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STUDY ON SHOCK WAVE-BOUNDARY LAYER INTERACTION ON A MIXED COMPRESSION AIR INTAKE

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ABSTRACT

In this study, flow characteristics of a mixed compression air-intake is investigated by experimental method. Tests are conducted in a trisonic wind tunnel for different flight conditions. Static pressure at the wall is measured with a pressure scanner and the flow inside the intake is visualized by Schlieren imaging technique. Investigation of characteristics of shock-wave boundary-layer interactions inside the intake is the scope of this work and results that are obtained from experimental measurements is presented.

INTRODUCTION

High-speed flight studies on shock wave interactions are an important topic since 1939. Shock interactions can be found in both external and internal flows, in which unsteady and high loads are present [Dolling, 2001]. The phenomenon is far more complicated since the interactions of the shock wave with its surrounding make the flow more unpredictable. Understanding the flow and the shock interactions carry a great importance for the designers.

Shock waves are formed due to a discontinuity in the flow field. Normal shock is produced when the backpressure forces the flow to be subsonic. An oblique shock is created when the flow encounters an inclination or more generally, the flow turns to itself according to Anderson [Anderson, 2011]. Every oblique shock has a maximum deflection angle for each freestream Mach number. Beyond this limit the shock can no longer form at the deflection point as a line but it forms on the upstream as an arc which is called detached shock [Babinsky & Harvey, 2011] (Figure 1). For a case of reflecting shock wave on a solid wall, if the Mach number across the incident shock is small enough such that the incident angle is above the maximum angle allowed, the shock can no longer reflected as a straight oblique shock. Instead, a curved normal shock is formed at the reflection surface to allow the flow to be parallel to the wall. The incident shock is reflected as a curved shock. This type of reflection is known as Mach reflection [Anderson, 2011].

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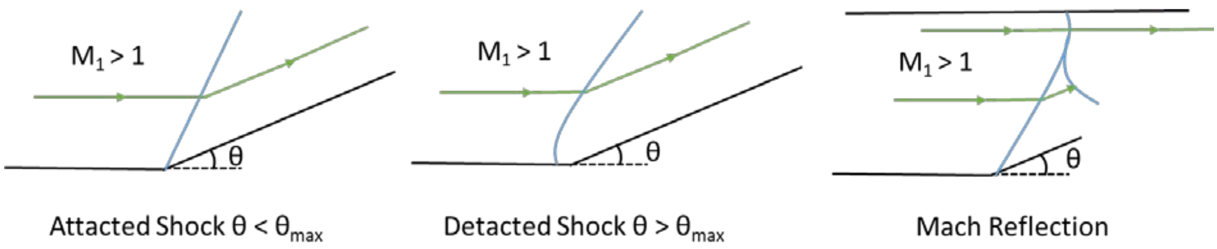

Figure 1: Oblique shock, attached and detached cases, reproduced [Babinsky & Harvey 2011, Anderson, 2011].

Shock waves and boundary layer can interact several ways depending on the flow conditions given in Figure 2. In general, a turbulent boundary layer has more developed velocity distribution, which makes it more resistant to separation compared to the laminar flow. Existence of the shock increases the static pressure, which creates an adverse pressure gradient. The interaction between shock wave and boundary layer can be classified as weak (non-separating) and strong (separating) interactions [Babinsky & Harvey, 2011]. For all interactions, when a shock hits the boundary layer, it affects mostly the subsonic layer. Adverse pressure gradient causes Mach number to decrease and subsonic layer to enlarge. For the weak interaction, the flow structure does not change significantly and the solution is close to inviscid flow interaction since the effect of viscous forces are negligible. If the adverse pressure gradient is large enough, the boundary layer separates and circulates near the wall. When the separation is present, a separation shock appears where the separation starts and reattaches with a reattachment shock except for the normal shock case since the flow turns to itself at these points. Due to the viscous forces play an important role, the interaction can no longer be treated as inviscid.

It is shown that, boundary layer separation in laminar flows is highly dependent on Reynolds number, heat transfer and Mach number while in turbulent flows the latter is dependent mostly on Mach number. Boundary layer separation or shock viscous interaction are problematic phenomenon since excess aerodynamic and thermal loads are introduced. When the separated flow reattaches, local heat transfer rises excessively creating “hot spots” at reattachment points. Similarly, viscous interaction with impinging shocks causes excess thermal loads at the points of interactions. This can cause “catastrophic failures” according to Korkegi [Korkegi, 1971].

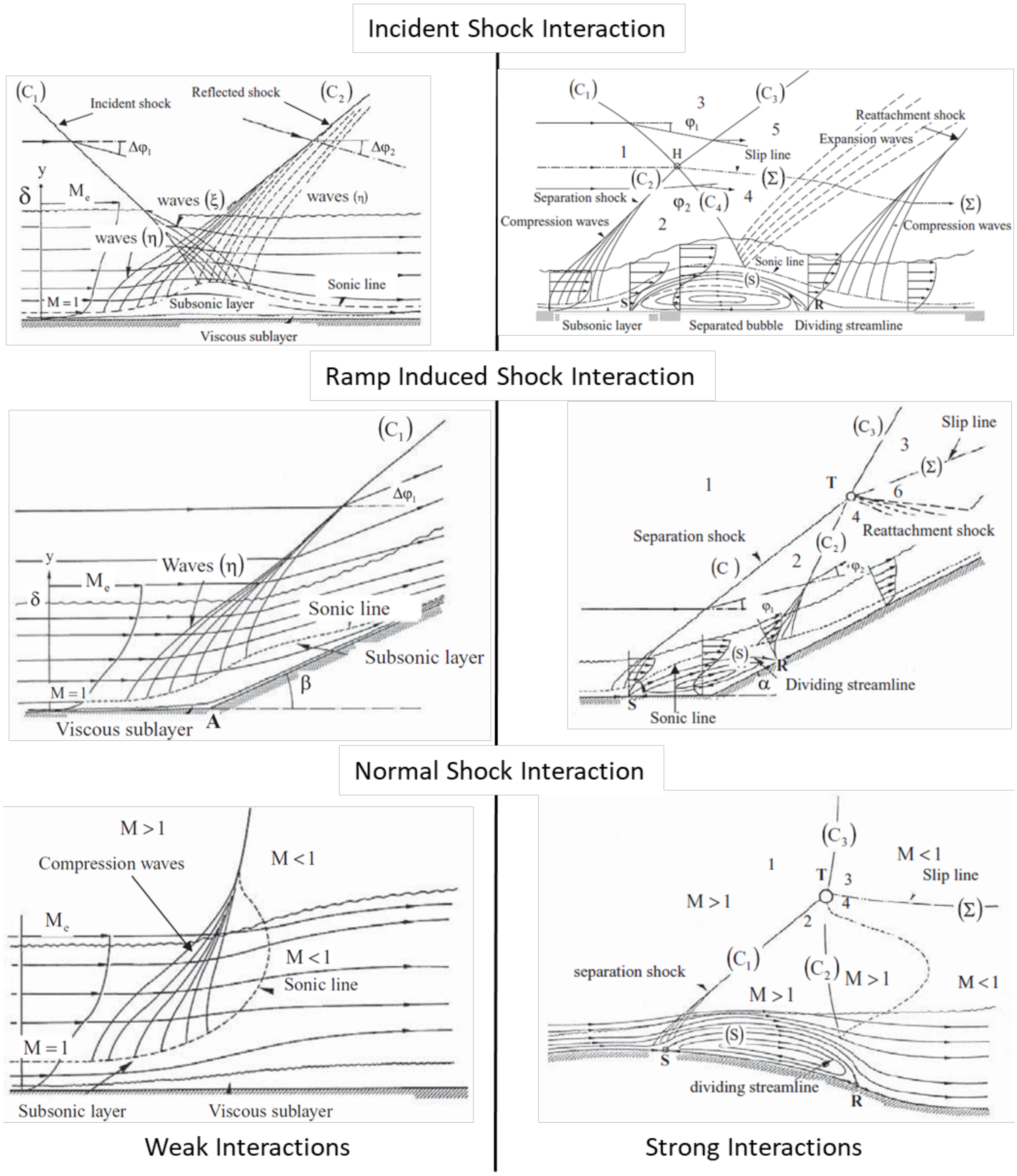

Figure 2: Shock wave boundary layer interactions. Left: Weak interactions. Right: Strong interactions [Babinsky & Harvey 2011].

Shock-shock interaction carries also a great importance since according to the interaction type their effect on boundary layer or the created conditions arises from the interaction of a shock with the boundary layer can change the flow pattern as well as the aero-thermal loads on the surface. Shock-shock interactions are classified under six different categories according to Edney given in Figure 3 [Edney, 1968]. Type-I interaction occurs when two shock of different families. Two shocks intersects at a Triple Point (TP), then refracted as new shocks. After first shocks, slipline is created due to existence of two distinct flows. Type-II interaction is similar to Type-I except one of them has a larger intensity. In this case, the flow behind the strong shock has a much smaller Mach number. Shocks cannot intersect. In order to obtain a compatible flow, an intermediate solution is created such as a strong shock appears between the first two shocks. This shock has a variable intensity between these shocks, which creates two distinct slipline.

In the Type-III interaction, a weak shock and a strong normal shock interacts. After the normal shock flow becomes subsonic. A third shock emits from the TP where the flow after this shock is still supersonic. Type-IV is similar to Type-III except the flow after the second shock flow is supersonic between the slip line and the shock after TP. Another TP is created and flow becomes subsonic after this shock. A jet flow is created between two subsonic flows separated by a slipline. Type-V interaction is a very similar case to Type-II except due to upstream conditions a supersonic jet forms from second TP. Type-VI is an interaction where two shocks of the same family. Depending on the conditions, in order to adjust the flow an expansion fan or a shock wave can emerge from the TP.

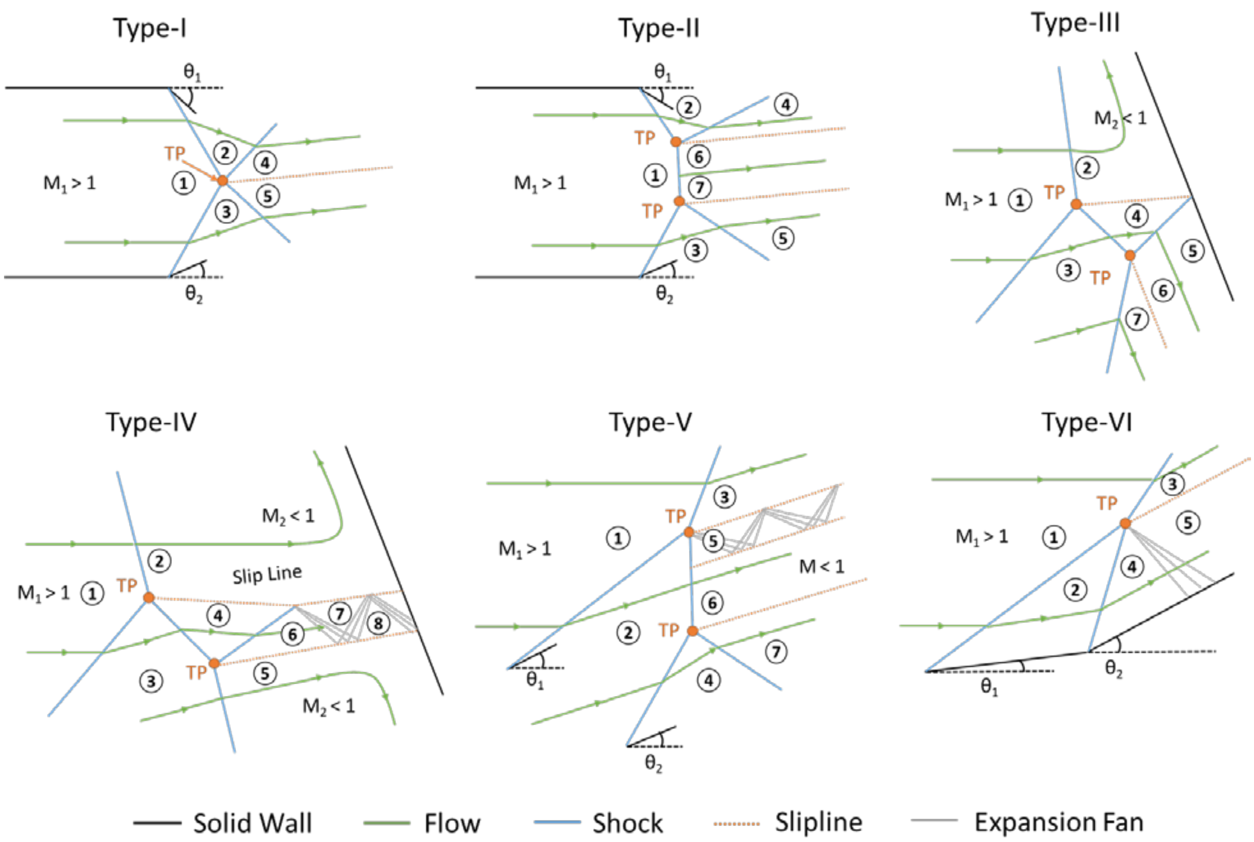

Figure 3: Edney's shock-shock interaction types, reproduced [Babinsky & Harvey 2011].

METHOD

Experiments were carried out at İTÜ Trisonic Wind Tunnel given in Figure 4. It is a blowdown wind tunnel with 0.15 x 0.15 m rectangular cross section. The experiments were performed using Block nozzle. Schlieren method is used for flow visualization. The Schlieren setup is consist of a high speed camera, a single wavelength continuous laser and two mirrors. The flow field is recorded at 8000 fps for 7.5 seconds. In addition, mean static pressure is measured on the test model with a pressure scanner at 20 Hz acquisition speed. The calibration of the pressure scanner was done by using an automated pressure scanner device.

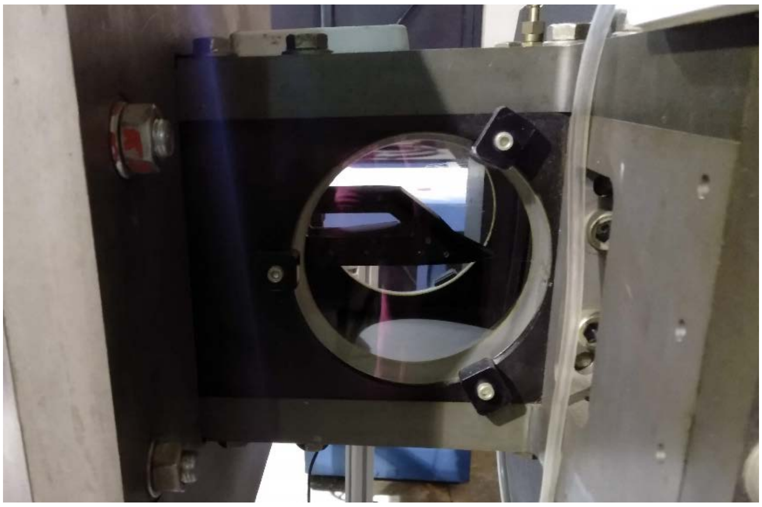

Figure 4: Trisonic Wind Tunnel

Test Model

The test model is a mixed type compression, rectangular supersonic inlet that is given Figure 5. Test model has 11 static taps, Schlieren access window and back pressure control mechanism which is a plug driven by an electric motor. The plug is placed after the subsonic diffuser to control the backpressure as well as mass flow rate to obtain performance characteristics. The total blockage of the model is 10.9%.

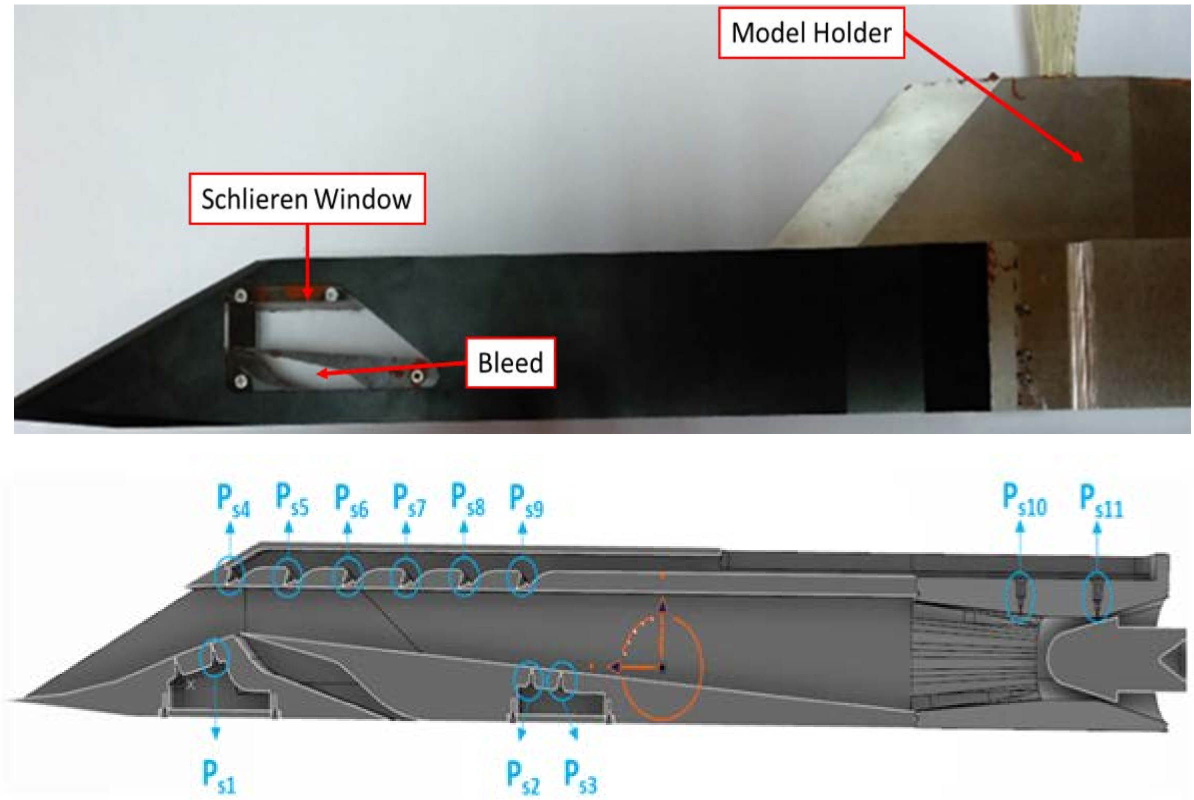

Figure 5: Test Model

Test conditions:
The operating Mach number is summarized in Table 1.

Table 1: Test conditions

Mach Number
2.77
3.2
3.65

Performance parameter calculations:
Plug moves back and forth and changes the area at the end of the test model indicated as A11 in Figure 6. The tests starts with plug is in backward position, fully opened, such that the A11 has its maximum value. Then plug starts its movement forward, closes the area entirely, stays fully closed for 0.5 seconds then starts to go backward until it reaches fully opened position. The entire plug movement is symmetric and lasts for 7.5 seconds in total. Meanwhile pressure scanner and Schlieren system starts recording data simultaneously with the plug. Performance characteristics are obtained using static pressure readings from the static tap located at A10. Total pressure as well as mass flow rate at this location were derived using analogy described in [Herrman, Blem, & Gülhan, 2011].

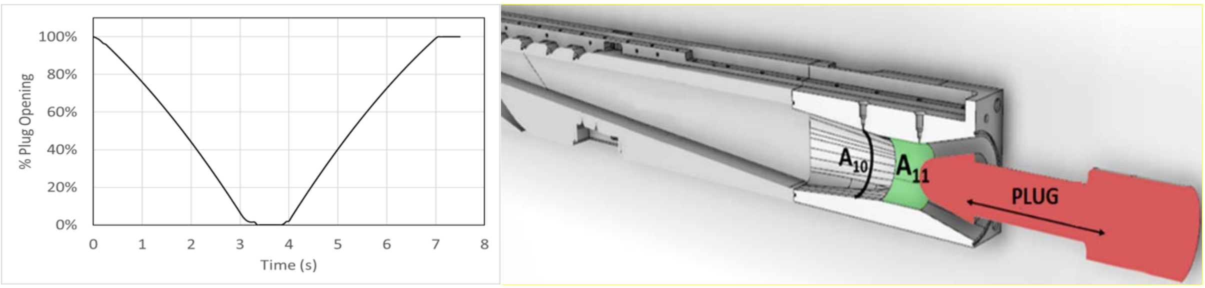

Figure 6: Plug movement (left), back area control scheme (right)

RESULTS

The pressure measurements results are presented with the corresponding Schlieren images at 100%, 70% and 50% plug openings in order to indicate the general behavior of the inlet. Inlet buzz is a self-sustaining phenomenon which is indicated by the oscillating shock wave structures. Little buzz is when the slipline created by the triple point of a normal shock and an oblique shock in front of the inlet enters the inlet. The effects of the little buzz are observed in the Schlieren images as small oscillations of the oblique shock. One cycle of the little buzz phenomenon can be seen in Figure 7. Big buzz triggered by a separated boundary layer on the ramp being ingested by the inlet. One cycle of big buzz phenomenon can be seen in Figure 8. When Figure 7 and Figure 8 are compared, the oscillations generated by big buzz are much more severe than those created by little buzz.

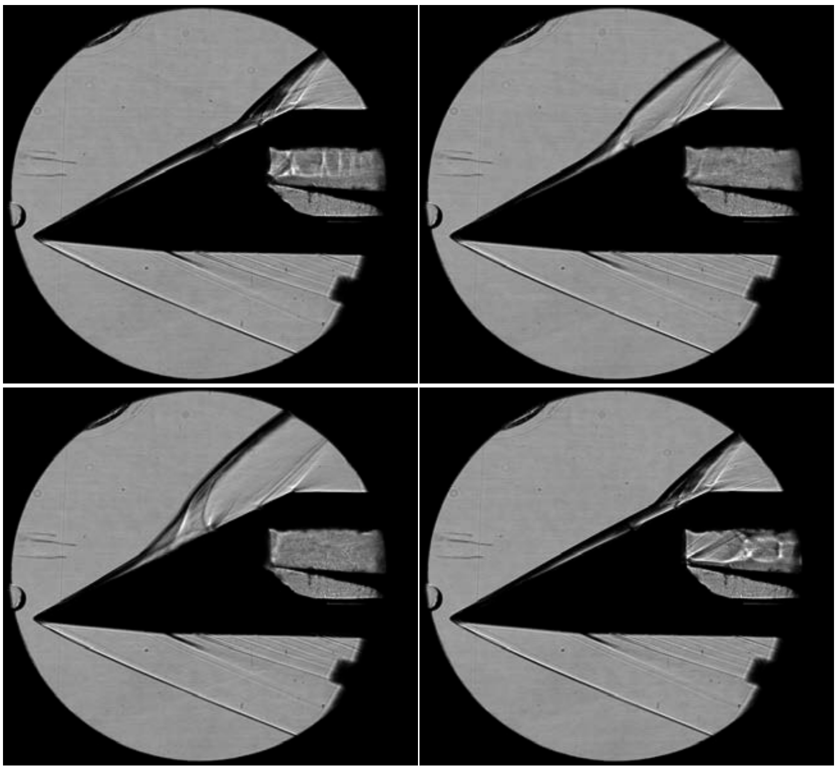

Figure 7. One cycle of little buzz phenomenon at Mach number of 2.77.

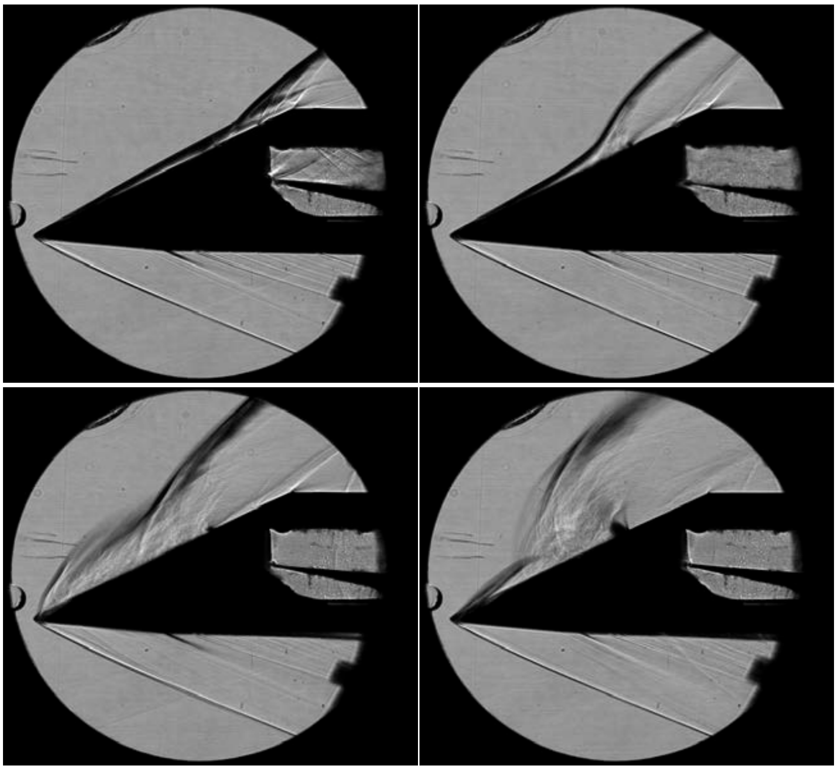

Figure 8. One cycle of big buzz phenomenon at Mach 2.77.

The shock structures and the shock wave boundary layer interaction could not be seen in the Schlieren images, because of the absence of Schlieren windows near the ramps.

Pressure measurement results at Mach 2.77 are given in Figure 9. The results indicate that at a plug opening of 82% (0.8 seconds) static pressure values started to become unstable leading to little buzz phenomenon, which is sustained until 61% plug opening (1.5 seconds). At plug openings lower than 61% big buzz is observed.

At Mach 3.2 (Figure 10), the static pressure values are increased until 76% plug opening (1 seconds). After this plug opening they have started to show an unstable behavior starting with a sudden decrease. Little buzz is observed after 71% plug opening (1.15 seconds), and after 70% plug opening (1.15 seconds) big buzz is observed.

At Mach 3.65 (Figure 11), the sudden decrease and unstable behavior are started at plug opening of 86% (0.65 seconds). At plug openings lower than 86%, little buzz is observed. For this Mach number, big buzz is started to be visible at 70% plug opening (1.2 seconds)

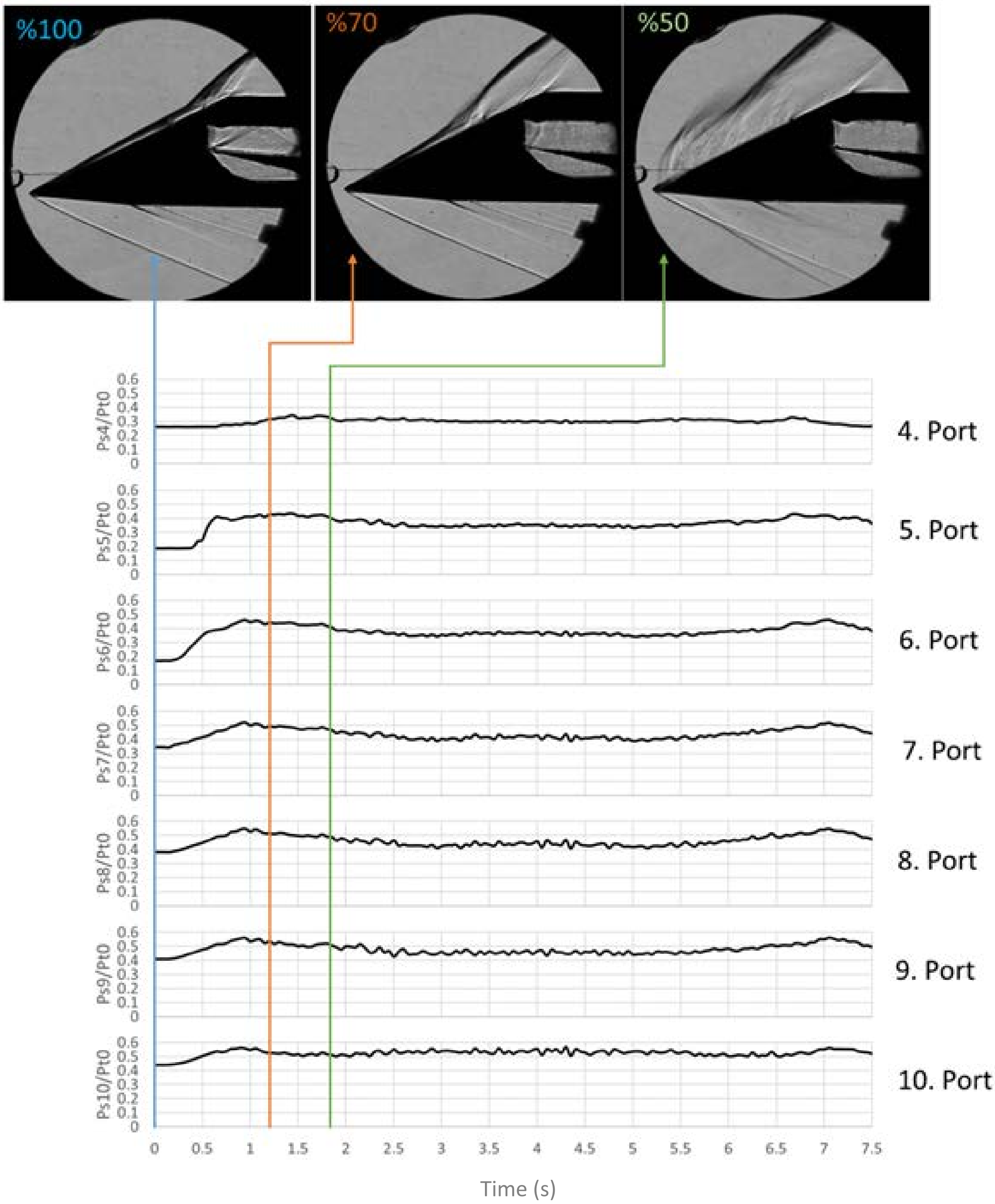

Figure 9. Pressure measurements and Schlieren results for M=2.77.

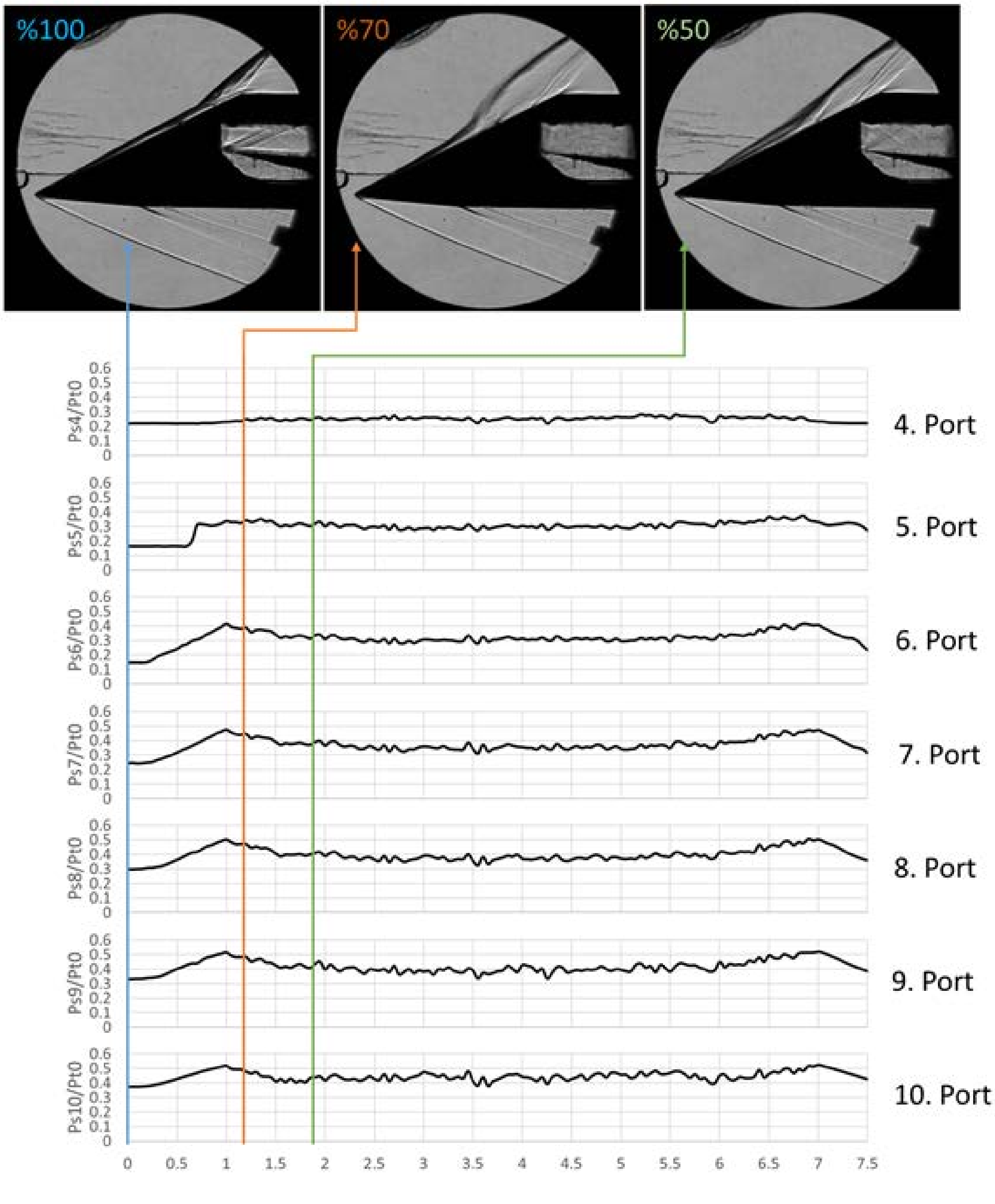

Figure 10. Pressure measurements and Schlieren results for M=3.2.

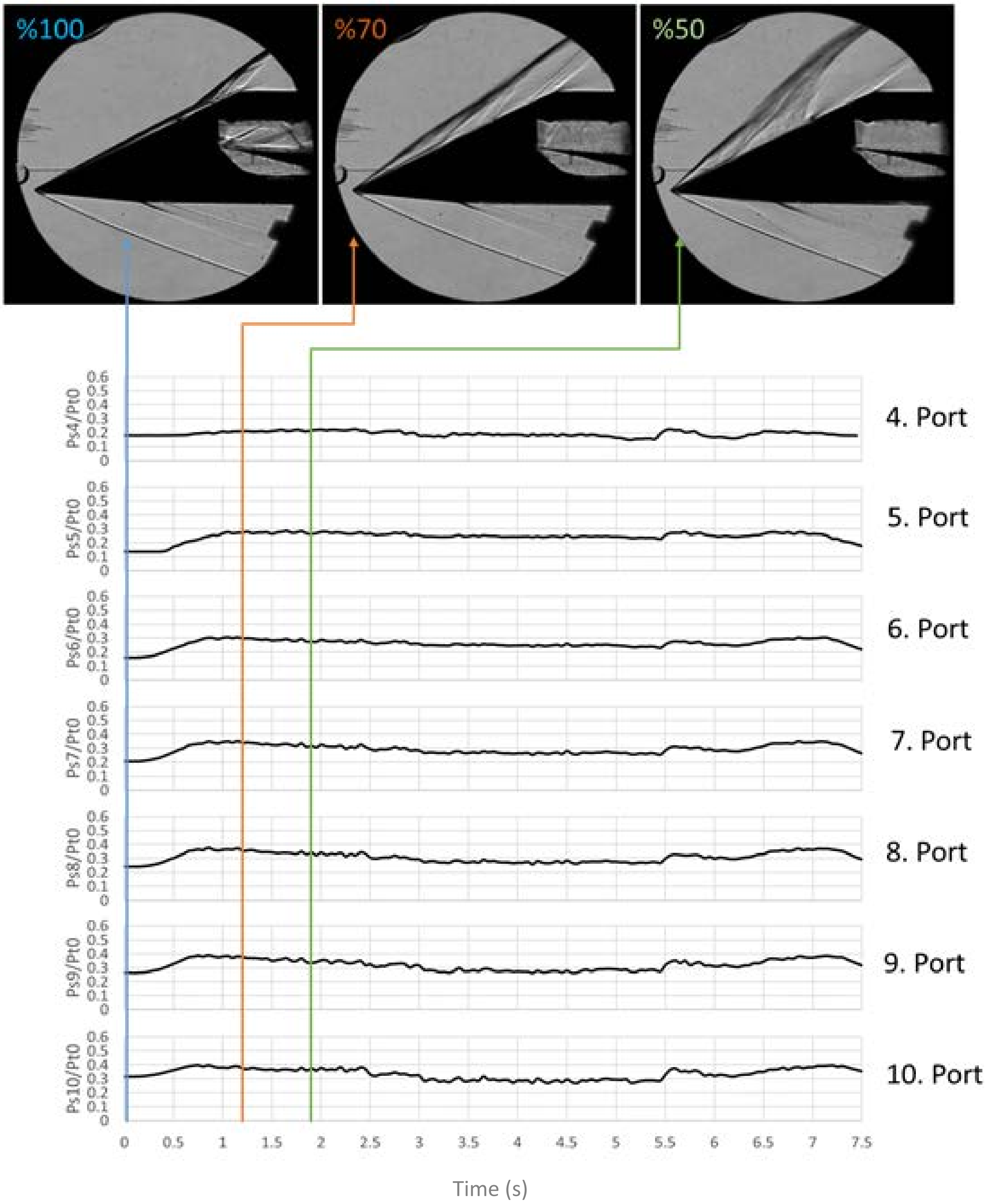

Figure 11. Pressure measurements and Schlieren results for M=3.65.

Preliminary results that are obtained from experiments at Mach number 2.77 are represented in Figure 12. Shown photographs are instantaneous flow filed obtained from Schlieren imaging at plug positions 100% and 80%. At %100 plug opening, the flow shows weak interaction where shocks reflects from the boundaries without causing boundary layer separation. The model represented has three inlet ramps. Although the Schilieren interrogation window does not cover the ramps, at this area Type-VI Edney interaction is expected. The dark long shock structure is seen at the inlet is a shock due to the chamfered sides of the model but not related to the ramps. The bleed section is clearly visible in the Schlieren images. At the beginning of the bleed, boundary layer separation, the incident shock, separation shock and expansion fan are visible. The boundary layer after the separation is quite thick and does not reattach.

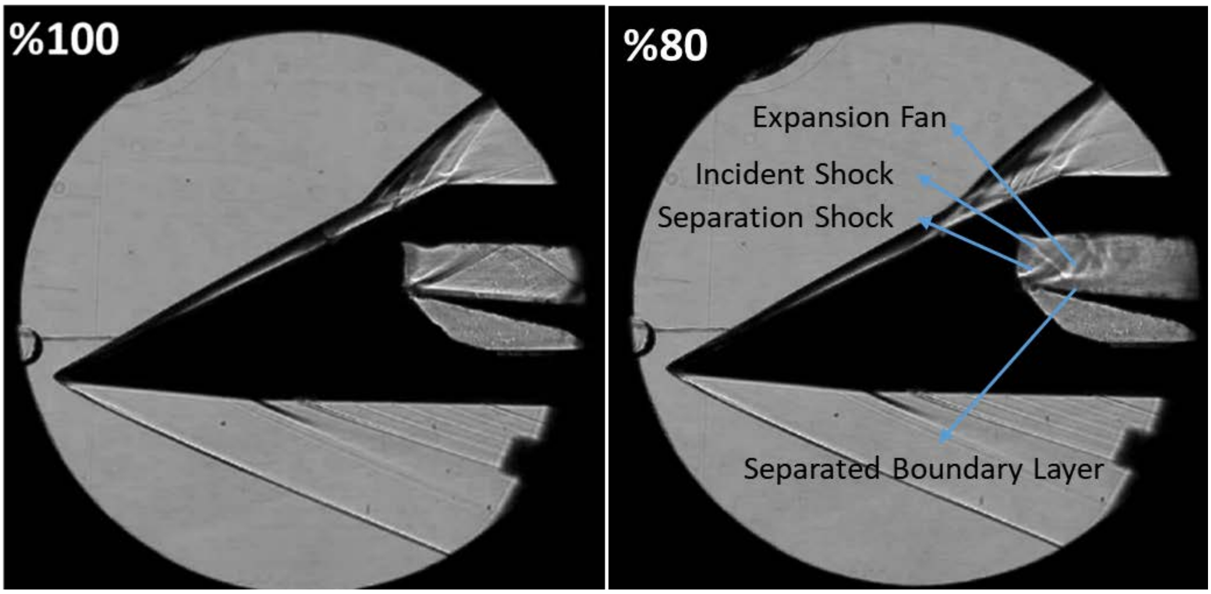

Figure 12: Schlieren images at Mach =2.77, for 100% and 80% plug openings

Figure 13 represents the instantaneous flow filed obtained from Schlieren imaging for Mach number 3.2 at plug openings 100% and 90%. For 100% plug opening flow separates at the end of bleed opening creating and expansion fan and reattachment shock without flow separation. For 90% opening, incident shock is not on the visible area however, the separation shock at the bleed entrance is visible. In this condition, the reattachment shock forms a Type-I Edney interaction with the reflected separation shock on the upper wall. The formed triple point is quite visible. After the interaction, the shock formed under the triple point impinges on the boundary layer and causes another separation on the boundary layer.

Figure 14 shows the Schlieren images at Mach number 3.65 at 100% and 90% plug openings. For 100% plug opening, flow separates near the end of the bleed opening, creating an expansion fan and a reattachment shock. The structure indicates a Type-I Edney interaction with a visible triple point. The shock formed under the triple point impinges on the boundary layer and causes another separation, which starts at the very end of the Schlieren window. At 90% plug opening, expansion fan, separation shock and the separated boundary layer are clearly visible.

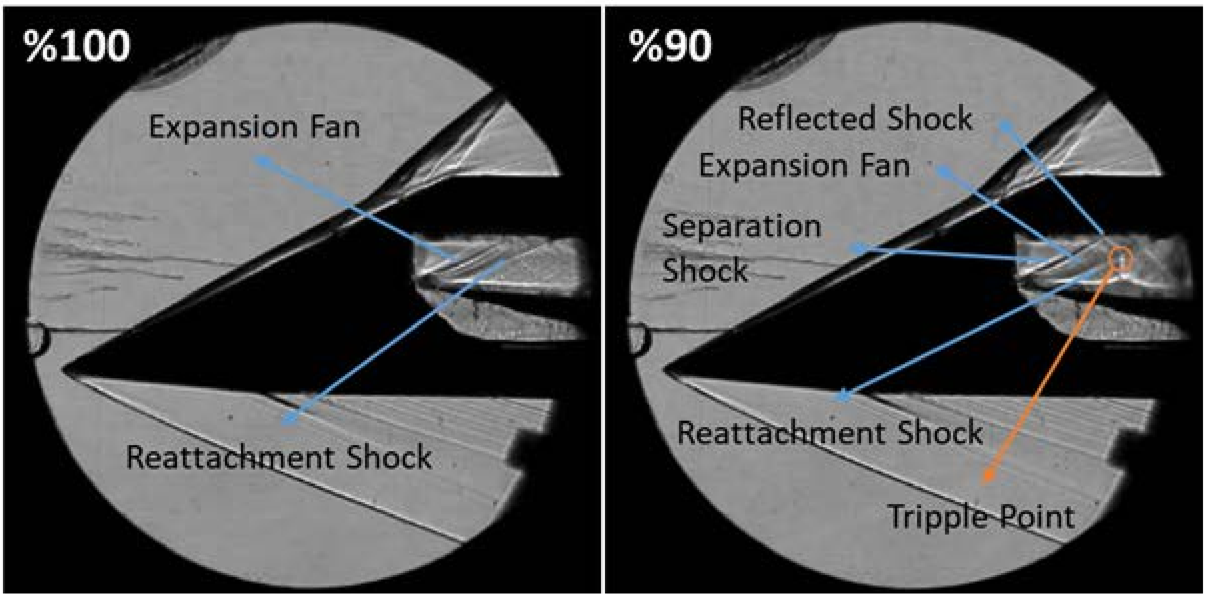

Figure 13: Schlieren images at Mach =3.2, for 100% and 90% plug openings

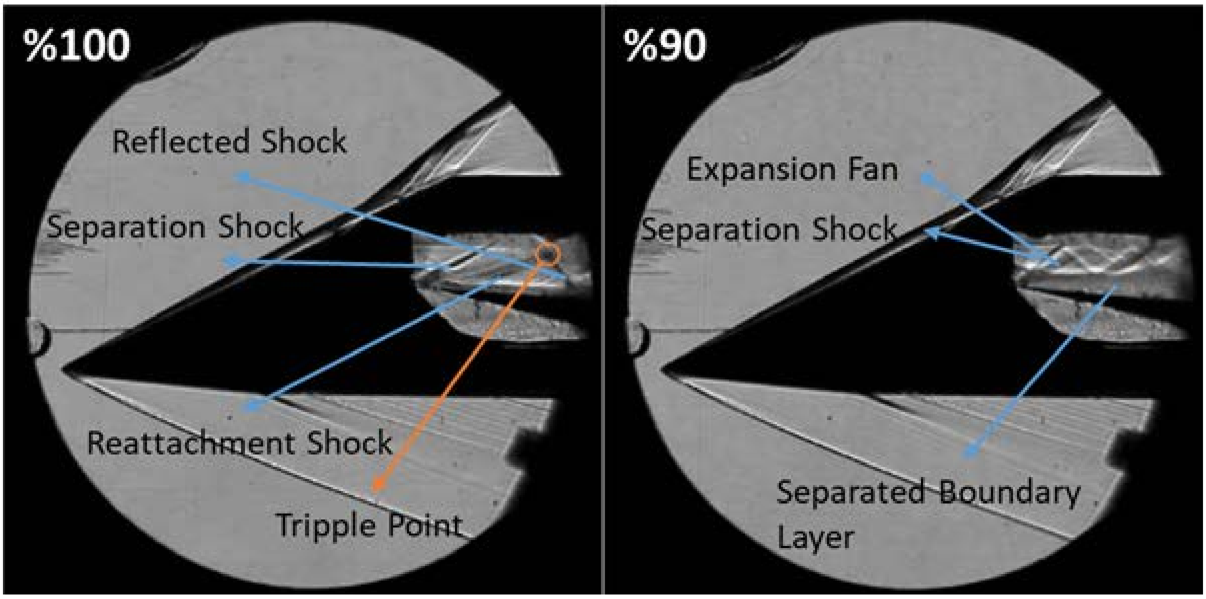

Figure 14: Schlieren images at Mach =3.65, for 100% and 90% plug openings

CONCLUSION

In this work, shock-boundary layer interactions as well as shock-shock interactions for a mixed type supersonic air inlet is examined experimentally. Instantaneous Schlieren images are analyzed for flow structure and preliminary results are given. Weak and strong boundary layer interactions and the resultant shock structures is tried to be shown. Type-I Edney shock-shock interaction is seen clearly. Moreover, Type-VI Edney interaction presence is most likely to be found at the inlet ramps.

FUTURE WORKS

Experimental work with a test model having Schlieren windows near the ramps and bleed reservoir will be conducted. Experimental analysis on inlet buzzing frequency will be done.

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