Computational Studies of Shock Wave Boundary Layer Interactions in Hypersonic Flow Over Double Cone Geometries

Siva Vayala and Ravi K. Peetala

Abstract Shock wave boundary layer interactions in the flows over high speed vehicles are considered to be challenging and essential to analyze. Importance of analyzing these for the design of thermal protection system brought it under the active research in the field of compressible flows. In this scenario, an attempt has been made to study the laminar shock wave boundary layer interactions in hypersonic flows over double cone geometry numerically to obtain thermal load variations as well as surface pressure variations on the surface of the vehicle. An open-source CFD tool OpenFOAM based on the finite volume method is used for the current study. The numerical solution captures all important features of the flow accurately and the obtained results are following the corresponding trend and matching with experimental results. Since slope limiters are capable of causing significant changes in the solution, two different slope limiters—vanLeer and superbee—have been used to check the influence on the solution. It is found that the superbee limiter is more accurate than vanLeer but inducing spurious spatial oscillations.

Keywords Hypersonic flows · Double cone configurations · OpenFOAM

1 Introduction

The future possibilities of hypersonic flow applications in civilian transport, defense sector as well as in space technology kept researchers carrying their work in the field of compressible flows. Hypersonic flows with the speed five times more than the sound speed has its own significance in the compressible flows from supersonic, transonic, and subsonic flows. It involves numerous complex phenomena that made it as a special category of supersonic flows. These include shock–shock interactions, shock wave boundary layer interactions (SWBLI), and high-temperature effects such

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as vibrational excitation, dissociation, and ionization. The presence of these phenomena in numerous applications of external as well internal flows gives a lot of importance to hypersonic flows. Out of many complex processes that hypersonic flows involved, shock–shock interactions and shock wave–boundary layer interactions grabbing the attention of researchers. Presence of these processes may induce massive thermal as well as mechanical loads on the surface of the space vehicles. The inevitable presence of boundary layer and shocks in hypersonic flows give chances to SWBLI which induces adverse pressure gradient inside the boundary layer. These results separated flows in the boundary layer accompanied by two or more additional shocks. Separation starts with separation shock and ends with reattachment shock. Flow passes through the reattachment shock will experience a large rise in temperature, which gives large thermal loads to the vehicle surface. A conscious study has to be carried out to understand and analyze these phenomena in the design of the thermal protection system of the space vehicles.

Many researchers have done experimental and computational studies on the SWBLI over many canonical geometries. Out of those, double cone configuration got importance due to its sensitivity to hypersonic flows and its ability to produce most of the possible complexities which are useful for the design aspects of space vehicles. Olejniczak et al. [1] have studied different shock interactions—type IV, V, V and a new interaction on double-wedge geometries computationally and stated that very fine mesh is required to capture these interactions accurately. Holden and Wadhams [2] and Candler et al. [3] have conducted experimental studies of hypersonic flows over double cone configurations to provide the benchmark dataset and to mitigate the preexisting differences between experimental and computational results. Gaitonde and Canupp [4] carried out numerical studies on the double cone hypersonic flows and concluded small changes in flow parameters, and numerical aspects give moderate changes in the flow properties. Later Candler et al. [5] extended his studies through computational works in which he stated possible reasons for the discrepancies between experimental and computational results. In this study, it is concluded that providing the incorrect free stream conditions is the main reason for these deviations of computational results from experimental results. Druguet et al. [6] analyzed a steady hypersonic flow over double cone configurations numerically and provided the insight of different numerical schemes and slope limiters that can be used for compressible flow simulations. It is concluded that less dissipation schemes and limiters provide an accurate solution and it is also shown that solution with very fine mesh will be independent of the changes in the numeric.

The present study focuses on the validation aspects of shock wave–boundary layer interactions over a sharp edge 25–55° double cone geometry at Mach number 11.30 using OpenFOAM.

2 Numerical Methodology

An open-source C++ based CFD toolbox OpenFOAM is used for numerical studies based on the finite volume method (FVM). A density-based solver named "*rhoCentralFoam*" based on central-upwind schemes of Kurganov and Tadmor for flux calculations at cell faces has been used for the current study. This solver solves fundamental governing equations in two steps—predictor and corrector. In prediction step, inviscid and convective terms of the conservative variables (ρ, ρu, ρe) are treated explicitly from which primitive variables (ρ, u, T) are calculated. In corrector step, earlier predicted primitive variables are corrected implicitly by adding viscous and diffusion terms. Courant number is chosen 0.5 and the time step is chosen according to the stability criteria.

The governing equations are given below.

Conservation of mass:

$$\left(\frac{\partial \rho}{\partial t}\right) + \nabla \cdot (u\rho) = 0 \tag{1}$$

Conservation of momentum:

$$\left(\frac{\partial(\rho u)}{\partial t}\right) + \nabla \cdot [u(\rho u)] + \nabla p + \nabla \cdot T = 0 \tag{2}$$

Conservation of total energy:

$$\left(\frac{\partial(\rho E)}{\partial t}\right) + \nabla \cdot [u(\rho E)] + \nabla \cdot [up] + \nabla \cdot (T \cdot u) + \nabla \cdot j = 0 \tag{3}$$

where the total energy density $E = e + \frac{1}{2}U^2$, specific internal energy e $= c_v T$, diffusive heat flux $j = -k\nabla T$ (Fourier's law of heat conduction), and T is the viscous stress tensor, assumed positive in compression. The detailed algorithm is provided by Greenshields et al. [7].

3 Results and Discussion

3.1 Validation Studies

The present study focuses on the shock wave–boundary layer interactions in hypersonic flows over a 25–55° sharp edge double cone configuration. The geometrical details are same as that of Candler [3] and corresponding geometry with the sample mesh structure used for simulation is shown in Fig. 1. The axisymmetric boundary condition is applied to the axis of the cone to facilitate 2D simulation of the double

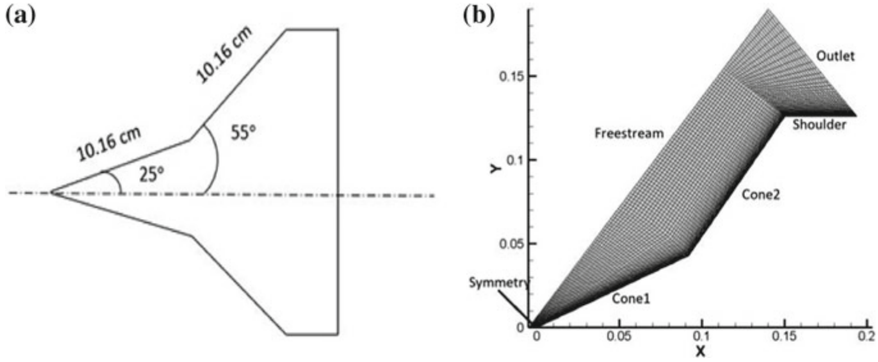

Fig. 1 Schematic of **a** geometrical configuration; **b** sample structured mesh

cone. Nitrogen is used as test gas with free stream Mach number of 11.30 and free stream temperature of 138.9 K with wall temperature of 296 K is same as that of Druguet et al. [6]. Kurganov–Tadmor flux scheme with superbee interpolation has been used for the simulations. Separation bubble size is taken as a parameter for the validation due to its sensitivity to the changes in the flow. This separation region can be measured from the variations of surface properties like surface pressure, surface heat flux, skin friction coefficient, etc., due to its strong influence on the surface properties. In surface pressure variation, sudden rise on first cone and peak value on the second cone represents starting and endings of the separation zone. The numerical results of present studies are validated with well-established experimental results of Holden and Wadhams [2]. The simulation results shown in Fig. 2 are following the corresponding trend and well in agreement with experimental results.

3.2 *Effect of Slope Limiter*

From the earlier studies, it is concluded that the selection of limiter has a significant effect on the accuracy of the solution. vanLeer limiter is recommended for all kinds of compressible flow simulations due to its less dissipation characteristics. Despite being more accurate than vanLeer limiter, superbee is not used as much as vanLeer due to its nature of inducing spatial oscillations in the flow properties. The present study investigated the ability of both the limiters vanLeer and superbee in providing an accurate solution for the same grid. It is found that for sufficiently fine mesh 512×256 with 5×10^{-7} m near wall spacing, superbee is significantly more accurate than vanLeer with negligible oscillations in surface properties which are shown in Fig. 3. It is also observed that superbee oscillations are grid-dependent and diminishes with grid refinement. To investigate the dependency of superbee limiter on the grid in producing oscillations, three different meshes 128×64, 256×128, and 512×256 with appropriate near wall spacings have been considered. Out of three meshes

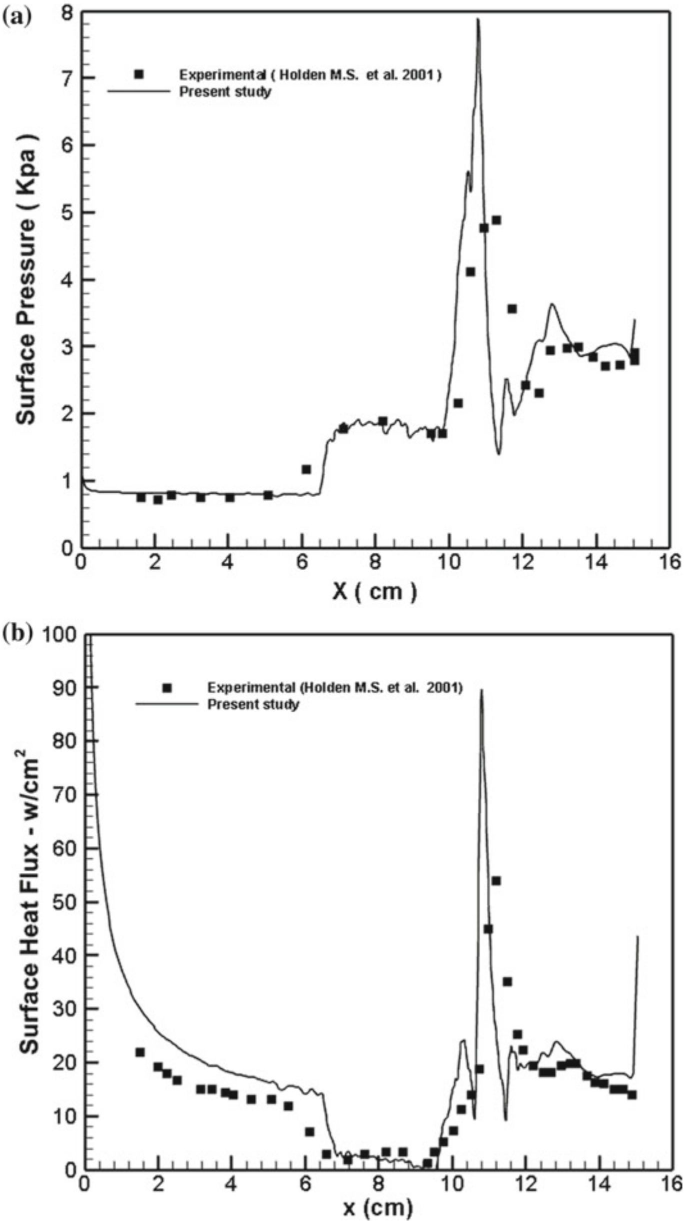

Fig. 2 Variation of surface properties along the streamwise direction **a** surface pressure; **b** surface heat flux

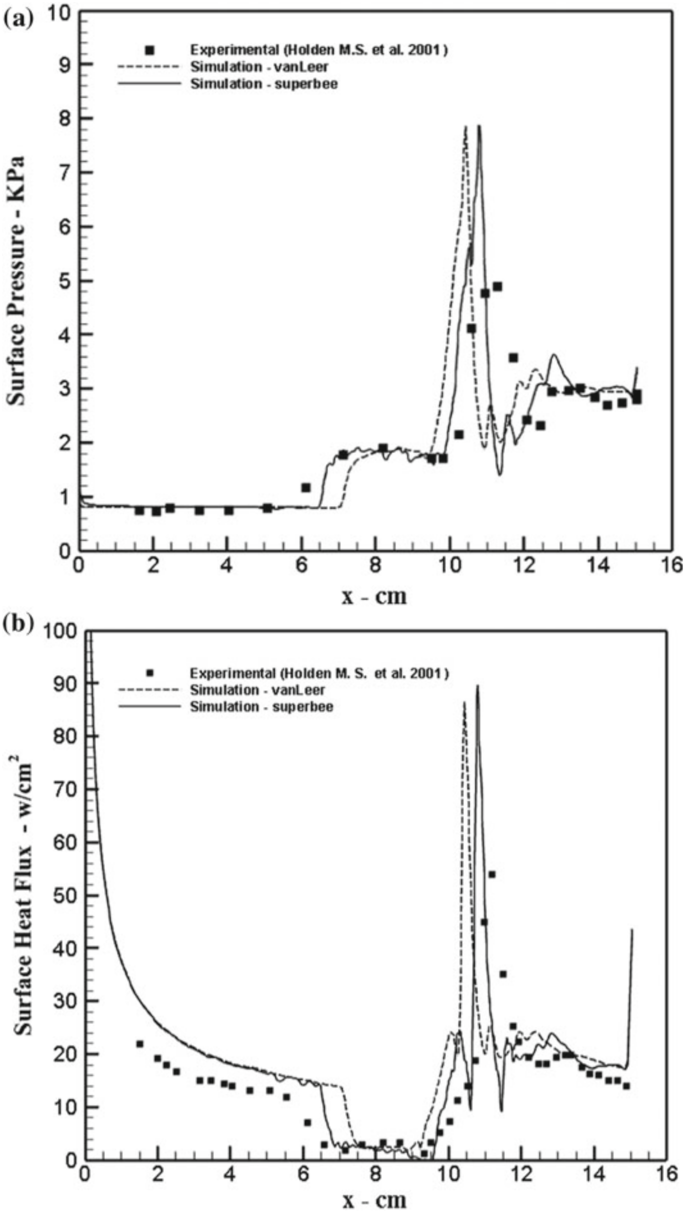

Fig. 3 Effect of slope limiter on surface properties **a** surface pressure; **b** surface heat flux

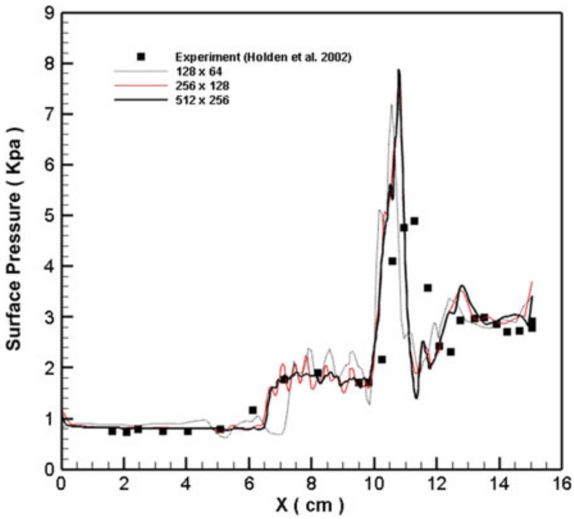

Fig. 4 Grid independence studies of superbee limiter

Table 1 Grid refinement details at important sections

S. No.	Mesh	Min. element near the wall Δy_{min}	Min. element near leading edge $\Delta x_{\text{min,le}}$	Min. element at cone–cone junction $\Delta x_{\text{min,junc}}$
1	128×64	5×10^{-5}	5×10^{-4}	4×10^{-4}
2	256×128	5×10^{-6}	5×10^{-5}	4×10^{-5}
3	512×256	5×10^{-7}	5×10^{-6}	4×10^{-6}

chosen, 256×128 and 512×256 are showing the same separation size and similar trends of surface properties. But oscillations with 512×256 mesh are in negligible magnitude than 256×128 mesh. So, 512×256 mesh is chosen as an optimum mesh from grid-independent studies and used for further studies. Grid-independent study results are shown in Fig. 4. Corresponding grid refinement details at important sections like leading edge, cone–cone junction, near wall region, etc., are provided in Table 1.

4 Conclusion

The numerical analysis of laminar shock wave–boundary layer interactions over a double cone configuration has been carried out using OpenFOAM. The results obtained from the computational studies are sharing the corresponding trend and are in good agreement with the experimental results. Effect of slope limiters also studied to check the accuracy of superbee and vanLeer limiters in providing an accurate solution and found that for same grid structure, superbee is considerably more accurate than the vanLeer. It is also observed superbee limiter's ability to produce spurious oscillations is strongly dependent on the grid and diminishes with grid refinement.

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