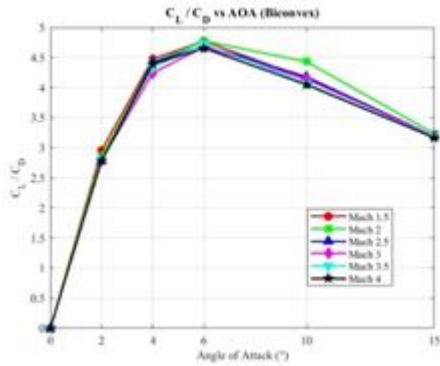


Figure 17. CL/CD vs AOA – Biconvex

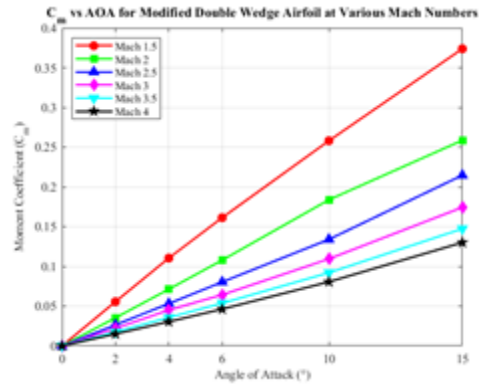


Figure 18. CM vs AOA - Modified double wedge

Moment Coefficient (CM)

The pitching moment coefficient (CM) is a critical factor in assessing longitudinal stability, with negative CM values typically indicating stable nose-down tendencies, while positive values can suggest instability. In this study, although the CM values appear positive due to the location of the moment reference point (likely placed near or ahead of the aerodynamic centre), the actual trend of the moment coefficients is negative across all angles of attack and Mach numbers. This implies that all three airfoils - modified double wedge, wedge-convex, and biconvex exhibit favourable pitching moment behaviour conducive to longitudinal stability.

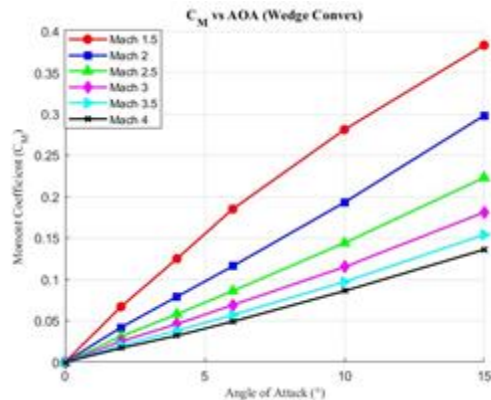


Figure 19. CM vs AOA –Wedge Convex

Among them, the wedge-convex airfoil shows the most pronounced nose-down pitching moment, especially at higher angles of attack, due to its upper surface curvature generating stronger leading-edge pressure gradients. The modified double wedge displays a more moderate moment response, while the biconvex airfoil, owing to its symmetric shape, maintains the most balanced moment profile. Despite these differences, all three airfoils demonstrate stable pitching characteristics, making them well-suited for supersonic configurations requiring long-term trim and stability control.

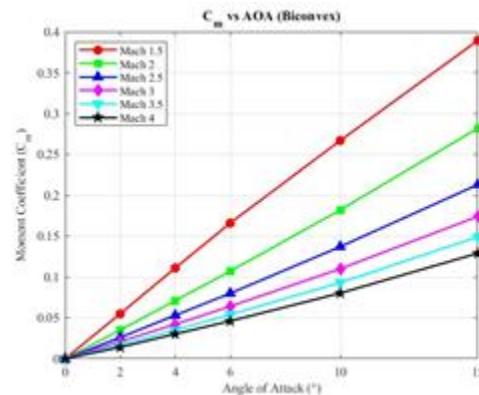


Figure 20. CM vs AOA – Biconvex

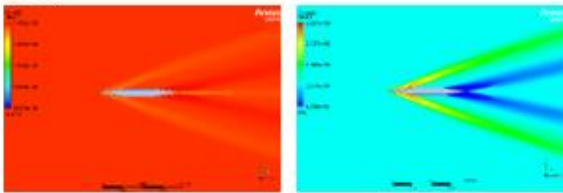
Velocity and Pressure Contours (MACH 4):

In this study, pressure and velocity contours were generated for all three airfoils—Modified Double Wedge, Wedge-Convex, and Biconvex across a wide range of Mach numbers (1.5, 2.0, 2.5, 3.0, 3.5, and 4.0) and angles of attack (0°, 2°, 4°, 6°, 10°, and 15°). Although contour data is available for the entire Mach–AOA matrix, for clarity and concise representation, only the contour plots

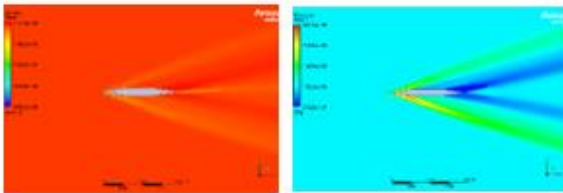
corresponding to Mach 4.0 have been presented for all three airfoils at the selected angles of attack. These high-speed flow visualizations effectively illustrate shock structures, expansion waves, and pressure distribution patterns unique to each airfoil configuration. The selected Mach 4 results provide a clear comparative insight into the supersonic aerodynamic behavior of the airfoils under extreme conditions, while full datasets remain available for deeper analysis.

Modified Double wedge :

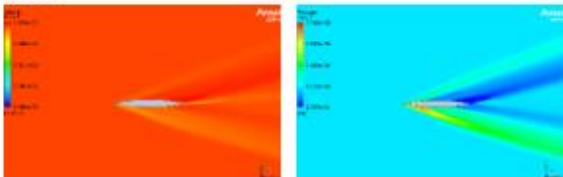
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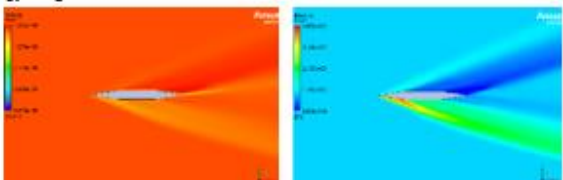
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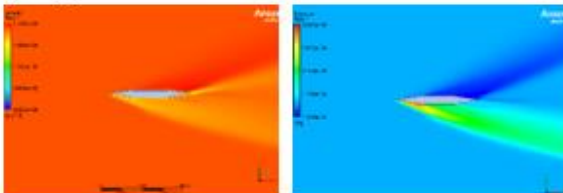
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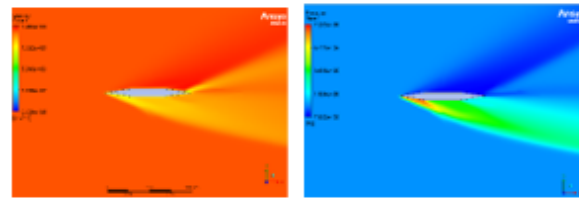
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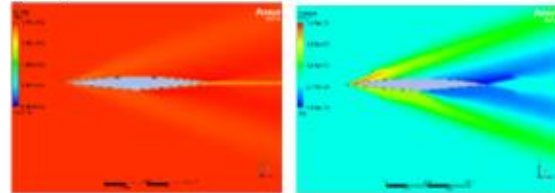


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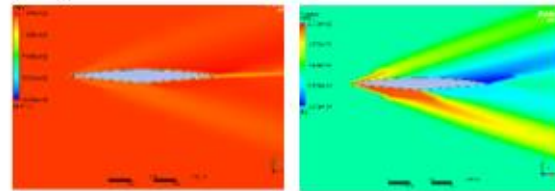


Wedge – Convex :

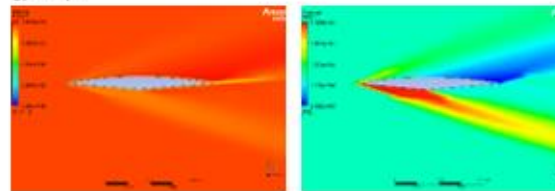
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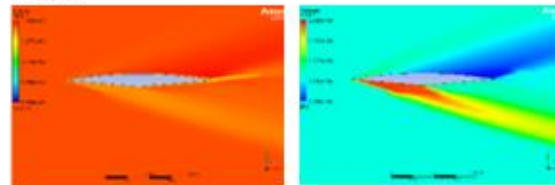
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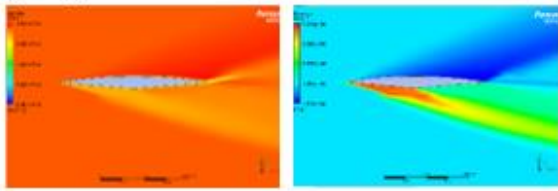
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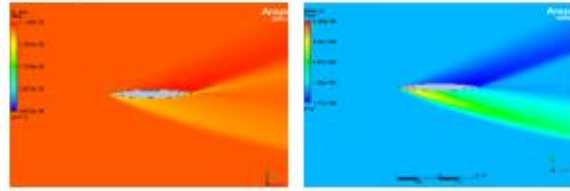
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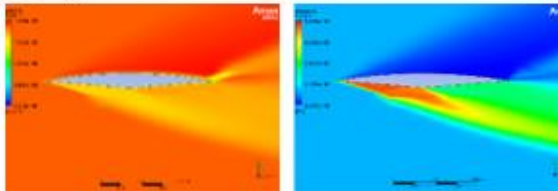
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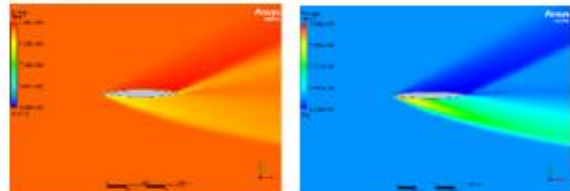
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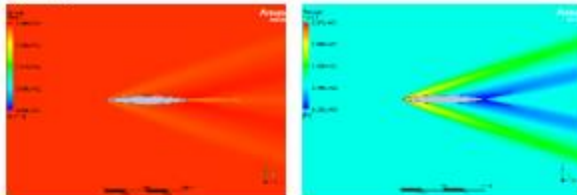


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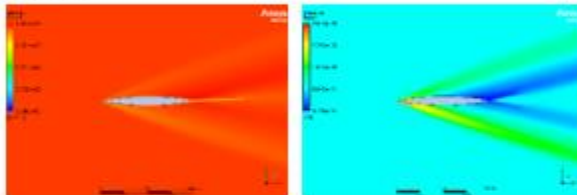


Biconvex:

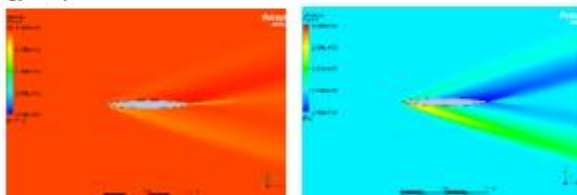
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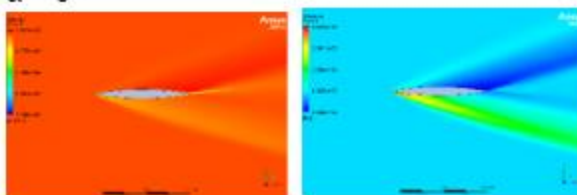
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IV. CONCLUSIONS

This work explored the aerodynamic behavior of three different supersonic airfoils, a modified double-wedge, a newly designed wedge-convex, and a conventional biconvex – through detailed CFD simulations over a range of Mach numbers and angles of attack. The objective was to understand how minor geometric changes influence lift, drag, and shockwave characteristics in supersonic flow.

The modified double-wedge airfoil behaved as expected for sharp-edged supersonic sections: it generated high lift-to-drag ratio at increasing angles of attack, especially at lower Mach numbers (1.5 – 3), but at the expense of significant wave drag. Strong oblique shocks formed near the leading edge and became more intense with increasing incidence, which explains its relatively lower aerodynamic efficiency at very low Mach numbers. Nonetheless, its ability to sustain high lift in extreme flow regimes reinforces its relevance for high-speed applications where lift is prioritized over drag economy.

The wedge-convex airfoil, which introduces a curved upper surface to the traditional wedge profile, demonstrated the use of advantages from both modified double wedge and biconvex, along with some disadvantages, along moderate Mach numbers. A biconvex upper surface to minimize wave drag and maintain structural simplicity. A double wedge lower surface to delay flow separation and increase lift by maintaining favorable pressure

gradients. The smoother curvature delayed shock formation and allowed a more gradual pressure recovery, which reduced wave drag compared to the sharp-edged configuration. This directly translated into a consistently higher lift-to drag ratio, making it well-suited for cruise conditions.

The biconvex airfoil, used as a baseline, showed stable and predictable aerodynamic performance, validating the numerical method by matching published experimental trends. Its lower drag and smooth pressure distribution at lower Mach numbers reaffirm its suitability for transonic and low supersonic cruising, though it does not perform as efficiently as the modified designs at higher speeds at moderate to higher angles of attack.

In summary, the results highlight that carefully introducing curvature to conventional wedge geometries can significantly improve aerodynamic efficiency without compromising lift in the supersonic regime. The wedge-convex configuration, in particular, shows strong potential for future supersonic transport or cruise vehicles, where drag reduction is critical. Further studies considering viscous effects, shock-boundary layer interactions, and optimization techniques could help refine such hybrid airfoil shapes for practical applications.

Table 1. Overall Results at All Mach range from 1.5-4

Mach Number	Angle of Attack (°)	Maximum C_L/C_D	Airfoil with Max C_L/C_D
1.5	6	5.127	Wedge-Convex
2.0	6	5.125	Wedge-Convex
2.5	6	5.05	Wedge-Convex
3.0	6	4.9	Wedge-Convex
3.5	6	5	Wedge-Convex
4.0	6	5	Wedge-Convex

Conflict Of Interest

The authors declare that they have no conflicts of interest regarding the publication of this paper .

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