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# Numerical study on the SWBLI Induced Flow Unsteadiness Characterization in a Hypersonic Backward Facing Step

*P Vignesh[1], Mohammad Ibrahim Sugarno[2]*

## Abstract

Shock Wave Boundary Layer Interaction (SWBLI) is inevitable in the case of supersonic and hypersonic flows. SWBLI is typically encountered in the intake of Scramjet inlet and isolator, vehicle surface geometry changes, control surface deflections, at the junction of body-wing of aircraft, etc. For BFS, the dynamics of the SWBLI region and the associated unsteadiness are available only for supersonic Mach numbers, to the best of our knowledge. This study will involve understanding the flow physics under different Hypersonic Mach numbers of 4 and 6. The free stream conditions used for this study including the free stream Mach number, pressure, and temperature correspond to the S1 Hypersonic facility (Ludwieg tunnel) at Hypersonic Experimental Aerodynamics Laboratory (HEAL) at the Indian Institute of Technology, Kanpur. The SWBLI region over a BFS consists of a boundary layer undergoing rapid expansion, Separation bubble, lip shock-reattachment shock interaction, shock shear layer interaction, etc. The aim is to study and characterize the SWBLI region and associated flow unsteadiness over a BFS configuration in a hypersonic flow. The effect of Reynolds number and step height on flow unsteadiness and its influence on the downstream flow field will also be studied. Work is in progress and the numerical results will be presented.

**Keywords:** Backward facing step (BFS), hypersonic flows, SWBLI, Unsteadiness, and separation bubble.

## Nomenclature

| | | | |
|---|---|---|---|
| $M_\infty$ | Freestream Mach number | h | Step height |
| $P_\infty$ | Freestream pressure | H | Static enthalpy |
| $T_\infty$ | Freestream temperature | $U_\infty$ | Freestream Velocity |
| $H_o$ | Total enthalpy | δ | Boundary layer thickness |
| $Re_\infty$ | Freestream Reynolds number | | |

## 1. Introduction

Hypersonic flight, characterized by velocities exceeding five times the speed of sound, represents a frontier in aerospace engineering and technology. One critical aspect of hypersonic aerodynamics is the interaction between the high-speed flow and complex geometries, such as backward-facing steps. SWBLI induces a local pressure gradient which can cause either local thickening of the boundary layer or flow separation, depending on the impinging shock wave strength. In the case of flow separation, the local flow field is complex; consisting of a separation bubble, separation shock, shear layers, and re-attachment shock. An important aspect of a separated flow field is the associated unsteadiness. SWBLI can induce significant unsteady local pressure and heat transfer loads which will not only modify the flow downstream but can also cause significant structural damage leading to the failure of the vehicle. Therefore, a complete understanding of the SWBLI region and the associated unsteadiness is essential before designing any mechanism to control/ mitigate its effects. A typical flow field over a BFS is shown in Fig 1.

*1 Student, Department of Aerospace Engineering, Indian Institute of Technology, Kanpur, pvignesh22@iitk.ac.in*
*2 Professor, Department of Aerospace Engineering, Indian Institute of Technology, Kanpur, ibrahim@iitk.ac.in*

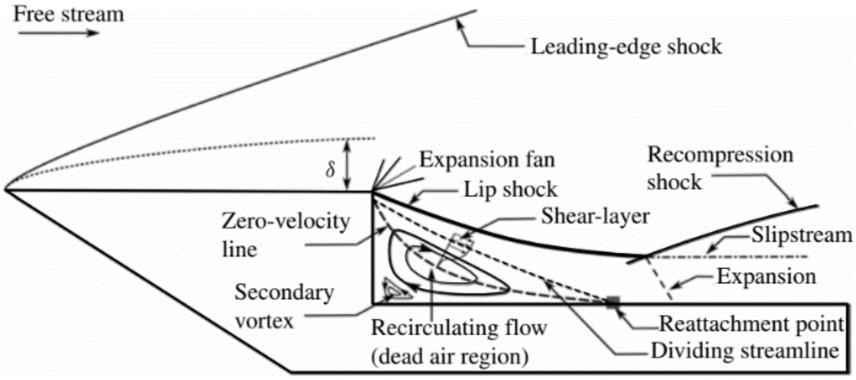

**Fig 1:** Schematic of flow field over a BFS [16]

This work aims to simulate a hypersonic flow over a BFS configuration experimentally and study the following.

- The influence of Reynolds number; and the incoming boundary layer (laminar/ turbulent) on flow unsteadiness in a BFS configuration.
- The effect of step height on the separation bubble dynamics, the unsteadiness induced both in the interaction zone and the region downstream.
- Understand and characterize the unsteadiness at hypersonic Mach number by comparing it with the data for supersonic flows.

### 1.1 Literature review:

- Bolgar et al (13) performed PIV analysis and dynamic pressure measurements to study sub-, trans- and supersonic flows over the backward-facing step and they concluded that the recirculation bubble length initially increases and then decreases as the Mach number is increased from subsonic to supersonic. The results clearly show that the dominant pressure fluctuations below sonic conditions are caused by Kelvin-Helmholtz instabilities in the form of the step mode, while in the supersonic regime, a low-frequency pumping of the recirculation zone is the dominant motion. This indicates that the underlying physics governing flow separation and reattachment in sub- and supersonic flows are vastly different and thus lead to distinct dynamics.
- Hama in 1968 [2] studied the effect of Mach number (2 to 4) and Reynolds number (0.2 to 2 million/m) over a wedge aft body configuration using optical techniques and pressure measurements. Though the experiments were carried out for a wedge configuration studying the wake, the flow field is analogous to that of a backward-facing step. He observed the flow to first expand around the compression corner and then it is compressed to the base pressure with the help of the lip shock. He reported that the lip shock strength was quite significant and was found to influence the flow field downstream through its interaction with the re-attachment shock. The interaction process was different for different Mach and Reynold numbers.
- Hayne and Gai (2010) [6] carried out experiments in the Mach number varying from 6.6 to 10, flow enthalpy varying from 1.5 to 26 MJ/kg with Reynolds number less than a million per meter on a BFS. They considered a very small step height, comparable to the separating boundary layer thickness, and proposed parameters to describe the heat transfer rate behind the step. It was also reported that the flow field was mainly dominated by viscous effects rather than real gas effects.
- Grotowsky and Ballmann (2000) [7] carried out numerical studies over a BFS configuration and compared the obtained results with the experimental data available for hypersonic flows. The flow field was in good qualitative agreement with the experimental results however, owing

to the complexity there was a huge difference in wall heat flux data. Despite the difference in heat flux data, the analysis provided significant insight into the flowfield over a BFS.

- DSMC method was used to study the effect of step height (3, 6, and 9 mm) on the flow parameters behind a BFS in a hypersonic Mach 25 rarefied flow by Paulo and Santos (2009) [8]. It was reported that the recirculation region size was dependent on the step height and with increasing step height the downstream disturbance was increased.
- Logan et al (2021) [9] carried out LES to characterize the frequencies encountered due to shear layer separation and reattachment over a BFS configuration. Studies were performed for a step height of 3 mm in a Mach 2 flow. The study identified high-frequency content in the shear layer near the step, shear layer shedding frequencies, and low-frequency content at the reattachment zone. The low-frequency unsteadiness was associated with local peak pressure fluctuation at the reattachment region.
- Weibo et (2021) [10], also performed LES over a BFS configuration in a Mach 1.7 flow for a step height of 3mm. Their numerical findings were similar to that of Logan et al, however, their DMD analysis revealed that strong Gortler-like vortices originating from the reattachment region were strongly correlated with the low-frequency unsteadiness.
- Experimental studies carried out by Chen et al (2012) and Zhu et al (2015) using nano-tracer-based planar laser scattering showed the presence of unsteady vortex shedding in the shear layer [11, 12].
- Soni et al (2017) carried out LES to study the unsteady dynamics associated with the BFS configuration. Several features associated with the unsteady flow field; K-H instability, shear layer, separation bubble oscillation, and the associated spectral content were reported. However, this work was carried out for a Mach 2 flow [15].

## 2. Test cases and freestream conditions:

A numerical study is carried out using Ansys Fluent to get an idea of the location of the reattachment shock on the BFS. Simulations have been carried out for Mach 4 and Mach 6 flow at two different Reynold numbers 34.73 and 15.6 million/m. The step height of 8, 10, and 12mm will be varied for each case of the Reynolds number. The step has to be positioned in such a location where the interaction between the Mach wave originating from the leading edge and the expansion fan from the BFS edge will not interfere with the flow field in the interaction region. The analysis will also enable us to get an initial estimate of the interaction region size and the associated dynamics.

The Experiments of this study are to be carried out using the Hypersonic test facility available in the Hypersonic Experimental Aerodynamics Laboratory (HEAL), IIT Kanpur. The cross-section and length of the test section of this Ludweig tunnel are 300 x 300 mm$^2$ and 450 mm respectively. Table 1 represents the freestream conditions of the tunnel and the simulations have been run for these freestream conditions.

**Table 1:** Freestream conditions used in the study

| $\mathbf{M_\infty = 4}$ | | $\mathbf{M_\infty = 6}$ | |
|---|---|---|---|
| **Freestream conditions** | **Values** | **Freestream conditions** | **Values** |
| $P_\infty$ | 4991.03 Pa | $P_\infty$ | 480 Pa |
| $T_\infty$ | 71.26 K | $T_\infty$ | 36.5 K |
| $U_\infty$ | 676.65 m/s | $U_\infty$ | 726.41 m/s |
| $H_o$ | 0.3 MJ/kg | $H_o$ | 0.3 MJ/kg |
| $Re_\infty$ | 34.73x10$^6$ m$^{-1}$ | $Re_\infty$ | 15.6x10$^6$ m$^{-1}$ |
| $P_{driver}$ | 10$^6$ Pa | $P_{driver}$ | 10$^6$ Pa |

## 3. Validation Study:

The results obtained by I.M.G. Grotowsky et al[7] were used for the validation of the backward-facing step. Both experimental and numerical results were validated using Ansys Fluent with the K-ω SST model, which captures the near-wall flow features and is not very sensitive to freestream conditions. Pressure far-field boundary conditions were used on all boundaries, with isothermal wall boundary conditions for the flat plate upstream as well as downstream of the step. Steady simulations were performed with all the flow assumptions listed above. The wall pressure data is compared and a fairly good match is observed between the experimental data and the simulation data. However, due to some limitations of numerical methods in resolving recirculation bubbles, some discrepancy is observed. Table 2 given below denotes the freestream conditions that have been used.

**Table 2:** Freestream conditions used for validation

| $\mathbf{M_\infty = 7.898}$ | |
|---|---|
| **Freestream conditions** | **Values** |
| $P_\infty$ | 613 Pa |
| $T_\infty$ | 122 K |
| $U_\infty$ | 1748.65 $ms^{-1}$ |
| H | 1.65 MJ/kg |
| $T_{wall}$ | 300 K |

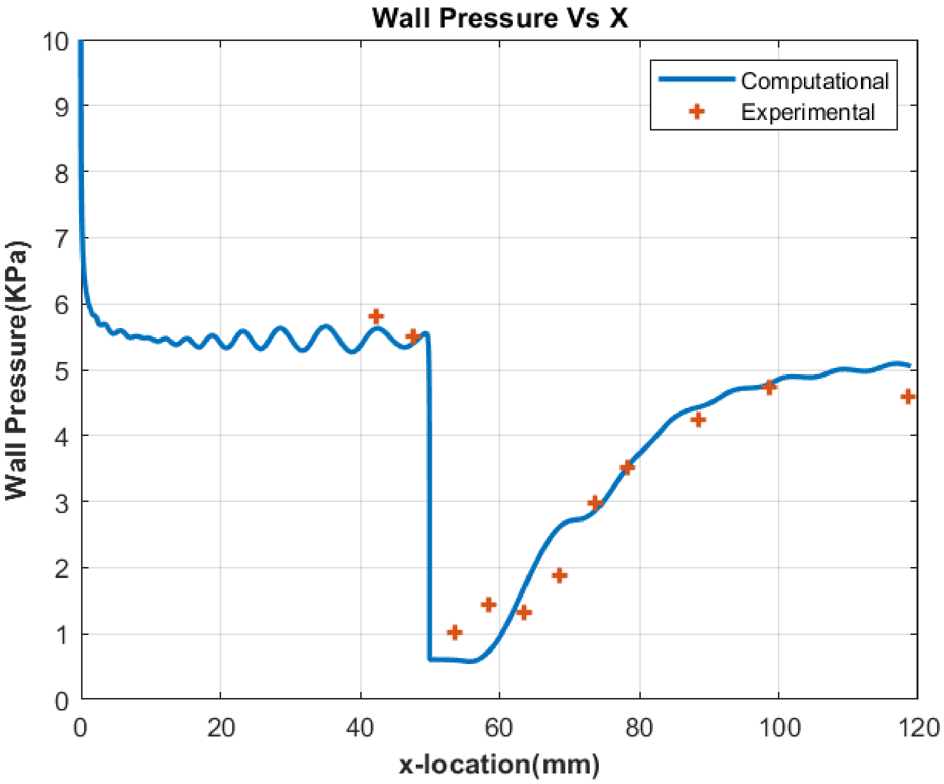

**Fig 2:** Comparison of experimental and computational wall pressure data

## 4. Geometry and Grid Independence study:

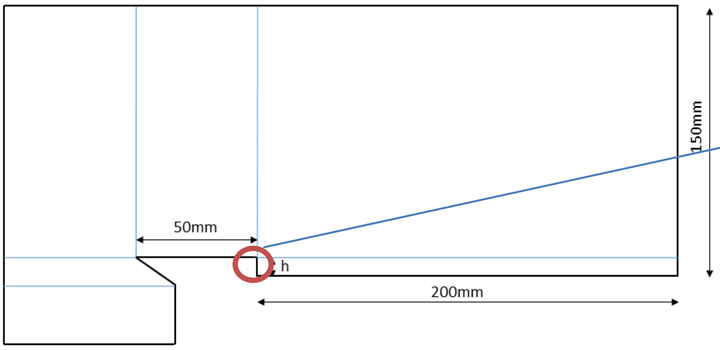

**Fig 3:** Domain (flow is from left to right)

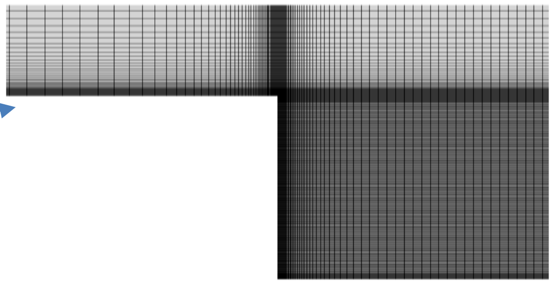

**Fig 4:** Grid Detail

The domain is chosen such that the flow features like reattachment shock and recirculation bubble are captured and the wall length before the step is chosen such that the leading edge shock does not interact with the expansion fan at the step. Three step heights of h=8mm, 10mm, and 12mm are chosen to study the recirculation bubble length variation as step height is increased. ICEM CFD is used to mesh the domain. Pressure far-field boundary condition is given at all the boundaries and the no-slip wall boundary condition is given at the walls. Grid independence study is performed using three meshes-Coarse mesh consists of 0.2 million elements, Medium mesh consists of 0.5 million elements and fine mesh consists of 0.7 million elements. The first cell height from the wall is kept to be 1 micron such that the maximum value of $y^+$ along the wall is 0.5. As shown in Fig 5 of wall pressure of Mach 4 flow over the step height of 8mm, we observe that the medium mesh and the fine mesh are very much identical, so the medium mesh is used for all the cases to reduce the computation time without compromising the accuracy.

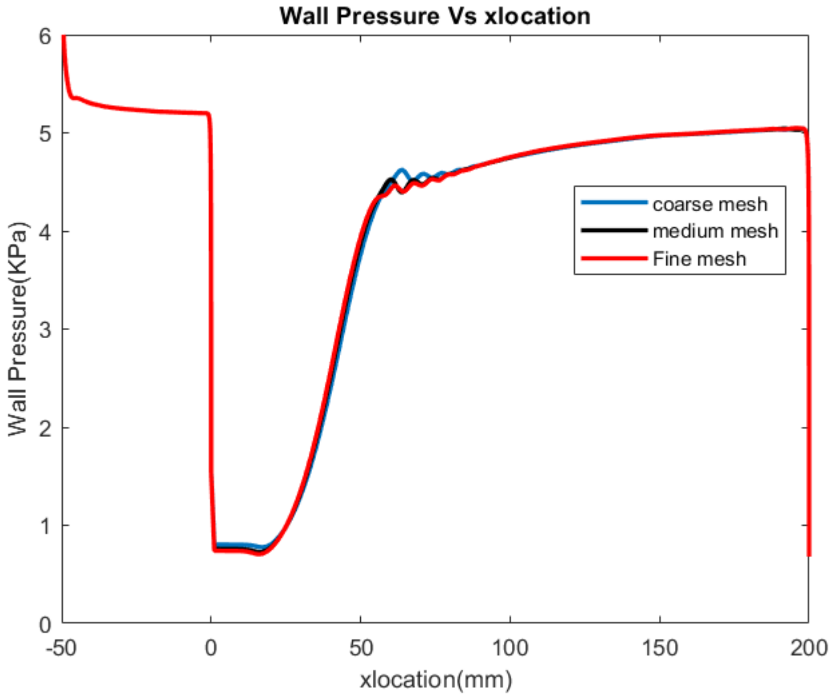

**Fig 5:** Grid Independence study

## 5. Results and Discussion:

### 5.1 Recirculation Bubble Lengths:

The flow features of the hypersonic/supersonic flow over the backward-facing step are given below. As the flow is turned away from itself at the lip of the step, the flow expands which results in the higher Mach number flow. This will be turned towards itself at the end of the step which results in the formation of lip shock. This lip shock and recompression shock coalesce and form a smooth single shock structure.

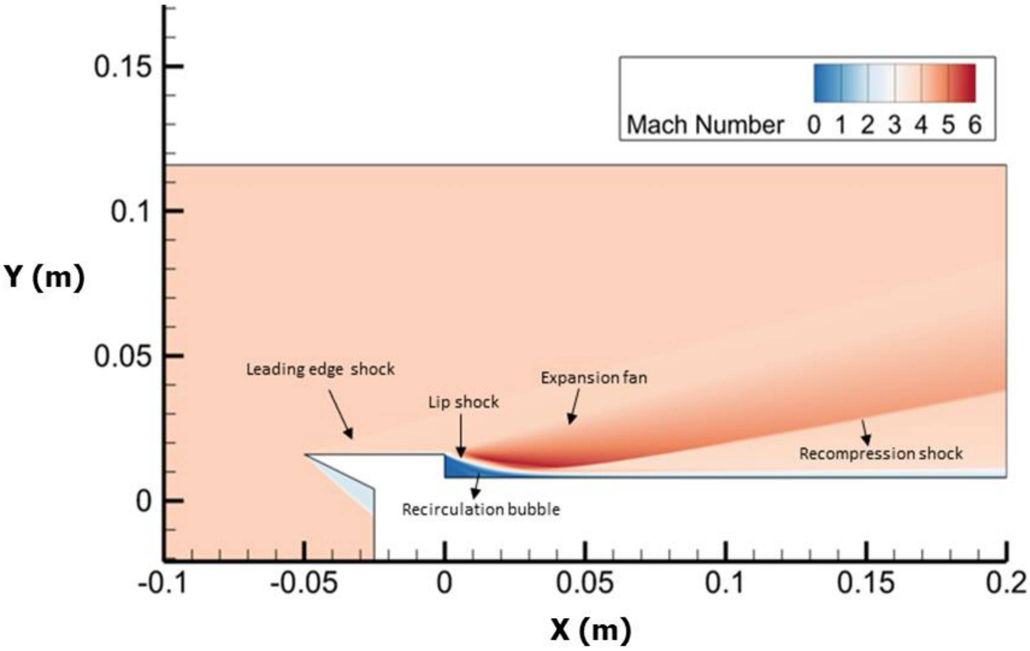

**Fig 6:** Mach 4 flow over Backward facing step of height 8mm

Recirculation bubble lengths for all the cases are presented in the table. This length is found by plotting the wall shear stress and the point at which the shear stress is zero denotes the location of the end of the recirculation bubble which is plotted in Fig 8. It can be inferred from the table that as the Mach number increases, the bubble length also increases. As the step height increases, the bubble length also increases. This shows that the recirculation bubble is directly proportional to both the Mach number and the step height.

**Table 3:** Recirculation Bubble lengths

| Step height | Recirculation Bubble length for Mach 4 flow | Recirculation Bubble length for Mach 6 flow |
|---|---|---|
| 8mm | 31.6 mm | 50.73 mm |
| 10mm | 39.3 mm | 68.15 mm |
| 12mm | 47 mm | 85.2 mm |

The Recirculation bubble lengths increase linearly with respect to the step height for both Mach 4 and Mach 6 flows which is represented in the fig 7. The physical interpretation for this might be that as the step height is increased, the dead air region is increased which causes more volume of the fluid to recirculate thus increasing the bubble length. It can also be seen that the recirculation bubble length is more sensitive to step height for the Mach 6 flow compared to the Mach 4 flow.

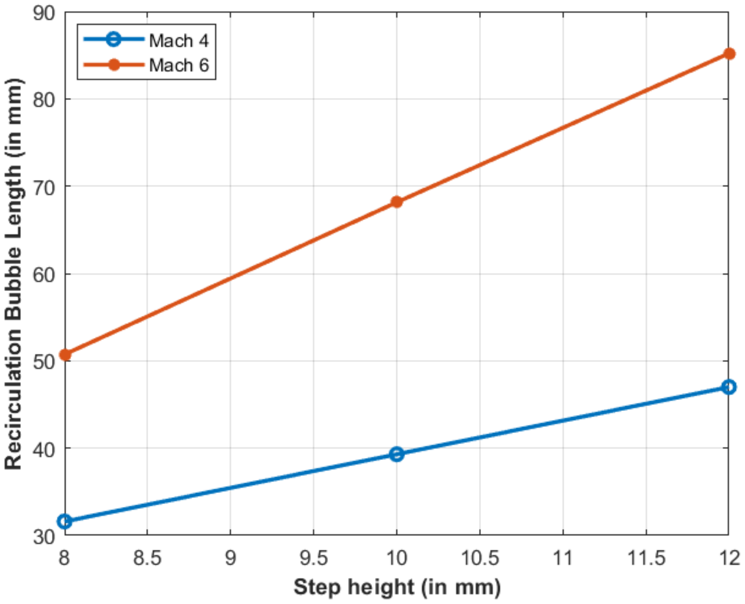

**Fig 7.** Comparison of Recirculation bubble lengths with step heights for Mach 4 and Mach 6 flows

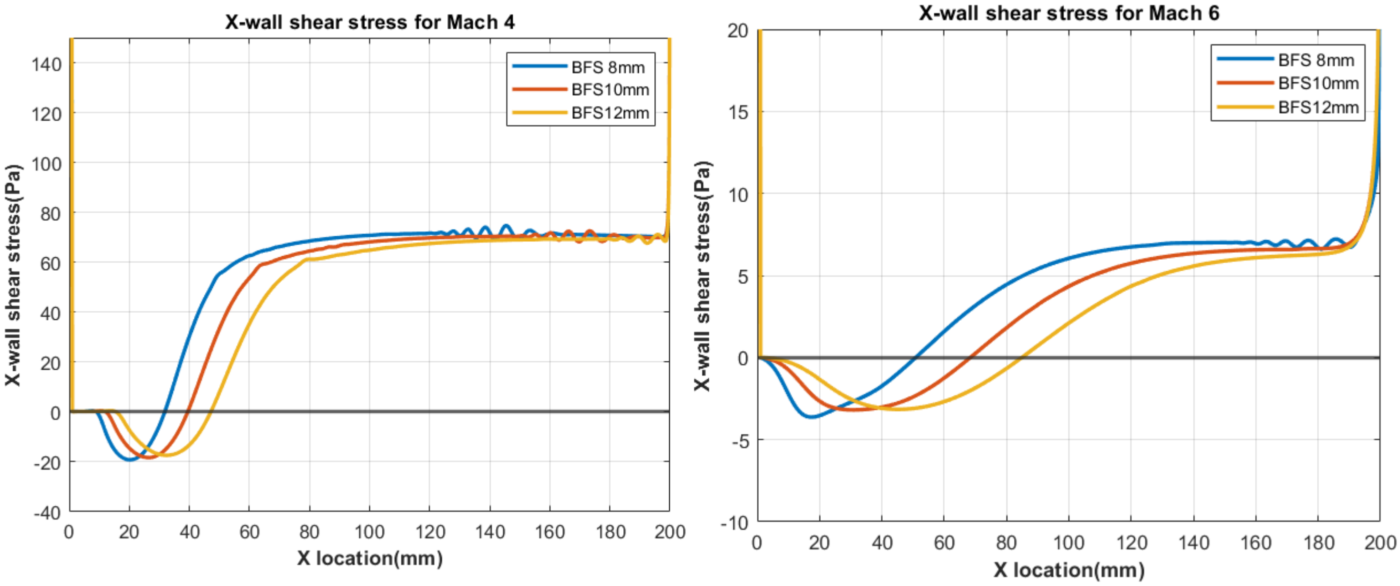

**Fig 8.** X-wall shear stress plots for Mach 4 and Mach 6 flows

## 5.2 Density Gradients

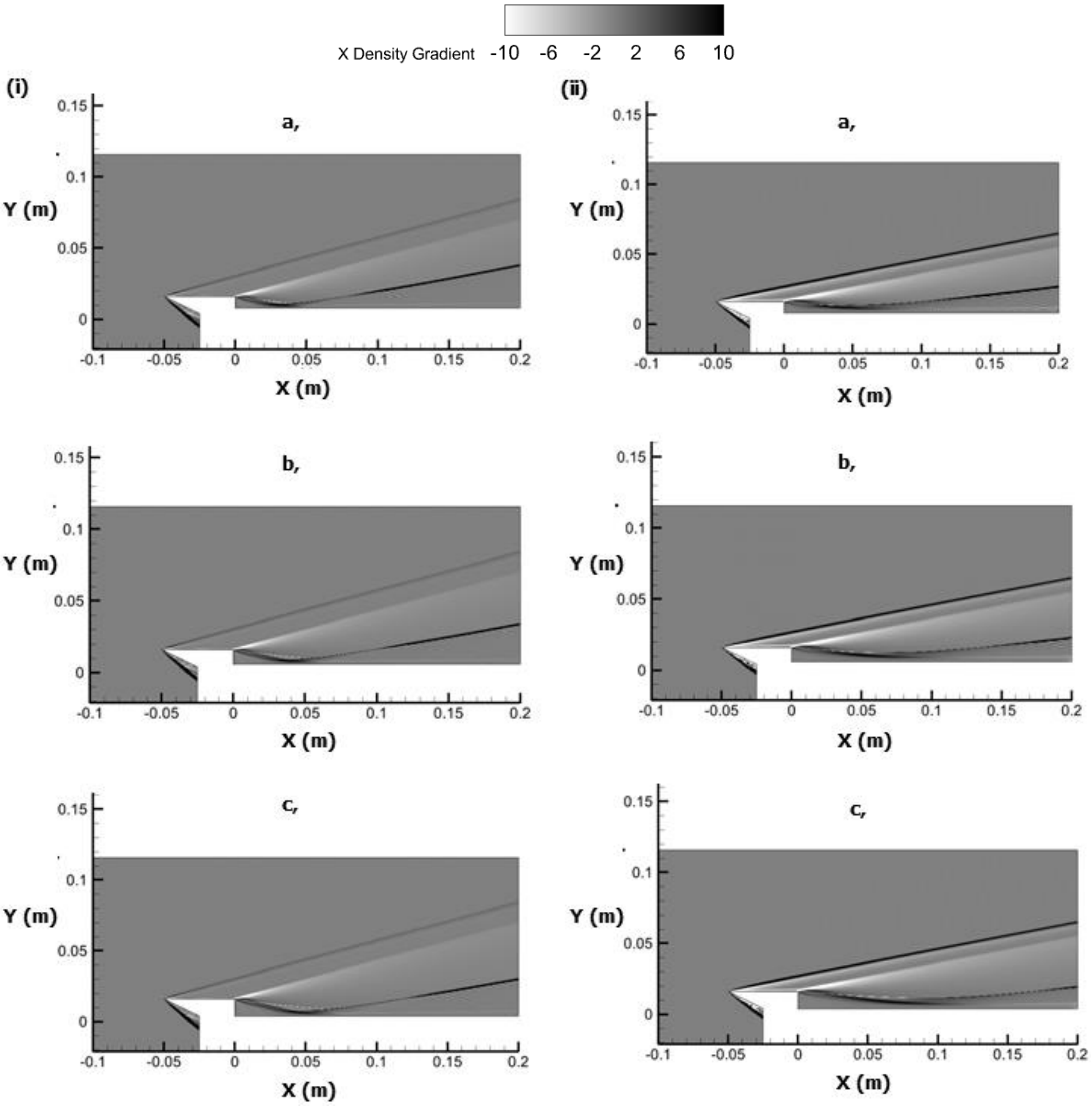

**Fig 9.** X-Density gradient contours of (i) Mach 4 and (ii) Mach6 flow over Backward-Facing Step of height a) 8mm, b) 10mm and c) 12mm

It can be observed from the above Fig 9 that the lip shock and the recompression shock coalesce close to the wall in the case of Mach 4 flow, whereas in the case of Mach 6 flow, it is quite distant from the wall. It is clear from the fig that the recompression shock in the Mach 6 flows are oriented more towards the wall whereas in Mach 4 flows, the reattachment shocks are oriented at the higher angles to the wall. This can be visualized through the wall pressure plots as well.

### 5.3 Wall pressure:

From the wall pressure plots (Fig 10.1 and Fig 10.2) given below, it can be observed that because of the presence of the leading edge shock, the wall pressure rises. There is a sudden drop in the pressure at the step because of the formation of the expansion fan and at some distance downstream from the step, the pressure starts to increase because of the formation of reattachment shock. All the cases follow the same trend but the difference arises in the location of the increase in pressure i.e. the location of the formation of reattachment shock. The slopes of the pressure curves in the Mach 4 are more steeper compared to the Mach 6 curves, this shows that the reattachment shocks in the Mach 6 flows are oriented more towards the wall leading to the gradual increase in the wall pressure, whereas in Mach 4 flows, the reattachment shocks are oriented at the higher angles, which results in the sharp rise of the wall pressures.

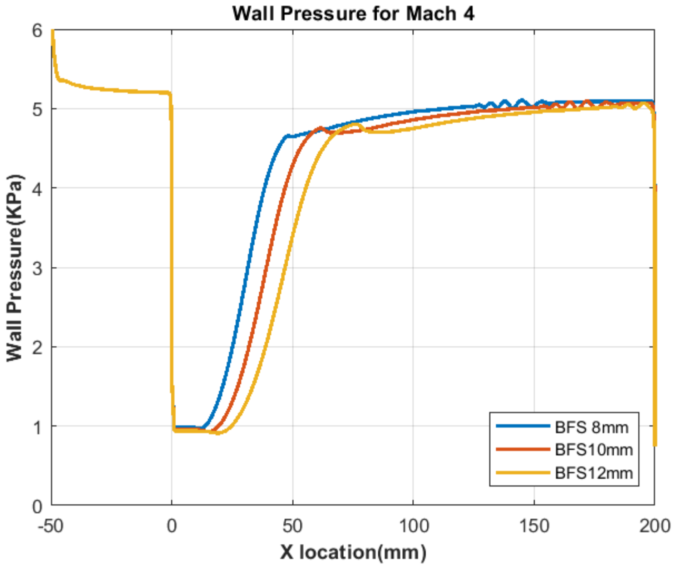

**Fig 10.1:** Wall pressure plots of Mach 4 flow over three different step heights

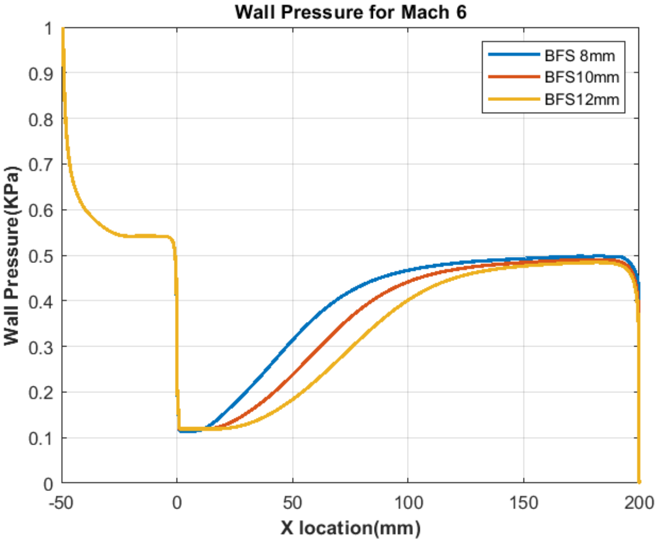

**Fig 10.2:** Wall pressure plots of Mach 6 flow over three different step heights

The wavy pattern at the approximate location of 150 mm in the above plots is due to the interaction of the expansion and compression waves hitting the wall. These waves are formed as a result of the interaction between the expansion fan at the lip of the step and the recompression shock. This can be observed in the x-density contour figures above.

## 6. Conclusion:

Numerical simulations of the hypersonic flow over the backward-facing step of three different heights were performed separately and the flow features such as the orientation of the recompression shock, and length of the recirculation bubble were studied. Unsteady simulations were performed using Detached Eddy Simulation (DES) but the oscillations of the recompression shock and the recirculation bubble were not captured as both oscillated at low frequencies. Large Eddy Simulation (LES) or Direct Numerical Simulation (DNS) can be used to capture these low frequencies. Currently, experiments are being carried out to capture the unsteadiness using the piezoelectric pressure sensors and the high-speed camera.

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