Shock wave Boundary Layer Interaction (SWBLI) in hypersonic flow over a Blunt body double wedge configuration

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Abstract. Present investigations are focused on the study of effects of dimensional and parametric changes in shock wave boundary layer interaction (SWBLI) for an axisymmetric double wedge with leading edge bluntness in hypersonic flows. This study is specifically the point of interest since it attributes most of the characteristics of the hypersonic flow around the atmosphere re-entry vehicles. Successfully implemented simulations in hypersonic flow are in a double wedge configuration, to study shock wave boundary layer interaction in hypersonic flows. Inversion radius was found at different deflection angles for change in leading edge radius (LER). It was found that for lower deflection angle Crocco’s theorem affect the flow early compared to higher deflection angles. Shock-shock Interaction-I (SSI I) and Shock-shock Interaction-II (SSI II) shifts downstream with increase in leading edge radius.
(Key Words: Hypersonic flows, Shock wave boundary layer interaction, Shock–shock interaction and Leading edge radius)

NOMENCLATURE

| Symbol | Description |
|--------|-------------|
| M      | Mach number |
| M∞     | Freestream Mach number |
| Reₙ    | Local Reynolds number |
| τ       | Shear stress |
| μ       | Dynamic viscosity |
| ρ       | Density |
| Cₙ      | Skin friction coefficient |
| q       | Heat flux |
| P       | Pressure |
| E₁      | x – component of inviscid flux vector |
| F₁      | y – component of inviscid flux vector |
| Eᵥ      | x – component of viscous flux vector |
| Fᵥ      | y – component of viscous flux vector |
| Lₜ     | Length of separation bubble |
| U       | Conservative variable vector |
| t       | Time |

ABBREVIATIONS

| Abbreviation | Description |
|--------------|-------------|
| SWBLI        | Shockwave boundary layer interactions |
| LER          | Leading edge radius |
| SSI I        | Shock – Shock interaction I |
| SSI II       | Shock – Shock interaction II |
| LS           | Leading shock |
| SS           | Separation shock |
| RS           | Re – attachment shock |
1. Introduction

The phenomenon of shock wave/boundary layer interactions (SWBLI) in supersonic and hypersonic flows has been studied for last five decades [1]. It has direct application in various configurations such as re-entry vehicles, spacecraft and missiles etc. In these configurations SWBLI has a strong influence in the following parameters: the levels of heating, the size of the recirculation regions, the loss of efficiency of control surfaces and the oscillation of transient pressure loads [1-3]. These interactions between shockwave and boundary layer are extremely important for the hypersonic flow problems where the aerodynamic heating is a major factor of concern because there can be a focal point where maximum peak can be obtained in the interaction region which is extremely severe. This problem was first encountered in one of the final flights of X – 15[4]. Marini et. al (1998), investigation was about the effect of flow and geometry parameters over two dimensional domain which was deeply studied by numerical and experimental executions. They have examined proficiency of flap deflection, leading edge blunt, Reynolds number and equilibrium gas assumption. The experiment was performed on flow over flat ramp compression ramp for Blunt Delta wing free – flight conditions for laminar and turbulent conditions at the altitude of 47.5 km. The predictions of wall cooling reduces the separation but thermal loads in flow remain high, with the increase in wall temperature there is an increase in separation which retrograde the controllability of flight even when the heat flux level decreases to a respectable level [5]. Dieudonne et al. (1999) carried out numerical study with VKI H3 Mach 6 wind tunnel on an axisymmetric blunted cone-arc for the surface pressure and heat transfer analysis [6]. R. Savino et al. (2003) studied a flow field around blunted cone flare in hypersonic flows where the results were presented through computational simulations. The region between cone and flare is very critical for the evaluation of surface heat flux, here the separation is instigated by the SWBLI with succeeding reattachment which abruptly increases the surface heat transfer. These results for effect of wall temperature shows that wall pressure and heat flux are very sensitive to small change in temperature [7]. Jahanmiri M(2011) investigated about the key role of the presence of separation bubble in various air and ground vehicles [8]. Duo Zhang et al., (2015) investigation was focused on complicated flow conditions in the inner or outer of the high-speed vehicle where the heating and cooling was executed with changing the wall temperature. The effect of heating and cooling in SWBLI, it is seen that with the increase in the separation point moves forward while the reattachment point remains at the same position which increases the value of separation bubble length [9]. Sachin et al., (2016) study was focused on the aerothermal analysis in hypersonic vehicles for the design of thermal protection system. Aero – Thermo environment of several stagnation regions across the nose, cylindrically swept leading edges, upper and lower fuselage surface was discussed [10].

The present study mainly focused on the effects of different geometrical parameters such as leading edge radius, flow deflection angle on the shock wave boundary layer interactions in hypersonic flows over an axisymmetric double wedge with leading edge bluntness. The main concern was about the variation of important surface properties such as surface pressure, surface heat flux, skin friction coefficient, etc., along the wall with different parametrical changes. Separation bubble dynamics studies also included in this study.

2. Mathematical Equations of Compressible Flows

The transient axisymmetric Navier – Stokes equation was given in conservative form [11]. Navier stokes equation in non–dimensionalize form is given as:

\[
\frac{\partial U}{\partial t} + \frac{\partial E_I}{\partial x} + \frac{\partial F_I}{\partial y} + \alpha H_I = \frac{\partial E_v}{\partial x} + \frac{\partial F_v}{\partial x} + \alpha H_v.
\]  

(1)
Here, $\alpha$ is zero for two dimensional planar flows and $\alpha$ is 1 for axi-symmetrical flow. The terms $U, E, F, E_v, F_v, H$, and $H_v$, are the flux vectors and axisymmetric source terms which are defined as:

\[
U = \begin{bmatrix}
\rho \\
\rho u \\
\rho v \\
\rho E
\end{bmatrix} \quad \quad E = \begin{bmatrix}
\rho u \\
\rho u^2 + p \\
\rho uv \\
\rho uH
\end{bmatrix} \quad \quad E_v = \begin{bmatrix}
0 \\
\tau_{xxxp} \\
\tau_{xy} \\
\mu u \tau_{xxp} + \nu \tau_{xy} - q
\end{bmatrix}
\]

\[
F = \begin{bmatrix}
\rho v \\
\rho uv \\
\rho v^2 + p \\
\rho vH
\end{bmatrix} \quad \quad F_v = \begin{bmatrix}
0 \\
\tau_{xy} \\
\tau_{yyp} \\
\mu u \tau_{xy} + \nu \tau_{yyp} - q_y
\end{bmatrix} \quad \quad H = \begin{bmatrix}
\rho v \\
\rho uv \\
\rho v^2 \\
(\rho E + p) v
\end{bmatrix}
\]

The subscript $v$ describes the viscous flux vector, on the right hand side of equation (1):

\[
H_v = \begin{bmatrix}
0 \\
\tau_{xy} - \frac{2}{3} \mu \frac{\cdot}{\cdot} \frac{\partial (\mu v)}{\partial x} \\
\tau_{yyp} - \tau_{\theta \theta} - \frac{2}{3} \mu \frac{\cdot}{\cdot} \frac{\partial v}{\partial y} - \frac{\gamma}{\gamma} - \frac{2}{3} \frac{\partial (\mu v)}{\partial y} \\
\mu u \tau_{xy} + \nu \tau_{yyp} - q_y - \frac{2}{3} \mu \frac{\cdot}{\cdot} \frac{\partial v^2}{\partial y} - \frac{\gamma}{\gamma} - \frac{2}{3} \frac{\partial (\mu v)}{\partial x}
\end{bmatrix}
\]

The viscosity of the flow is calculated by using Sutherland’s law [11]. Present investigation is focused on the study of effects of dimensional and parametric changes in shock wave boundary layer interaction (SWBLI) for axisymmetric double wedge with leading edge bluntness in hypersonic flow using ANSYS FLUENT. The laminar flow computation has been executed using Navier–Stokes solver, with freestream condition of Mach number 6, absolute pressure 1063.6kPa and absolute temperature 550K [6]. Further study carried out by varying deflection angles 15.5°, 17.5° and 19.5° and leading edge radius. Geometry of the domain and boundary conditions are as shown in Fig. 1. Complete geometrical details are given in Fig. 3. Grid independence studies have been carried out for present studies. Three meshes 240 x 40, 480 x 80, 960 x 160 considered and surface properties such as surface pressure and skin friction coefficient are chosen as parameters to judge the grid independency.
From these studies it is found grid 480 x 80 produces results close to the experimental results with negligible deviations. Further refinement (960 x 180) is not producing significant changes in the results with the previous mesh (480 x 80) which confirms grid independency of the solution. So, 480 x80 grid is chosen as an optimum mesh and used for further studies. Corresponding variations of surface properties with grid refinement is shown in Fig. 2. and separation bubble size details are provided in the Table. 1.

| Boundary   | Boundary conditions |
|------------|---------------------|
| Hypersonic inlet | Freestream conditions |
| Outlet     | Supersonic outlet   |
| Wall 1     | Axis                |
| Wedge      | No slip             |
| Nose       | Slip                |

Fig. 1. Geometry with appropriate boundary conditions

Fig. 2. Grid Independence Study – variation of surface properties along the wall
(a) Surface pressure (b) Skin friction coefficient
Table 1. Details of separation bubble size with different grids

| S.No | Grid       | Length of separation (mm) | Length of reattachment (mm) | Separation bubble size (mm) | Experimental separation bubble size (mm) | Error (%) |
|------|------------|----------------------------|-----------------------------|-----------------------------|------------------------------------------|-----------|
| 1    | 240 x 40   | 70.95                      | 93.34                       | 22.39                       | 26.5                                     | 15.5      |
| 2    | 480 x 80   | 69.08                      | 94.91                       | 25.83                       | 2.52                                     | 2.52      |
| 3    | 960 x 160  | 69.06                      | 94.96                       | 25.9                        | 2.26                                     | 2.26      |

3. Results and Discussion

The study is mainly focussed on length of separation bubble, inversion radius for different leading-edge radius with the calculation of pressure, heat flux and skin friction coefficient of the wall. The following Fig. 4-(a) shows the variation of surface pressure along the wall from first compression ramp to second compression ramp. Fig. 4-(b) illustrates the variation of heat flux along the wall at the first compression ramp and the second compression ramp and is in well agreement with experimental results [6]. At pre-separation region there is a decrement in the surface heat flux due to the expansion of flow in the stagnation region which is followed by nearly constant heat flux region with very gradual decrement. Sudden fall of heat flux can be seen where the shockwave and boundary layer interacts with each other in the compression corner. In SWBLI region v–shape of heat flux is formed. After the reattachment of flow in post reattachment region the heat flux overshoots due to reattachment of flow and attain a maximum heat flux value at a point and further starts to gradually decrease due to the expansion of flow. It is noticeable that the heat flux decreases more gradually at post re-attachment region compared to the heat flux in the pre separation region, this is due to the weaken expansion of flow in the post–reattachment region than the pre-separation region.

Fig. 3: Computational domain with corresponding dimensions.
Skin friction coefficients ($C_f$) along the wall is as shown in Fig. 5. Wall shear distribution plot is beneficial for the comprehension and calculation of the length of the separation bubble in the presence of SWBLI. As skin friction coefficient is directly proportional to wall shear distribution hence, this can be used for calculating the length of separation. The decrease in skin friction coefficient can be noticed in the pre-separation region. The sudden drop in the magnitude of local skin friction coefficient is perceptible in the compression corner i.e. separation region due to the presence of SWBLI. This sudden drop of skin friction coefficient is due to separation is termed as an upstream influence. Local thickening of separation due to SWBLI as a move from first compression ramp to second compression ramp is the reason of decrement of skin friction coefficient. At post – reattachment of flow the skin friction coefficient displays increasing trend followed by nearly constant trend due to weakening of expansion of flow. Length of separation can be calculated from above skin friction coefficient by evaluating the linear distance between the point of separation and point of reattachment. The first point where the curve touches zero is separation point which is noted 69.48 mm and second point where the curve touches zero line at a point which is 94.91 mm both from the starting point of first compression corner. this gives the length of separation bubble as 25.43 mm which holds satisfactory results compared to experimental results where the bubble length obtained was 26.5 mm. computational results gives an error less than 5 %.
Fig. 5: Variation of skin friction coefficient ($C_p$) along the wall (m).

Fig.6-(a) shows the variation of growth of separation bubble with respect to time step. It is noticeable that after 3500 time steps there is no change in length of separation bubble. From this it can be stated that the simulation has reached steady state after 3500 time step where the flow time is 0.0032 sec. Mach number contours in the flow field are demonstrated as shown in Fig. 6-(b). Bow shock due to leading edge radius i.e. nose is evident, also isolines gives clear picture in the variation of Mach number. At clone flare junction, interaction between shockwave and boundary layer is clearly visible. Mach contours also show two triple point. These points are called as shock - shock interactions, location of this shock – shock interaction is very critical to understand the behaviour of flow and wall properties after the reattachment of flow in post – reattachment region of SWBLI. First triple point is formed when interaction occur between separation shock and reattachment shock this interaction is termed as shock – shock interaction I and second interaction is formed when there is interaction between shock – shock interaction I and first standing shock coming from leading edge radius this interaction is termed as shock - shock interaction II. SSI I and SSI II is clearly visible in Fig. 6-(b). It is clearly noticeable that the flow approaching the second compression surface passes through shocks of different layer and strengths.

Fig. 6: Surface properties variations of along double wedge (a) Length of separation bubble ($L_b$) with respective time step (b) Mach number contour (M)
Fig. 7-(a) and (b) showed in zoomed view of stagnation region at the nose i.e. leading edge radius in terms of temperature and pressure. The maximum pressure noted in the simulation at the stagnation region is 32.488 kPa and post–shock temperature value is noted as 558 K which is in good agreement with the normal shock theory of values 31.538 kPa and 533K respectively. According to the post shock temperature the calculated heat flux obtained if 226 kW/m² which holds eminent agreement with the Fay–Riddel formula which yields 221.8 kW/m². Fig. 8 shows the contour of velocity whereas the zoomed portion of blue shade region shows the separation region. It is clearly evident that occurrence of separation where the velocity is in opposite direction to the direction of flow. It can be seen that the current simulation is establishing a fair consensus with the experimental data and the compressible normal shock theory, therefore it can be stated that various boundary conditions used for different boundary holds true for the geometry and further changed and simulation can be done.

Fig. 7: Contour plot of blunt body region (a) Temperature contour (K) (b) Pressure contour (Pa)

Fig. 8: velocity contour.
3.1 Effect of deflection angle

The investigation is focused on the affect of deflection angles on the shock intercations with boundary layers which are interpreted with the variation of surface properties along the wall. For this three different deflection angles 15.5°, 17.5°, 19.5° with the leading edge radius of 3.5 mm have been considered. Variation in surface properties are shown in the Fig. 9. and Fig. 10.

Fig. 9. Variation of surface properties with deflection angle (°)  (a) Surface pressure (Pa) ;
(b) Surface heat flux (w/m²) ;

Fig. 10. Variation of skin friction coefficient with deflection angle (°)

From the results it is found that separation bubble length increases with increase in the deflection angle which is due to increment in adverse pressure gradient resulted by the shock wave boundary layer interaction phenomenon. The separation bubble length changes with deflection angle is shown in the Table. 2.
Table. 2. Details of changes in separation bubble length with deflection angle.

| S.No | Deflection angle | Length of separation (mm) | Length of reattachment (mm) | Separation bubble size (mm) |
|------|------------------|---------------------------|-----------------------------|-----------------------------|
| 1.   | 15.5°            | 76.7                      | 89.8                        | 13.1                        |
| 2.   | 15.5°            | 69.48                     | 94.91                       | 25.43                       |
| 3.   | 15.5°            | 58.49                     | 99.26                       | 40.7                        |

3.2 Shock – Shock Interactions

Position of SSI I and SSI II is very critical to understand the behaviour of flow also wall properties at post – reattachment zone of SWBLI. As mentioned earlier SSI I is interaction of separation shock and reattachment shock and SSI II is interaction of first standing bow shock and SSI. Fig.11 shows comparative Mach contour for different deflection angles. These Mach contours give variations in near wall and far field. SSI I is present in all cases of leading edge radius. The 15.5° deflection angle it is noticed for 1.5 mm LER both SSI I and SSI II are present but with the increase in LER to 3.5 mm which is happen to be inversion radius there is absence of interaction between SSI I and standing bow shock therefore SSI II is unseen. Both SSI I and SSI II are seen to be shifting downstream. For 17.5° deflection angles both SSI I and SSI II are visible for variation in LER for 0 mm to 3.5 mm. For 3.5 mm LER the interaction between SSI I and first standing shock is very close to outlet boundary of the domain. The trend in shifting of interaction is similar to 15.5° it moves downstream with increase in LER. It is noticed that SSI II is not visible for further increase in leading edge radius. For 19.5° deflection same trend is noticed of downstream shifting of both SSI I and SSI II. For this deflection angle both interaction are present from 0 mm to 4.5 mm LER but for 5.5 LER very less difference can be seen visible for the interaction of first standing shock and SSI I, therefore it can be said the downstream shifting is due to increase in expansion of flow at post – reattachment region and the variation in the interaction of SSI I and SSI II with change in LER is responsible for discrepancy on post – reattachment region.
4. Conclusions

CFD has been a beneficial tool for analysing the SWBLI in axisymmetric model. Length of separation and reattachment are determined based on simulations. These simulations are useful for determining length of separation bubble and point of peak heat flux at second compression corner. A computational result shows good agreement with the experimental results. Inversion radius was found for different deflection angles for change in leading edge radius. SSI I and SSI II shifts downstream with increase in leading edge radius (LER). Effect of deflection angle on the separation bubble characteristics also has been investigated. It was found that higher deflection angles are very prone to separation and results larger separation regions due to larger adverse pressure gradient imposed by shock interactions with boundary layer.
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