

Numerical Study of Hysteresis related to the Unstart/Restart Cycle in Scramjet Engines

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Abstract

A Turbine Based Combined Cycle (TBCC) with a dual mode scramjet is a key candidate for future end-to-end hypersonic flight. The design of scramjet inlets is critical for the overall performance of the engine. With a variable supersonic inlet, the throat area decreases to alter the aerodynamic losses, but extreme constriction seen in terms of Internal Contraction Ratio (ICR) increases the chances of unstart. Two-dimensional unsteady numerical simulations are conducted to study the features of the flow and the process of start, unstart, and restart states in scramjet engines. Hysteresis of the flow is observed in the results obtained and it is concluded that a restart is found after increasing the aerodynamic throat area. It is found that separation ahead of the inlet held in place by the separation shock affects the hysteresis and the ability of the engine to return to its original operating condition. The option of utilizing bleed to delay unstart and to bring stability to the flow is also explored.

Keywords: Unstart, TBCC, Scramjet, Flow Separation, SBLI

1. Introduction

A Turbine Based Combined Cycle (TBCC) is one key candidate with a dual mode scramjet taking up the reins beginning Mach 3 and generating thrust in the hypersonic regime. TBCC can be divided into two variants - serial stacked and parallel stacked. In the case of former (figure 1), the turbine section as well as the ramjet/scramjet section is placed in-line, sharing the same inlet and exhaust path.

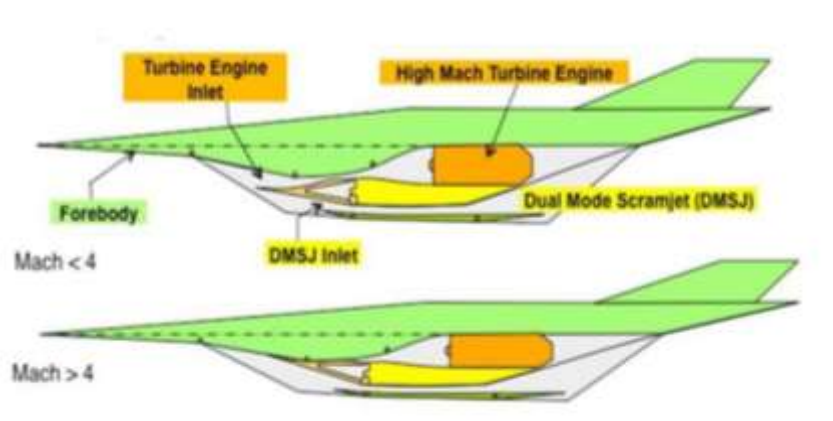


Figure 1: A parallel stacked TBCC.

The major complication here is the design of inlet that allows for a wide range of inlet Mach numbers as the common duct supplies airflow to both the engine stages. In the latter (figure 2), the turbine stage and the scramjet stage are placed in such a way that each has an inlet of its own along with an exhaust. The structural complexity is higher in this case as not only does this configuration require a larger frontal area but also needs efficient structure integration such that the loads from one of the stages does not cause damage/failure in the other.

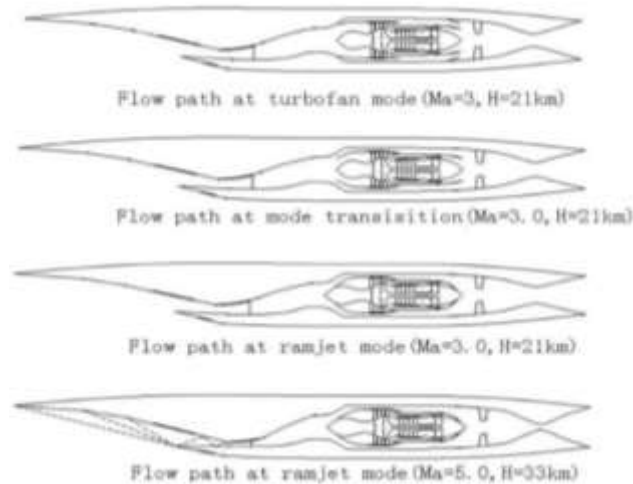


Figure 2: A serial stacked TBCC.

2. Literature Review

In scramjets, at elevated Mach numbers, inlets with mixed compression - a combination of the external and internal compression, have shown self-starting capabilities permitting excellent and stable performance along wide range of Mach numbers in terms of basic, 2-D supersonic inlet with variable geometry that offers greater application in practical or real flight cases [1].

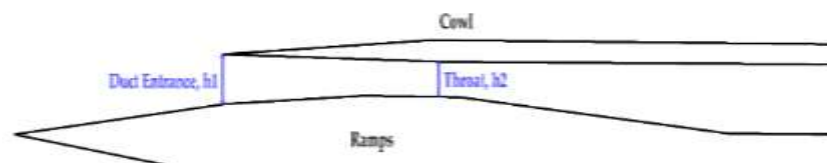


Figure 3: Geometrical representation of the Internal Contraction Ratio (ICR).

This variation of geometry can be implemented by movement of the cowl - translation or rotation or by variation of the duct height at the throat section. This is quantified as the Internal Compression Ratio (ICR) i.e., the fraction of the height at duct entrance (h_1) to that of the throat (h_2) (figure 3).

In real flight conditions, operation of a varying geometry inlet involves several hurdles such as the dynamically varying high back pressure, steep AoA, fluctuating Mach number etc. caused by inconsistent fuel supply or due to the well-known Shock - Boundary Layer Interaction (SBLI). From experimental studies available in the literature, it is seen that an uncharacteristically large ICR has huge effect on the flow stability with high likelihood for unstart [2]. This usually occurs as increasing of ICR also has its benefits seen in the form of better total-pressure recovery at the combustor leading to better combustion.

But while desiring for higher performance, the chances of the occurrence of unstart also rises. Hence, a deeper understanding of this careful balance is necessary for safe operation of a scramjet engine. This is achieved by focusing on the boundaries of unstart or restart so as to operate the scramjet within those bounds.

Hysteresis of the flow response is the cyclic motion of the flow state within the scramjet from the start phase followed by an unstart phase ending with that of restart of the engine [3]. Primary reasons for the appearance of such a hysteresis cycle is attributed to variation in the downstream pressure at the combustion region or variation in the Mach number at the duct entrance as a result of the change in shock strength due to unforeseen alteration of the flight AoA. Therefore, the flow responding along a specific cycle during every unstart & restart cycle will be a common happening. To obtain such a verifying simulation case, a transient two-dimensional simulation was performed using a varying geometry achieved using a dynamic mesh (figure 4).

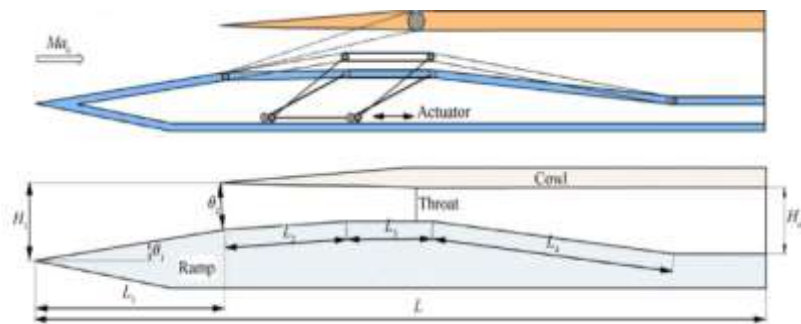


Figure 4: Schematic of inlet and dynamic motion of throat compression.

The geometry utilized in this study is that of a serial stacked TBCC where the focus is laid on the dual mode scramjet positioned post the turbine stage. Hence, the starting Mach no. for the scramjet has to be low enough for it to efficiently transition from a turbine powered vehicle to a scramjet powered vehicle. The low momentum flow section of a parallel TBCC type engine from a 2D varying geometry supersonic inlet is focus of this project. The simulation begins with the model with a minimal ICR of 1.4 in its started state. During the course of the unsteady simulation, the contraction at the throat is increased at a constant rate to bring about the unstart as a result of flow choking. Following the observance of unstart, the contraction at the throat is relaxed until the flow is no longer choked and it returns back to its initial state where the inlet is now said to be restarted. This allows simulation of the unstart/restart process induced by controlling the ICR.

3. Numerical Method

Two-dimensional compressible RANS equations based on the Menter's SST $k-\omega$ turbulence model were employed to simulate the supersonic flow field. This model predicts separated flows and flows with large gradients in pressure close to the wall of the scramjets with a good degree of accuracy compared to other turbulence models. The AUSM flux differentiation method was used to separate the inviscid convection flow in the numerical simulation paired with a 2nd order upwind scheme to discretize the domain, and the Sutherland's three-temperature model to determine the viscosity terms.

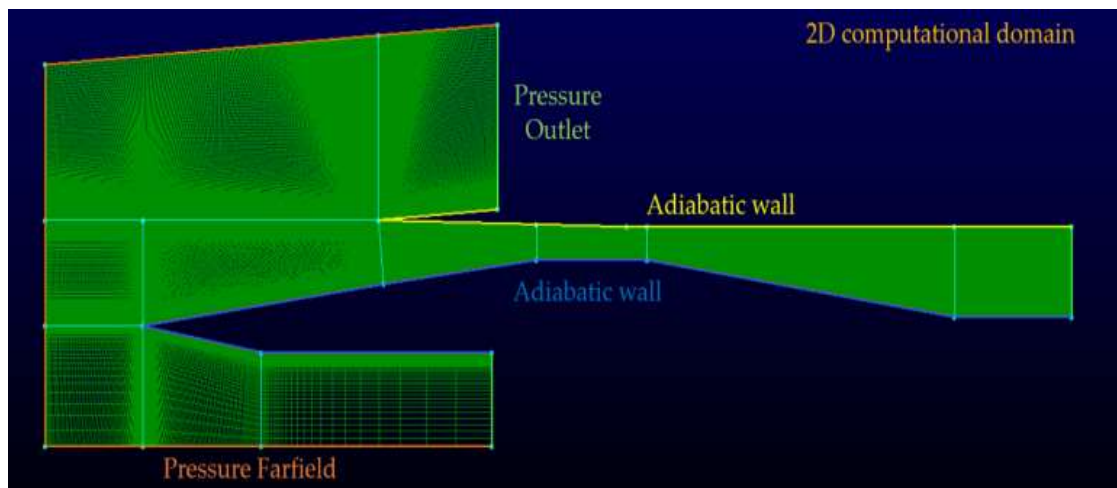


Figure 5: Computational domain with boundary conditions.

The freestream conditions specified include a pressure of 8060 Pa with a freestream temperature of 107.1 Kelvin. An unsteady time step of 5×10^{-5} s was used to carry out the simulation as it provided stable results that showed the flow coinciding with the features at time instances as observed in the literature [1]. The computational grid (figure 5) was built using 350,000 cells as a coarse mesh performed well enough in comparison to that of a refined grid with 600,000 cells for the given time step size. An average wall y^+ plus of 10 was utilized with certain areas of focus around the throat having a local y^+ close to 01. To simulate the variation of the throat height, a dynamic mesh was utilised. An UDF was used to provide the geometry movement requirements in this case.

4. Results and Discussion

A. Steady Simulations

In order to verify the accuracy of the simulations performed, first a steady case was performed. This was done by selecting the initial geometry condition i.e., ICR 1.4 at $t = 0$ ms. The pressure plots were used as the verification media. Figure 6 shows result obtained from the steady simulation for the flow parameters obtained from the literature [1].

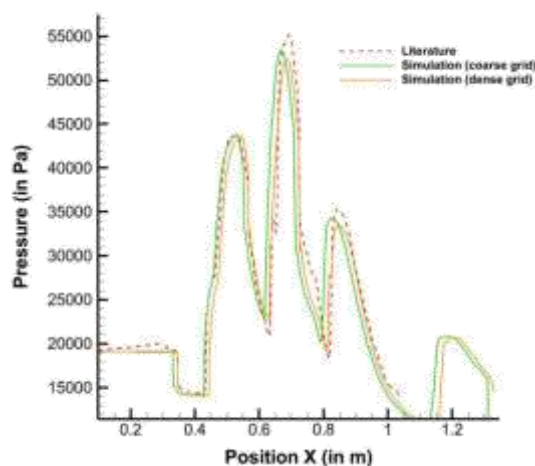


Figure 6: Static pressure along the ramp.

It is observed that a relatively coarse mesh with 350,000 cells predicted the shock impingement and the pressure variation within the shock train with good accuracy (figure 7). Hence, the same mesh was utilized for the remainder of the dynamic simulations due to its ability to provide accurate enough results at relatively low computational time and costs.

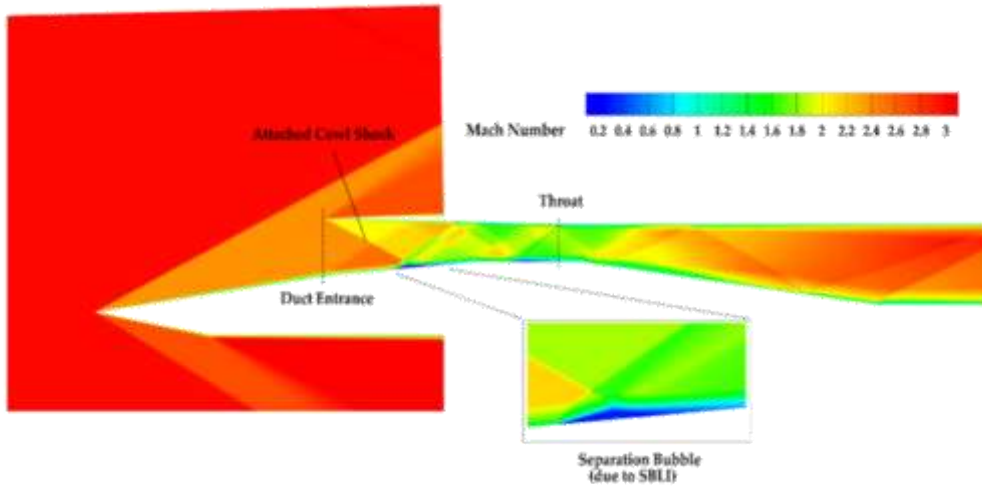


Figure 7: Mach contour of flow field at ICR = 1.4

B. Transient Simulation with Dynamic Mesh Motion

Although a steady simulation helps in simulating the flow within the scramjet geometry, the very nature of unsteadiness, an inherent part of any physical problem, can lead to certain interesting flow phenomenon, such as hysteresis in our study.

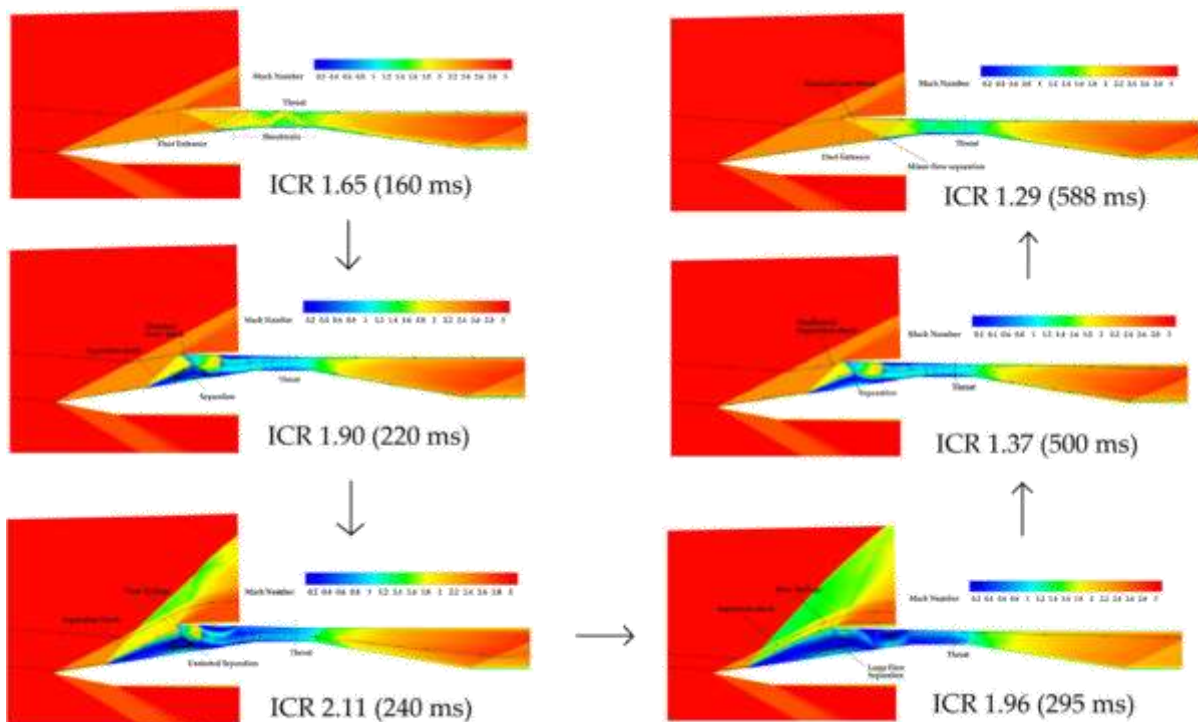


Figure 8: Mach contours showing flow field at various time instances of the Unstart/Restart hysteresis cycle.

Understanding this case helps in accurately predicting the actual flight condition (figure 8). The Unstart-Restart cycle can be seen in the variation of the mass flow rate as time progresses. The same is plotted in the figures 9 and 10. The entire process can be analyzed in three sections.

- a. Started phase: This phase is defined by the constant mass flow rate along with the stable operations.
- b. Unstarted phase: Predominant effects include decrease in mass flow rate, loss of thrust and a highly unstable working cycle.
- c. Restart phase: In this phase, the stability is re-attained while a minutely lower thrust magnitude is observed due to loss of flow at the separation region.

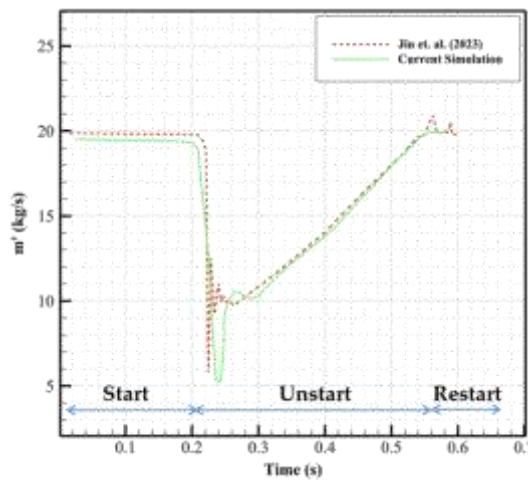


Figure 9: Variation of mass flow rate with time.

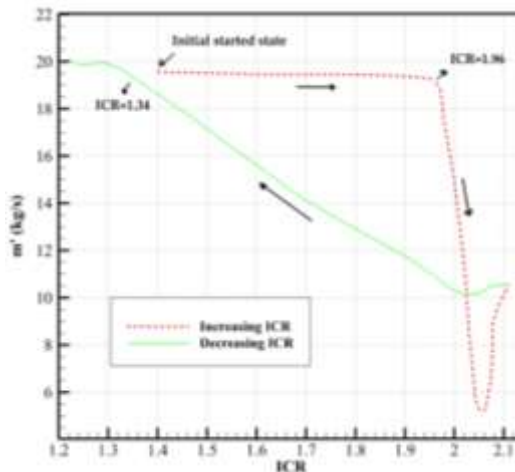


Figure 10: Variation of mass flow rate with change in ICR.

With an increase in the ICR i.e., a decrease in throat height, the count of shock reflections generated by the cowl is seen to increase. With this process, the intensity/strength of the shock waves increases gradually implying higher compression evident in the higher pressure. The rate of mass flow toward the end of the duct in the scramjet remains more or less constant until ICR 1.96 when the strong SwBLI causes an unavoidably large separation at the point of incidence of the cowl shock over the ramp 1- ramp 2 intersection. In this state, the flow within the scramjet is highly unstable with both, the rising pressure downstream and the growth of the separation region. On further increasing the ICR, the downstream

pressure gains an edge over flow stability leading to further enlargement of the separated flow. At this instant (ICR 2.11), the unstart is said to have occurred with the flow spilling outward, over the edge of the cowl. The separation shock does not help in stabilizing the spillage as its now located further upstream of its initial position at the cowl. Thus at this instant, the mass flow through the inlet significantly drops to 5.2 kg/s from its initial stable state at 19.56 kg/s. The now detached cowl shock decelerates the remaining part of the flow that hardly makes it way though the inlet to subsonic limits. This is however negated by the expansion fan over the separation region as it accelerates the flow back to supersonic regime again (fig. 8). Hence, the pressure drops in the isolator region to values lower than those observed at ICR 1.96. From the figures 11 and 12, it is seen that with throat contraction, the location of peak pressure moves upstream. This upstream location for the peak pressure is not a design case for the scramjet as the region to contain maximum pressure is the downstream of isolator and the combustor. Such high pressure at the inlet acts as a hurdle to the incoming low pressure air flow. Such blockage can lead to a decrease in mass flow through the scramjet leading to downgrade in its thrust performance.

Getting the inlet to restart at this stage requires sudden increase in the throat height i.e., a decrease in ICR. This phase starts at 260 ms where the ICR is 2.11. While lowering the ICR down to 1.96 at the 295 ms mark, the unstarted region seems to be unaffected. Decreasing it further at a steady rate shows improvement with the separation bubble not only receding but also is getting smaller. Observing the flow at 500 ms at an ICR of 1.37, the restart is said to attain restart as the separation shock is incident over the cowl leading edge thereby stopping the flow spillage. Now, on further decrease of ICR, down to 1.29 at 580 ms, analyzing the flow reveals the flow system mimics that of the started state with a very minute separation region held local close to the boundary layer (fig. 8). This small scale separation does not disappear until the throat height is increased further which is not a possibility as this sacrifices the compression strength of the isolator. Hence, post unstart, for a particular ICR such as 1.4 observed at the start, a 100% regaining of aerodynamic parameters as well as the mass flow is not possible where initially, the mass flow at ICR 1.4 was 19.2 kg/s and post the unstart-restart procedure, the flow rate is down to 18.3 kg/s meaning some minimal loss of performance as could be evident in the thrust output of the scramjet.

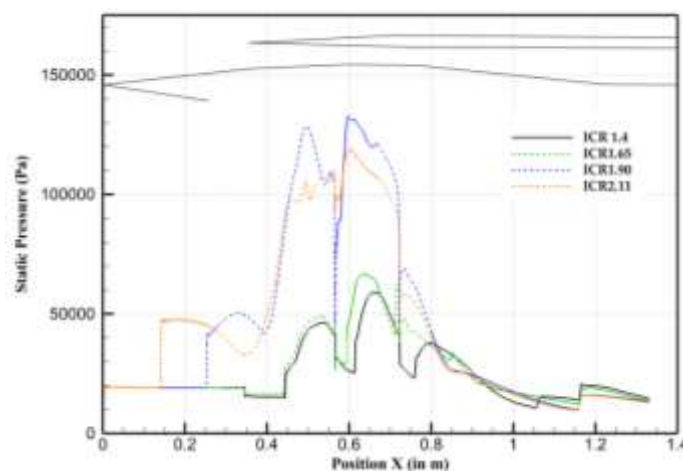


Figure 11: Distribution of Ramp-side Static Pressure during ICR increase phase.

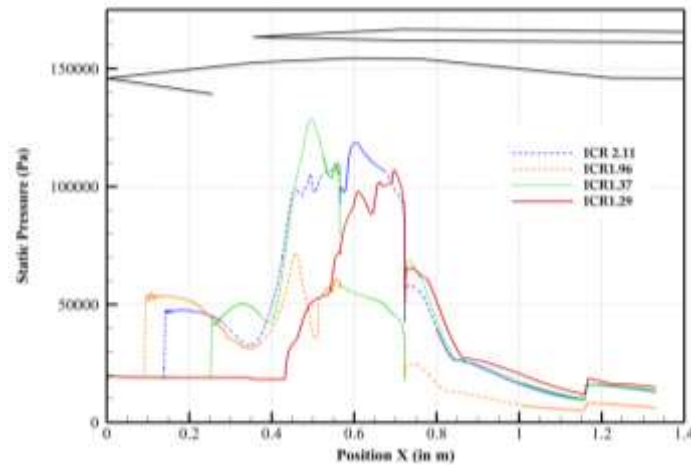


Figure 12: Distribution of Ramp-side Static Pressure during ICR decrease phase.

C. Effect of Bleed

Additionally, cases using bleed slots are explored and simulated using steady flow conditions to observe the variation of the separation bubbles at the ramp. Solving the SBLI at these sections helps in better control of the inlet if it were to unstart. The use of bleed although results in decrease in mass flow at the outlet, plays a vital role in stabilizing the separation caused at regions of strong SBLI by maintaining a lower suction pressure. With the region of the first bleed slot having a smaller separation bubble/region, it is evident that a larger quantity of low momentum mass is bled out, thereby removing the separated flow region.

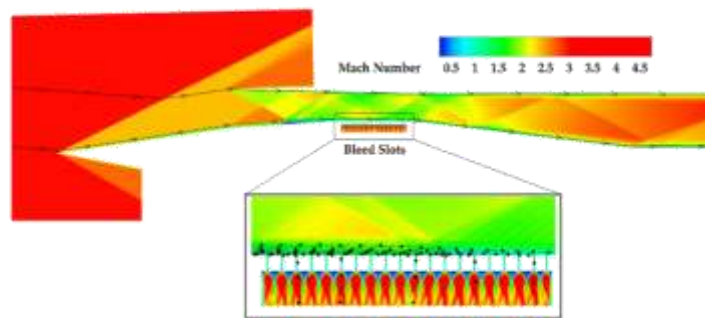


Figure 13: Mach contours for the case with single bleed slot on the ramp side of the geometry.

Bleed at two locations were checked. First, the one within the combustor is analyzed as shown in figure 13 and another case with two bleed opening is also simulated to remove the separation further upstream. Figure 14 shows the Mach number contours for the case with double bleed slots on the ramp side of the geometry. Two sections of bleed are designed based on the presence of local separation within these sections. First, the simulation considers the second bleed region as that is located closer to the region of high pressure followed by opening both the bleed slot sections. When stabilized (see Figure 15), the mass flow through the bleed accounts for roughly 4.4% of the flow rate during initial stable operations. Although, the bleed layout would need optimization based on the location of maximum separation and its magnitude.

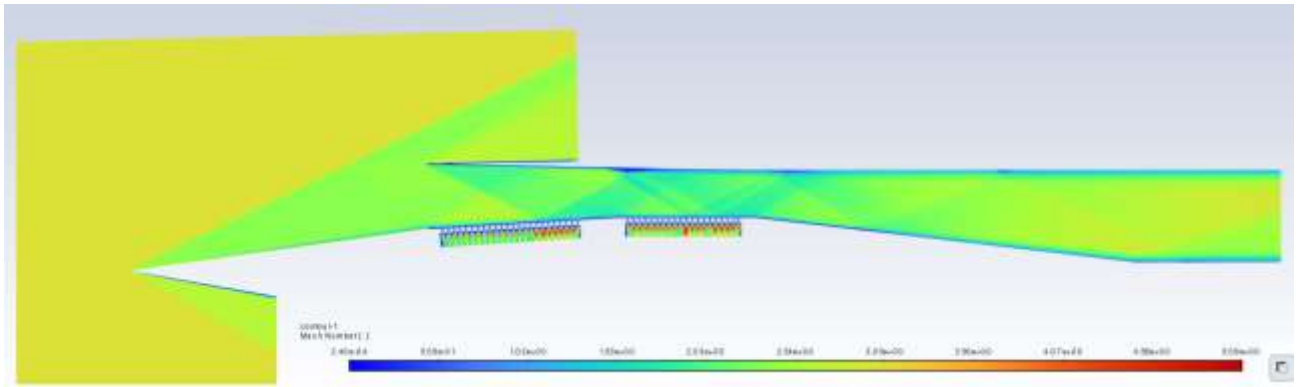


Figure 14: Mach contours for the case with double bleed slots on the ramp side of the geometry

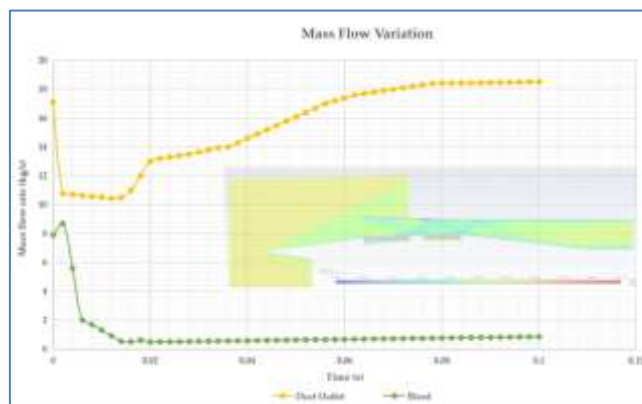


Figure 15: Variation of the mass flow rate at the duct outlet and bleed outlets.

Table 1: Mass flow rates while dual-bleed slots are employed.

Location	Mass flow rate (kg/s)
Duct Outlet (without bleed)	19.8387
Bleed (with single set of bleed slot)	0.52
Duct Outlet (with single set of bleed slot)	19.318
Bleed (with two bleed slot sets)	0.89
Duct Outlet (with two bleed slot sets)	18.9

5. Conclusions

The mismatch between the restart and unstart paths creates a flow response hysteresis loop in the throat regulating mechanism. Cowl-shock causes large-scale separation and sophisticated wave structure in the inlet internal contraction section by generating a complex shock wave system. The separation bubble at the duct entry is the key influencing element in the inlet unstart/restart operation, as it decreases the inlet's collected airflow and increases the reverse pressure gradient in the internal contraction section. In the case with bleed, it is observed that the low momentum flow within the separation bubble is drained by the slots.

Although bleeding of mass has a negative effect on thrust, the magnitude remains small (~4.4%), hence, it offers a considerable trade-off for the stability.

References

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