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Shock Wave-Boundary Layer Interaction: Studying the Effects of Shock Waves on Boundary Layers at High Speeds

Bishnujee Singh
Research Scholar, PhD in Engineering (2025) , BIR TIKENDRAJIT UNIVERSITY

Abstract: Shock Wave Boundary Layer Interaction (SWBLI), in High-Speed Flows, such as hypersonic flight and re-entry vehicles, is critical for design. The study focuses on the characteristics of high-speed shock-induced transition with a boundary layer, such as boundary layer separation, drag, and heat transfer increase. In this paper computations are carried out with the use of computational fluid dynamics (CFD) of the viscous SWBLI at various shock forces and Mach numbers. The results show that the stronger the shock waves, the greater they cause the flow separation and thermal load on the surface. The report also studies ways to mitigate such adverse effects, including the use of shock tips and active flow control. Such findings would be even more useful in designing high-velocity planes, bearing in mind that shock wave management would be of the essence in improving the aerodynamic and thermal efficiencies.
Keywords: Shock Wave Boundary Layer Interaction, Hypersonic Flight Aerodynamics, Flow Separation, High-Speed Flow.

I. INTRODUCTION

This interaction of boundary layers and shock waves is the fundamental fluid dynamics phenomenon in high velocity. This encounter is more commonly known as shock wave-boundary layer interaction (SWBLI) and dictates much of the performance of aerospace vehicles at speeds surpassing and next to Mach 1(Tang et al., 2024). The compressibility effect causes shock waves to be generated at high velocity; therefore, pressure, temperature, and velocity can be subjected to rapid increase and decrease in the boundary layer. These changes can result in flow separation, cranked drag, and increased thermal loading, none of which are wanted in vehicle performance. This paper looks to conduct research on the impact of shock waves on boundary layers to have a closer look at the interaction and consequences on high-speed flows. The article concludes with the key theoretical models together with experimental and numerical studies that have been conducted with the aim of investigating SWBLI and offers some practical solutions to diminish the adverse effects of the findings.

II. LITERATURE REVIEW

The interaction between shock waves and boundary layers has been a central research subject in fluid dynamics during recent decades. Variable conditions of the flow change rapidly in conditions of shock waves, which are formed due to the strength of the flow speed exceeding the velocity of sound (Tang et al., 2025). The fact that these waves meet with the so-called boundary layer is to blame for the latter being a layer in which the fluid facing the surface of an object moves more gradually. The impact is complex, and the shock wave can produce several other undesired impacts in the boundary layer.

A. Boundary Layers Shock Wave Impact

Shock waves cause rapid compression and deceleration of the fluid; therefore, the pressure and the temperature in the boundary layer are raised at high speeds.

Such variations may make the boundary layer unstable, and it may detach itself from the surface. The degree of separation is a function of the shock and boundary-layer relative position and strength. This separation, in most instances, results in large-scale vortex structures and enhances drag and stability. The strength of shocks and the thickness of the boundary layer were important parameters figuring out separation. One would expect stronger shocks to cause a flow to separate earlier and boundary layers to be thinner and thus more likely to separate (Sun et al., 2025).

B. Experimental and Numerical Investigations

The interactions of SWBLI are complex, and thus, an elevated level of numerical simulation has been employed to study this issue. Simulation of SWBLI in hypersonic flow has been carried out by Zhou et al. (2024), indicating that the shock strength and angle play an important role in the behavior of the boundary. It was seen that the stronger the shock value, the quicker and further separation occurred, thus giving an increased drag and a higher heat transfer on the surface. These have also been confirmed by experimental works using wind tunnels, where the findings show that shock waves over a flat plate can result in large flow separation that is dependent on the shock intensity and the Mach number.

C. Hypersonic Flight Applications

SWBLI is of special importance in hypersonic flight, where vehicles fly above Mach 5. Such high speeds will cause increased shock waves, which have a greater influence on the boundary layer. The boundary layer of hypersonic vehicles goes through very harsh thermal/aerodynamic conditions. The impact of SWBLI within hypersonic flows and pointed out that the interaction increases thermal loads that might cause damage to the surface of the vehicle(Giehler et al., 2024). Other possibilities of management shock methods, which were also seen by the study, were a way of reshaping the surface of the vehicle to weaken the shock and limit the separation of the flow.

III. METHODOLOGY

In order to analyze SWBLI, this work uses computational fluid dynamics (CFD) as a simulation with Reynolds-averaged Navier-Stokes (RANS) equations. The approximation equations are suited for modelling the turbulent flows that take place and offer an actual way to compute the SWBLI at high-speed conditions. ANSYS Fluent was used to carry out the simulations because it is a popular computational fluid dynamics program that has the capability of solving complicated fluid dynamics problems(Popovich et al., 2025).

The boundary-layer encounters with shock waves modelled in the simulations covered the Mach numbers of 2 to 6 and linked to subsonic, supersonic, and hypersonic regions. The flat plate with different shock strengths and angles was put in the computational area, and the calculation basis supposes the boundary layer to be turbulent. The different parameters, including shock intensity and shock angle, were changed to investigate their influence on the boundary layer pressure distribution and heat transfer. Another point is that the numerical results were checked against experimental data in the past works (Smith et al., 2005).

IV. RESULTS

The simulation's findings prove that there is a high sensitivity of shock wave intensity and location on the boundary layer. Wider shock waves caused the boundary layer to be stable at lower Mach numbers (Mach 2-3). But with shock strength or with the shock angle, steeper flow separation arose earlier in the boundary layer. Such a separation translated into big recirculation zones and augmented drag (Wang et al., 2025).

At higher Mach (Mach 4-6), they generated a stronger separation effect on the shock waves, and at lower Mach numbers, the boundary layer was set freer much earlier. The simulations showed that such conditions placed considerable thermos loading on the surface because separation flow caused increases in heat transfer rates. The current temperature profiles showed that hotspots in areas caused by the increased shock wave would destroy the vehicle surface after a prolonged time (Navarro et al., 2024).

The results further showed that a slanting shockwave led to the complex interaction with the boundary layer, leading to the formation of shock-induced separation bubbles. Such bubbles caused a high increment of drug and heat flux, and this proves the importance of shock management capability towards fast flight applications.

V. DISCUSSION

One can justify that the implications of the current study make sense compared to the earlier studies, since the production of shock waves and their positioning are vital in deciding the boundary layer behaviors. The shock-induced flow separation will introduce added drag and heat-flux costs that cannot be desirable in high-speed flight vehicles. These findings signify that the provision of shock management stands to have a good chance at removing the adverse factors of SWBLI (Navarro et al., 2024).

There is also one possible way to buffer the worst effects of SWBLI, which involves shock management, i.e., by manipulating the surface of the vehicle to deflect the shock waves into a more favorable position and thus avoid contact with the boundary layer. Active flow control, i.e., the application of devices such as synthetic jet or suction/blowing, has been proved to be capable of controlling shock strength and suppressing flow separation.

Possibly more promising, recent developments in adaptive surface materials, which are able to alter their shape due to external conditions, offer a potential new avenue of dynamically controlling SWBLI(Yan et al., 2024).

The findings also show that future studies of the best location of shock waves and the design of cars are necessary. The severity of SWBLI may be mitigated by the careful design of vehicle surface and shock interaction areas, allowing better overall vehicle performance. Moreover, potential applications of new flow control strategies have the potential to achieve more economical high-speed flight systems that have improved aerodynamic and thermal qualities(Ye et al., 2024).

VI. CONCLUSION

The boundary layer/shock interaction is an important phenomenon within the high-speed fluid dynamics field and has a significant impact on the aerodynamic design of hypersonic and supersonic vehicles. The paper gives great details of the impact of shock waves in the boundary layers, showing that a more severe shock yields a distinction to a flow at an earlier breach, big drag, and big thermal loads. The findings confer the significance of shock management and flow control methods in alleviating such negative outcomes. Future studies must be devoted to the optimization of shock wave positioning, the discovery of new management shock measures, and the development of better control technologies to better steer high-speed vehicles.

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