Mitigation of shockwave induced boundary layer separation through a secondary recirculation duct in a hypersonic flow

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Abstract. A secondary recirculation duct which leaks fluid from a high pressure reattachment zone to a low pressure upstream location of a shock wave boundary layer interaction zone is discussed in the below article. The mitigation can be attributed to both suction and blowing. Computational analyses of the above problem at a freestream of Mach 8.6 with various jet injection locations were studied for its effectiveness via a commercial software ANSYS Fluent 19 and the results are very promising. The jet injection close to the separation point is found to be most effective in delaying separation and reducing the separation bubble.

Keywords: Hypersonic, CFD, Ansys Fluent, SWBLI, Shock Wave

1. Introduction

With humans aiming to travel faster and faster, hypersonic cruises are a reality in the near future. Such cruises would need an air breathing engine like a SCRAM jet engine for efficiency and sustainability. In SCRAM jet engines, the flow compression prior to ignition is brought about by a series of shock waves, hence are susceptible to Shock Wave Induced Boundary Layer Interaction (SWBLI). As hypersonic flows have thick boundary layers, adverse pressure gradient caused by SWBLI can result in large boundary layer separation [1]. Shock wave induced boundary layer separation can result in total pressure losses, flow unsteadiness, choking, high wall temperatures, flow non-uniformities etc. [2-5]. As SWBLI cannot be avoided most research is aimed at reducing its adverse effects like boundary layer separation.

As boundary layer separation is attributed to low momentum BL and adverse pressure gradient, its mitigation techniques should involve either energizing the boundary layer, eliminating the low momentum boundary layer or reducing the adverse pressure gradient [6]. Energizing the boundary layer is done through active mass injection into the boundary layer, while elimination is done through suction or passive bleeding [5-10]. Attempts to isolate BL separation via stream wise slots and cavities were also found to be effective BL control techniques [11-12]. The cavity modifies and weakens the incident shock to a spread out lambda shock, resulting in reduced BL thickness, suppression of BL separation and improved pressure recovery across the shock wave. BL control was also achieved through the introduction of 2D bumps which weakens the incident shock wave through a simultaneous compression
and acceleration effect [13-14]. Microramps and vortex generators with dimensions less than the thickness of boundary layer height was also found to energize the BL and sometimes trip the BL to turbulence resulting in delayed separation [15-16]. Another concept with a secondary recirculation jet providing both BL bleed and suction simultaneously was proposed by Li Yan et al. [17]. Li Yan observed that the suction slots placed downstream of the separation were efficient in BL control and that the suction and blower slot dimensions had less impact on efficiency. Further studies on duct design optimization were carried out by Zhao-bo Du et al. [18] and a reduction of separation bubble area of up to 81.43% was reported for a Mach number of 3. The studies on the secondary recirculation jets are still in its infancy and more studies are required, especially experiments.

An attempt to study the effect of secondary recirculation jet in a large separation bubble at a Mach number of 8.6 is attempted through a 2-D ANSYS Fluent laminar solver. A deflector with an angle of $15^\circ$ was used as incident shock generator. High Mach number (8.6) and strong incident shock combination creates a large separation bubble of length: 15.5 cm, due to SWBLI in the present case. A simple secondary recirculation duct with varying lengths were designed with tangential suction and blowing and was studied for its efficacy in BL control. The area ratio between the suction and blower slots was maintained at 2 and this ratio ensured a choked flow and a sonic fluid injection. The suction slot was always fixed at the peak pressure spot near the reattachment point and the blower slot position was varied.

2. Methodology

2.1 Computational Domain

In the present work, all the numerical simulations have been carried out by using commercial software ANSYS FLUENT 19 R2. The computational domain consists of a simple wedge on the top (to generate an oblique shock) and a slender sharp plate at the bottom as shown in Fig. 1.

![Computational Domains](image)

**Figure 1.** Computational domains used for the simulations. $AG$ is the oblique shock generated by the wedge $ABC$. The wedge is oriented such that $AB$ is horizontal and $\angle BAC$ is $15^\circ$. $S$ is the point of attachment of boundary layer. The domain is 32 cm long (KJ) and 22 cm wide (IJ).

The computational domain used for the simulation is 2-D such X and Y axes are pointing towards the stream wise and vertical directions respectively. The origin of the coordinate system is placed at the leading edge of the bottom plate (Marked as O in Fig. 1). The bottom plate is 25 cm long ($OD$) and the wedge is placed at 4.12 cm from the bottom plate ($OD$) [19]. The leading edge of the wedge and the bottom plate was kept in the same plane. To capture the oblique shock from the leading edge of the plate, the inlet of the domain was placed 2 cm ahead. The point of attachment ($S$) was identified through a simulation without secondary recirculating duct. Slots were provided at the reattachment point and the high pressure fluid was entrained to various upstream locations through a constant are duct with a convergence at the point of fluid injection (F). The suction and injection was done tangentially through curved countered ducts so as to ensure minimal disturbance and pressure loss. In the present numerical
simulations, a parametric analysis was carried out by varying the distance of fluid injection from the leading edge (OF). OF was maintained at 30 mm, 60 mm and 90 mm in the three cases reported. The study was carried at a Mach number 8.6 with a static pressure and temperature of 61 Pa and 40 K, respectively.

2.2 Governing equations and boundary conditions.
The flow-field is modelled as 2-D, steady, compressible, and laminar with double precision. At inlet to the domain the freestream conditions are imposed by using pressure farfield boundary condition. At outlet all the flow variables are determined from the interior by extrapolation as flow is supersonic. The boundaries on the top and bottom of the computational domain is taken as symmetry as flow velocity is predominantly horizontal. The working fluid is air, with variable density (determined using the ideal gas equation of state) and temperature dependent specific heat (8th order piecewise polynomial). The dynamic viscosity and thermal conductivity are modelled using Sutherland’s law and kinetic theory (L-J parameters \(-3.711 \ \circ A \) and 78.6 K, for air), respectively. All the wall boundaries are modelled as isothermal (\(T = 300 \ K\)) with no-slip surfaces. Time marching is carried out by Euler implicit scheme. The convective term is discretized using second order upwinding scheme, whereas central difference scheme is used for the viscous term. During the simulations the inviscid fluxes were calculated using Advective Upstream Splitting Method (AUSM). The resulting system of linear equations are solved iteratively by Gauss Seidel method. The convergence of the iterations is enhanced by algebraic multi-grid method.

2.3 Grid independence and code validation
All the numerical predictions are obtained by steady state calculations until a reasonable level of convergence is attained (residue falls below \(10^{-6}\) based on the initialization using freestream conditions). Thereafter the convergence is assessed using mass, momentum, and energy balances. All the results reported here have a net imbalance below 0.01% of mass flow rate, momentum, and energy.

The grid sensitivity analysis was carried out by grid independence study. The computational domain is discretized using a structured quadrilateral mesh. The details of the mesh used in grid independence study is presented in the Table 1. The mesh used were progressively resolved in the boundary layer and by adaptation based on the velocity gradients in the shock wave. In the Table 1, the grid independent study is shown only for the case without entrainment. Based on this study, a fine mesh was used for the various cases of entrainment as it was found to be more capable of capturing the gradients present in the flow.

**Table 1.** Details of the mesh used for the grid independence study. \(\Delta x_{\text{min}}\) and \(\Delta y_{\text{min}}\) are minimum cell distance in X and Y directions, respectively and \(\delta^*\) is the displacement thickness of the Boundary layer [19].

| Level of resolution achieved | Number of cells | \(\Delta y_{\text{min}} / \delta^*\) | \(\Delta x_{\text{min}} / \delta^*\) | \(\Delta y_{\text{min}} / \delta^*\) at SWBLI |
|-----------------------------|----------------|-----------------------------------|-----------------------------------|-----------------------------------------------|
| Coarse                      | 584,500        | 0.005                             | 0.06                              | 0.03                                          |
| Intermediate                | 1,564,000      | 0.002                             | 0.002                             | 0.003                                         |
| Fine                        | 2,797,870      | 0.0001                            | 0.00015                           | 0.0001                                        |

The validation of the numerical simulation is carried out by comparing the static pressure distribution over the flat plate (without entrainment) with that of experimental data reported by Maitri et al., [19]. The results obtained (Fig. 2) clearly shows that the trends of static pressure distribution have been captured by all the mesh schemes used. Even though course mesh as well as fine mesh scheme seems to agree well with the experimental predictions, the static pressure values are over predicted for the former.
As the over prediction of the peak pressure was more than 50% for the coarse mesh, the fine mesh was used for other cases.

Figure 2. Comparison of numerical predictions with the experiment [19] for the static pressure distribution along the plate surface OD.

3. Results and discussion

3.1 Contours of Mach number
The distribution of Mach number across the flow-field with and without entrainment of flow is shown in the Fig. 3. The Mach contour is presented as the separated BL is a shear layer with velocity gradient. As the separated BL has low momentum, it’s visible as dark blue shades in Fig. 3. The points a, b and c in Fig. 3 are the locations of separation, top of the separation bubble and reattachment of BL. The points a and c and are identified based on the distribution of skin-friction drag coefficient whereas point b is identified based on the change in direction of the shear layer towards the bottom wall. Mach contours in Fig. 3 also validates choking in the duct and the sonic jet at the blower slot. The plots also verify that with tangential sonic blowing, there is minimal interaction with the outer flow.

3.2 Point of boundary layer separation
The determination of separation point of the boundary layer is based on the skin friction drag coefficient distribution along the length of the flat plate. The point of separation of BL on the flat plate is presented in Fig 4. From the figure, it is observed that BL separation is delayed with the introduction of secondary recirculation duct and that the delay is substantial when the blower slots/ injectors are placed farther upstream on the flat plate. These observations can be attributed to the delay in boundary layer separation brought about by BL energization. As the distance of the blower slots from the leading edge (OF) increases, the low momentum BL has to traverse larger distance against the adverse pressure gradient and hence results in earlier separation.

3.3 Point of attachment and Length of Boundary layer separation
The point of attachment of boundary layer from the leading edge of the bottom plate (O) was found to be almost similar for all the cases (the difference is less than 2%). The reason for almost similar location for the boundary layer attachment is due to the fact that the separated boundary layer is turned back to the bottom plate by the shock wave, generated by a common wedge. The minor differences in the point of attachment between the cases, could be due to the modification of the incident shock wave by the separation shock. The length of BL separation is calculated as the difference between the point of
separation and point of attachment. The length of separation of BL with and without entrainment is presented in Fig. 5.

### 3.4 Area of separated bubble

For the calculation of the area, the separation bubble is approximated as a triangle with vertices at point of separation (a), point of deflection of shear layer by shock wave (b) and point of attachment (c) [19]. This approximation is shown in the Fig. 6. Percentage of separation bubble area reduction is presented in Fig. 7. Results clearly shows that early energization of incoming boundary layer significantly reduces the size of the separation bubble. Separation bubble area reduction of up to 75% was observed when the blower slots were fixed at 30 mm from the leading edge.

**Figure 3.** Contours of Mach number for the supersonic flow over flat plate with and without secondary recirculation jets.

**Figure 4.** The point of separation of boundary layer on the bottom plate from the leading edge.
Figure 5. The length of separation of boundary layer on the bottom plate.

Figure 6. The approximation of a separation bubble as a triangle with vertices at the point of separation of boundary layer (a), point of deflection of shear layer by shock wave (b) and point of attachment (c) of boundary layer.

Figure 7. The percentage reduction in the separation bubble area with the introduction of secondary recirculation jets for various blower slot locations.
4. Conclusions
The present work focuses on a new passive hypersonic BL control technique using both suction and blowing. The technique involves a secondary recirculation duct connecting the high pressure zone (near reattachment) to the upstream low pressure zone. It has been found that the point of separation of boundary layer is delayed and the size of the separation bubble is significantly reduced by positioning the blower slots of the secondary recirculating ducts closer to the leading edge. Separation bubble area reduction of up to 75% was observed in a certain case when the blower slots were closer to the leading edge. The present concept can be applied to complex hypersonic intake geometries to suppress SWBLI and reduce losses.

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