Review Paper on Hypersonic Air-Intakes

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Abstract - Scramjet engine propels the vehicle at Hypersonic speeds i.e at M > 5. The scramjet combusts the flow at supersonic speeds, thus the freestream hypersonic flow has to be reduced to supersonic speeds through Air –Intake which compresses the flow. The performance of scramjet powered hypersonic vehicle is determined by its Air-Intake efficiency as the engine depends very much on the quantity and quality (uniformity and total pressure) of the flow required for its smooth performance. Hypersonic intakes are designed as mixed compression intake which is a combination of internal and external compression. One major problem of hypersonic intakes with internal compression is the 'unstart problem' which describes the phenomenon that supersonic internal flow is not reached in the internal compression region. This paper reviews about different techniques to solve the unstarting problem of Hypersonic Intake.

Keywords – Air Intake, Shock boundary layer interaction, pressure recovery.

I. INTRODUCTION

The function of an air breathing vehicle intake is to capture and efficiently compress requisite quantity of air for engine operation. The intake which is designed for Scramjet Hypersonic vehicles is known as hypersonic intakes. It should compress the flow as efficiently as possible, minimizing the viscous and shock losses. Intake contribution to overall vehicle drag should be kept at minimum. Intake performance should not be significantly reduced by operation at incidence and must be able to tolerate the back pressure caused by heat addition.

The overall vehicle performance depends greatly on the energy level and flow quality of the incoming air. Small loss in intake efficiency translates to a substantial penalty in engine thrust. Therefore the detailed analysis and assessment of flow behavior through the intake and its interaction with external flow play an important role in the design evaluation and the performance of the vehicle.

II. STARTING AND UNSTARTING CHARACTERISTICS OF INTAKE

The intake should compress the freestream Mach number by a factor of about 3 before it reaches the combustor for scramjet operation which can be done by a highly convergent duct. But any duct in given hypersonic Mach number flow, can achieve two distinctly different flow configurations: first one is a bow shock in front of the intake that diverts some flow overboard and the intake flow is subsonic which is known as 'unstarted' condition of intake (ii) no bow shock, no overboard spillage, and the flow is supersonic throughout ('started flow'). In a hypersonic intake, the incoming flow is compressed through a series of oblique shock waves. These shock waves interact with the boundary layer known as Shockwave Boundary Layer Interaction (SBLI) that forms on the inlet wall. The adverse pressure gradient of the shock can be strong enough to cause local flow separation and reattachment. Separation bubble act as blockage in the inlet duct and can cause problems in starting, high localized heat transfer rate and skin friction, and degrade the quality of the flow entering the combustion chamber. In three-dimensional configuration, the shock boundary-layer interaction and resulting flow separation can be quite complex. It is important to understand the flow physics in detail, so as to explore ways of minimizing or eliminating flow separation and its adverse effect. The typical flow phenomenon of air in scramjet engine is shown in figure 1.

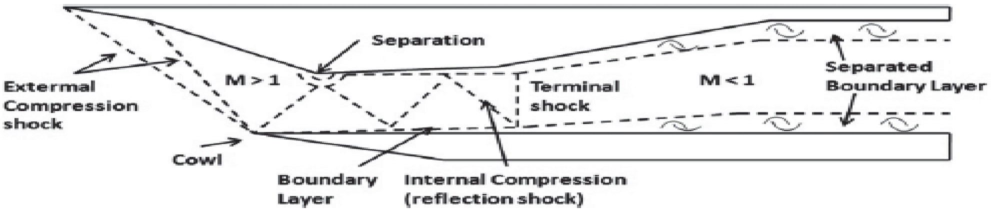

Figure 1 Flow phenomenon in scramjet engine

The unstart of the intake could occur due to several reasons, e.g. over contraction, variation of flight conditions, perturbations in combustor operation, back pressure, angle of attack, etc., or due to a combined effect of these factors. Interaction of the boundary layer with shock reflections and subsequent thickening of the boundary layer inside the internal duct, are believed to be the prime cause of a separation leading to a complex oscillatory flow structure and expulsion of the shock and the unstart of the intake. Usually, to start supersonic inlets at any flight condition, variable intake geometry, bleeding, cowl deflection or Micro Vortex generators (MVG) is used. But in a hypersonic flow situation which contains high enthalpy flow with high total temperature (~1800 K), any complex mechanical control system may cause severe structural and cooling problems.

III. TECHNIQUES TO REDUCE UNSTARTING PROBLEMS

The prediction of intake unstarts or SBLI and the techniques to reduce its occurrence or its effect are very much essential for hypersonic intake design. It seems almost impossible to avoid the occurrence of SBLI in any practical applications hence, this leads to the idea of developing control mechanisms by manipulating the flow either before or during the interaction itself. The objectives of the control mechanisms are to prevent shock-induced separation and also stabilizing the oscillating shock. The momentum of the turbulent boundary layer appears to be an important factor affecting the upstream in turbulence of the shock as well as the resistance of the boundary layer towards separation. Hence, by increasing the incoming boundary layer momentum prior to the interaction with the shock proves to be one of the beneficial mechanisms. This can be done using several boundary layer manipulation techniques listed below.

A. Variable intake geometry-

Schneider and Koschel[1] studied both experimentally and numerically the start and throttling behavior of a supersonic intake system of 9 different configurations with geometric variation at different inlet Mach number and exit throttling conditions. It was shown that by proper geometry selection, the size of the separation bubble at the ramp surface could be minimized without applying boundary layer bleed and high intake performance could be achieved.

Goonko, et al[2] reported experimental studies of three dimensional inlet at Mach number range 4 to 8 with ramp and side-swept compression wedges and depicted complex system of multiple shock waves, expansion waves and vortex structures leading to significant non uniformity of the flow field at the inlet entrance and exit.

B. Bleeding

Currently this is one of the most popular techniques due to its effectiveness. The introduction of bleed system is aimed to suppress the boundary layer separation induced by the impinging shock wave by removing the low momentum portion of the boundary layer. This is achieved through different designs such as holes, porous wall sections, slots and scoops which are distributed at designated locations predicted for boundary layer separations which SBLIs are likely to occur. The locations are along the compression ramp, cowl and sidewall of the intake.

Numerical investigation of different bleed models for a mixed compression inlet has been reported by Mizukami, et al[3] and Vivek and Mittal[4]. Gawienowski[5] conducted series of experiments with different bleed slot size and mass flow rates to assess the performance of an external compression intake at supersonic speeds. Pressure recovery and distortion levels were estimated and it was found that increasing the bleed slot area as well as the bleed mass flow increases the intake performance. Selection of bleed hole geometry and its inclination for an effective and efficient bleed system is reported by Syberg, et al[6]. The effect of different bleed system at various locations on hypersonic intake is studied by Pandian, et al[7]. Shock wave-boundary layer with bleed slot interaction studies were reported by Hamed, et al[8].

SBLI control by air jet stream wise vortices studied by Ryszard Szwaba [9]. This shows that stream wise vortices influence the static pressure level downstream of the shock wave, which implies reduction of separation. The vortices cause the entertainment of higher momentum fluid into the lowest sub-layers of a boundary layer, which counteracts separation. The streamwise vortices penetrate the separation area and are terminated at the reattachment line.

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C. *Cowl deflection*

Effect of cowl deflection angle has been studied by Das and j. k. Prasad [10], to capture the overall flow field and performance of intake for free exit flow and with back pressure. For free exit flow , increase in cowl deflection angle increases the overall performance, however for pressurized exit flow, small cowl deflection angle of the order of 2° leads to improvement in performance. Due to flow separation in the larger area of the intake due to back pressure, the flow gets distorted at the exit plane. It is also observed that improvement in performance with cowl deflection of around 2º is comparable to performance with 2.8% bleed; hence the cowl deflection could be also as an alternative to bleeding.

Figure 2. Density gradient contour using *k*-w turbulence model Flow unstart without cowl bending[10]

Figure 3. Density gradient contour using *k*-w turbulence model for q = 2° Flow start with cowl bending[10]

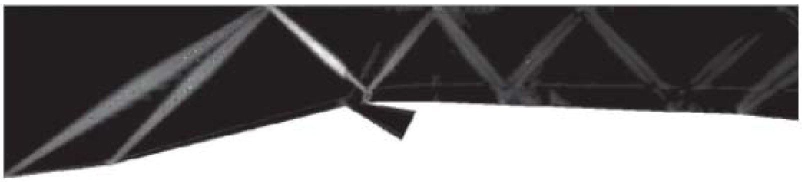


Figure 4. Density gradient contour for bleed using *k*-w turbulence model Flow start with cowl bending[10]

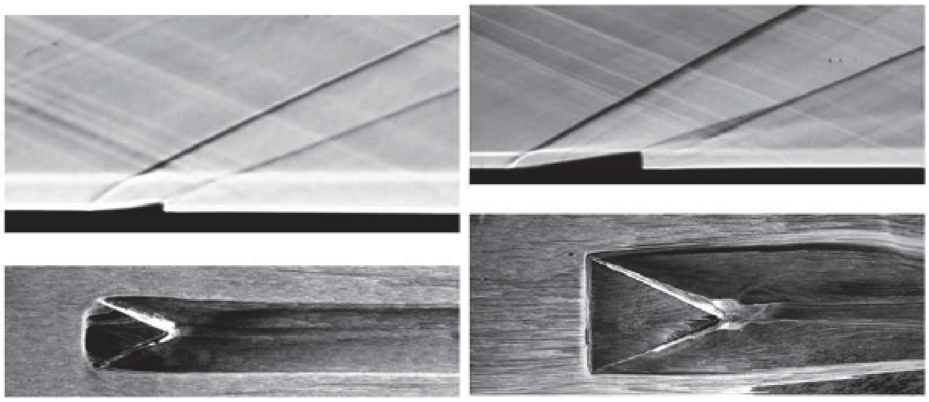
Donde ,et al[11] carried out numerical simulations of a starting problem in a variable geometry hypersonic intake with a movable cowl. Dynamic meshes have been used for depicting motion of the cowl. It was shown that the cowl needs to be rotated through 15.7° and then be brought back to the original position for restarting of the intake after an 'unstart'. The free stream Mach number for which intake unstarting occurs is found out from the sudden drop in the mass capture ratio. It is observed that wall boundary condition for temperature (adiabatic or isothermal) has a pronounced effect in determining the starting Mach number. Computed free stream Mach number for which unstarting occur is higher for adiabatic condition compared to isothermal condition. Heated boundary layer for adiabatic condition is seen to cause large separation bubble at the intake entrance causing flow unstarting; while flow separation bubble is not observed for isothermal condition for same free stream Mach number.

D. *Vortex generators-*

The vortex generator devices are placed upstream of the shock and produces counter-rotating vortices that transfer high momentum flow from the outer region into the low momentum flow near the wall. This will in produce a more energize boundary layer and high resistance to adverse pressure gradient. Flow field analysis inside the mixed compression inlet was found to be within acceptable tolerances of the available data by Vivek V. Kumar, Surendra Bogadi [12]. There was little variation in the flow field results between inviscid and laminar flows. This was due to the low molecular viscosity 1at the altitude considered ($\mu=1.5287 \times 10^{-5}$ kg/ms) and consequently a thin boundary layer. The line and contour plots presented in the report have given considerable amount of information on the nature of the flow field existing within the inlet. The comparison between the mixed inlet and the inlet with MVG shows the thinning of separation occurring in the case of mixed inlet with MVG. The amount of pressure is also gaining in the case of MVG and thereby proper compression for efficient combustion.

Micro-Ramps: The micro-ramp is a novel flow control device that is a part of the micro-vortex generator family. It has recently shown great potential in controlling the adverse phenomena. The term micro relates to the device having the height less than the boundary layer thickness. In most present literatures, the height range of the micro-ramp is between 30% to 90% of boundary layer thickness. Due to the small size, the micro-ramp is embedded inside the boundary layer hence reducing the parasitic drag compared to the conventional full size vortex generator.

The study on the effect of the micro-ramp height was done by Babinsky et al. [13]. It was shown that the height has little effect on the fundamental flow development specifically the region downstream of the device. After comparing experimental results of different heights from both surface flow visualization and pressure ratios, it can be deduced that the main flow features are almost identical. When comparing the stream wise effect, all of the micro –ramps with different heights also showed similar development in momentum exchange behavior. The flow development although similar but still vary with height. The flow development over microramps cane seen from figure 5 and pressure recovery can be seen from figure6.



(a) 2mm micro-ramp (b) 6mm micro-ramp

Figure 5. Schlieren photograph and surface flow visualization [13].

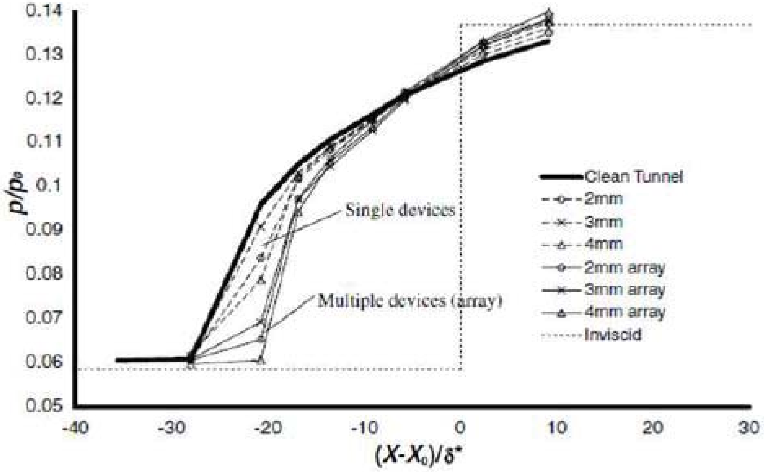


Figure 6. Centerline surface pressure for interaction controlled by 3mm micro-ramp for both single and array configurations [13].

IV. CONCLUSIONS

There are four main conclusions that can be made from the literature review:

1. All of the investigations had shown improvements in the boundary layer health compared to their baseline results. The boundary layer separations due to the shock-impingements were able to be suppressed. Yet, there is still no evidence at the moment that which technique can enable to completely prevent or diminish the separations.
2. The potential of various techniques in improving the boundary layer health and suppressing the SBLIs have been given extensive attention by experimentalists. This can be seen from the numerous types of experimental methods conducted such as schlieren photography, Particle Image Velocity me try (PIV), oil-flow visualization, laser Doppler anemometry (LDA) and not forgetting the conventional pressure tapings measurements.
3. All of the work has been done for certain design Mach numbers. A full fledge investigation is required to enhance operating range of Scramjet engine which can be done by CFD simulations.
4. The investigations on the effect of micro-ramps are done for supersonic conditions. However, there are still no investigations being made in hypersonic flows. The geometries of micro-ramps used in the investigations are also obtained from the optimization made in supersonic condition.

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