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Investigation and numerical simulation of shock-boundary layer interaction in supersonic flow and the effect of boundary layer suction on flow separation

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Extended Abstract

Introduction

The boundary layer is a thin region adjacent to a surface where viscous effects are dominant and play a vital role in aerodynamic phenomena. One major challenge in this field is the phenomenon of boundary layer separation, which occurs due to adverse pressure gradients and can lead to increased drag, reduced efficiency, and flow instability. To control this phenomenon, numerous methods have been developed, including boundary layer suction, flow injection, surface modification, the use of porous materials, active flow control, and vortex generators. Each of these methods employs specific mechanisms—such as reducing boundary layer thickness, injecting energy, or creating controlled vortices—to prevent or delay flow separation. Selecting and optimizing these methods according to flow conditions and design considerations is essential for achieving maximum efficiency in aerodynamic and propulsion systems. Controlling flow separation is of great importance in many engineering applications. In jet engines, controlling flow separation can increase efficiency and reduce fuel consumption. In supersonic air intakes, controlling flow separation can improve performance and reduce thermal and mechanical loads on the surface. In gas turbines, controlling flow separation can enhance efficiency, increase the service life of components, and reduce maintenance costs. Ultimately, a precise understanding of shock wave-boundary layer interaction mechanisms and the development of effective methods to control it are critically important. This research, by investigating the effect of boundary layer suction on reducing flow separation, has taken a significant step towards improving the performance of aerodynamic and propulsion systems.

Review of the laboratory experimental method

The experimental data were obtained from work conducted by the German Aerospace Center (DLR) using the Ludwieg Tube facility (RWG) in Göttingen. This facility operates in the Mach number range of 3 to 7 and unit Reynolds numbers from 5×10^5 to 60×10^6 m^{-1}. The study investigated shock wave-turbulent boundary layer interaction using a flat plate model with a sharp leading edge and an adjustable shock generator. For the numerical simulation, a density-based solver was employed to compute the compressible Navier-Stokes equations coupled with the k-ω SST turbulence model, which is recognized for its accurate prediction of flow separation under adverse pressure gradients.

Results and Discussion

Based on the results, a structured grid with 400,000 cells was selected after grid independence study. The numerical simulation using the k-ω SST turbulence model showed excellent agreement with experimental data for static pressure distribution and schlieren images, accurately capturing the shock wave-boundary layer interaction and the resulting flow separation region. The study demonstrated that increasing the shock generator deflection angle (β) intensified the interaction and enlarged the separation zone. Crucially, the application of

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boundary layer suction through five strategically placed holes effectively eliminated the separation region, as clearly evidenced by the Mach contour comparisons, demonstrating this method's efficacy in controlling flow separation.

Conclusion

In this research, the numerical simulation of the interaction between an oblique shock wave and a turbulent boundary layer in a supersonic flow at Mach 5 was successfully conducted. The simulation results not only demonstrate the high accuracy of the numerical method in predicting the flow structure and shock wave behavior, but their comparison with experimental data also shows acceptable quantitative and qualitative agreement. This congruence confirms the importance of using advanced numerical models to analyze the complexities of supersonic flows and the mutual effects of shock waves and boundary layers. Furthermore, the effect of boundary layer suction in improving flow conditions and eliminating the separation region was clearly observed in the numerical simulation results. The use of five small suction slots, each five millimeters long, in the separation region led to the complete removal of the recirculation zone and the reattachment of the flow to the wall surface. As observed, this method completely eliminated the separated region. These findings indicate that boundary layer suction, as a practical solution, is highly effective in controlling flow separation caused by shock wave-boundary layer interaction and can contribute to improving the stability and efficiency of supersonic engineering systems. This research provides an important step towards a deeper understanding of shock wave-boundary layer interaction mechanisms and highlights the role of modern technologies like boundary layer suction in mitigating adverse effects such as separation and instability. From an applied perspective, the results can be used for the optimal design of advanced engineering systems in areas such as jet engine intakes, supersonic nozzles, supersonic compressors, and other high-speed flow equipment. Additionally, this study lays the groundwork for future research, which could include investigating the effects of parameters such as Reynolds number, surface roughness, and different shock impingement angles to achieve a more comprehensive understanding of flow behavior. The results of this research clearly confirm the effectiveness of the boundary layer suction method in controlling the separation phenomenon caused by shock wave-boundary layer interaction. However, despite the notable effectiveness of the suction method in eliminating the separation region and improving flow stability, it is crucial to note that this method inherently incurs a cost. The sucked fluid requires a pumping system which itself consumes energy. Therefore, utilizing this technology necessitates a trade-off between the obtained aerodynamic benefits (such as drag reduction and increased stability) and the energy cost required for generating suction. Future studies could focus on optimizing suction parameters to achieve maximum efficiency with minimum energy cost.

Keywords: Shock-boundary layer interaction, flow separation, boundary layer suction, numerical simulation.

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