Chapter

# Design and Performance of Hypersonic Intake for Scramjet Engine

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## Abstract

Rockets are the only vehicles to reach hypersonic speeds with non-airbreathing engines carrying both fuel and oxidizer increasing budget of space exploration. So, the desire to achieve hypersonic speeds at low cost has led to the development of air-breathing engines known as supersonic combustion ramjet engines or scramjet engines. The most complex part in the development of the scramjet engine is the intake. Free-stream hypersonic speed flow will be compressed in intake and processed into the combustor as per the required pressure and temperature. The high-pressurized flow can be provided to the combustor based on the strength of shocks attained in the intake due to ramps. So, the design of intake depends on the number of ramps and the angle of ramp, which decides the strength of shock for compression. All the scramjet intakes designed based on oblique shock theory will start efficiently in the designed conditions, but the main problem is unstarting the performance of intake at off-design conditions. It is very important to know the flow behavior at off-design conditions to enhance the operating range of the engine. So, in this chapter, a detailed procedure for the design of hypersonic intake and techniques to mitigate the unstarting conditions of scramjet engines is discussed.

**Keywords:** intake, shock wave angle, deflection angle, Kantrowitz limit

## 1. Introduction

The major parts of scramjet engine and the flow process is shown in **Figure 1**. Scramjet engine propels the vehicle at hypersonic speeds, that is, at M > 5. The scramjet combusts the flow at supersonic speeds; thus, the free-stream hypersonic flow has to be reduced to supersonic speeds through air-intake, which compresses the flow [1]. The performance of a 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. As speeds increased, the simple inlets used in the early years could no longer provide efficient compression and still produce meaningful thrust, because the total pressure loss incurred was too great. New techniques are needed to be found in order to

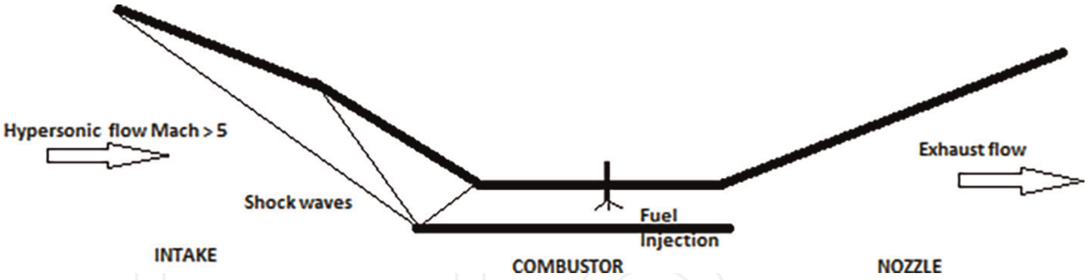

**Figure 1.**
*Schematic diagram of scramjet engine geometry [1].*

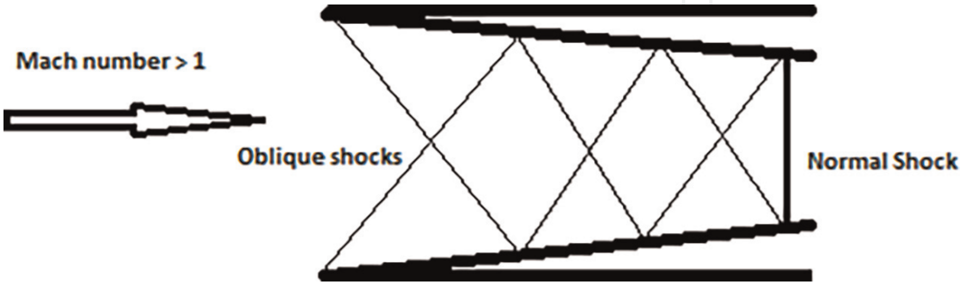

**Figure 2.**
*Example of an internal compression inlet [1].*

improve the efficiency of inlets. The use of oblique shocks was a likely answer to the question, but the exact technique for use was not as clear. Emerging from this idea were the internal, external, and mixed compression inlets (**Figures 1** and **2**).

### 1.1 Internal compression inlet

In an internal compression inlet, the shocks are first reflected inwards from a wall toward the centerline of the inlet, similar to that shown in **Figure 2**. This guarantees that at least one shock wave-boundary-layer interaction will occur, not counting those for the normal shock. Some form of boundary layer control is needed to make these inlets effective, but these are uncommon on aircraft because of the complexity required in the design, and the need for multiple operating point designs.

### 1.2 External compression inlet

External compression inlets, like that shown in **Figure 3**, have been the “go-to” solution for many years. They are the simplest in principle but have some complexity in their design, and variable geometry is needed for these inlets. The plates, the bleed, and the mechanisms for the variable geometry ramps tend to increase weight, and are the enemy of performance in all aircrafts. So, while the system worked, improvements could be made to make designs rely less on their heavy features. The bleed and mass spillage also add a fair amount of drag to the inlet, since subsonic air needs to be discharged into a supersonic free stream. In external compression inlets, there is not an oblique shock boundary-layer interaction, rather bleed is needed at the root of the oblique shock to help control the separation that occurs.

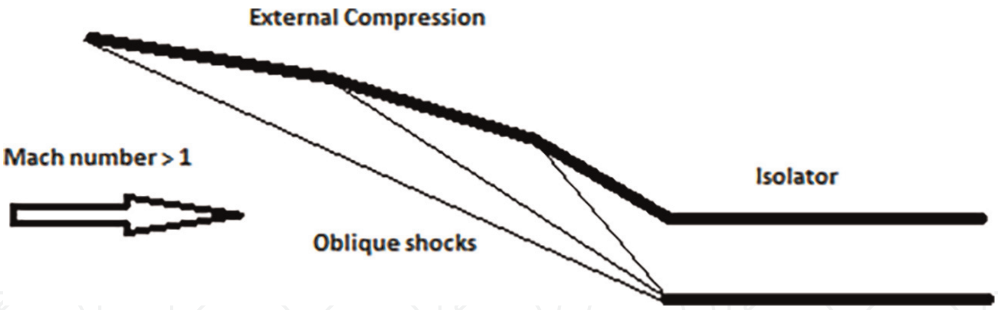

**Figure 3.**
*Sketch of an external compression inlet [1].*

### 1.3 Mixed compression inlet

A mixed compression inlet, like that shown in **Figure 4**, combines both the internal and external compression inlets. Initially, one or more oblique shocks form that miss the inlet lip (like an external compression inlet). After that, one or more shocks reflect inward toward the centerline of the inlet (like an internal compression inlet). This type of inlet is generally used only for higher Mach number aircraft (M = 2.5 and above) because of the increased design complexity. Very few of these high Mach aircraft have been made, with the SR-71 as the only one ever in production. However, mixed compression inlets have been used for several experimental aircrafts, such as the X-43a and the XB-70. The number of oblique shocks used in inlets has slowly increased over time. At first, a single oblique shock was used, but the Mach number was relatively small, approximately 1.6. As top speeds increased, to Mach numbers above 2, two shocks started to be used as well as variable geometry ramps to adjust shock angles and shock standoff distance. The F-14 and F-15 were some of the first to use a set of three oblique shocks in their inlet capture systems. The theory states that the more oblique shocks in the inlet, the lower the total pressure loss through the compression system.

### 1.4 Hypersonic intakes

Mixed compression intake is used for the design of hypersonic intakes. It is a blend of external and internal compression. The main function of intake is to compress the flow and supply the required pressurized flow to the combustor following a bow shock

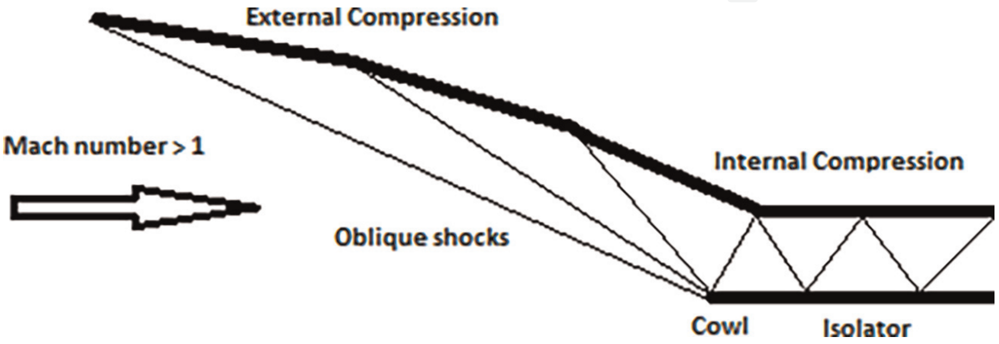

**Figure 4.**
*Sketch of mixed compression inlet [1].*

at the forebody of the vehicle and the multiple number of oblique shocks through the ramps of internal and external compression. These waves will coalesce at the cowl leading edge for the design of Mach number satisfying shock-on-lip condition. As the flow deflects through the several ramps of external compression, thus the flow is deflected back into the axial direction through reflected shocks and cowl leading edge shock in the internal compression region and isolator. The reflected shocks interact with the boundary layer of the walls, such as ramp, cowl, and isolator. This interaction leads to a flow separation region, and the level of separation is influenced by the strength of the reflected shock and the thickness of the boundary layer along wall surfaces.

Scramjet engine starting Mach number is 5. So, the engine has to be integrated with turbojet and ramjet to achieve Mach 5 speed. The intake of the scramjet engine has to be designed to withstand shock waves due to the hypersonic speed of Mach 5. The intake starts efficiently at the designed condition but at off-design conditions, it leads to the "unstarting problem," which means the flow turns to subsonic due to normal shock or shock wave boundary-layer interaction. So, the starting and unstarting of hypersonic intake play a vital role in knowing the operating range of the scramjet engine.

### 1.5 Starting of intakes

The inlet total pressure recovery, including both shock and viscous losses, is the governing factor determining the starting of these inlets; this is in contrast to the generally accepted criterion of considering contraction ratio based only on normal-shock pressure recovery, which is applicable to inlets with relatively thin boundary layers. Although boundary-layer separation in the vicinity of the cowl lip station does not appear to directly govern starting by adversely affecting the contraction ratio, it does significantly affect the inlet pressure recovery by increasing the viscous losses through mixing. The geometric and aerodynamic parameters investigated also affect starting by their effect on the pressure recovery. The total-pressure recovery required for starting these inlets can be predicted reasonably well by a one-dimensional analysis; however, at present, there is no accurate means of predicting the total-pressure recovery, accounting for separation and viscous losses as well as internal shock losses, for a given configuration. Basic data are provided, which can be used to verify future empirical or theoretical methods to predict inlet-pressure recovery, and thus starting conditions.

### 1.6 Unstart of intakes

Unstarting of intake is the major challenge of hypersonic intake, which is to be addressed. It describes the chocked flow due to a very low area ratio of the throat to intake with an increase in Mach number. Mostly, the unstart of the intake is detected through the ejection of the shock system and spillage of mass flow, which leads to reduced pressure recovery and also huge distortion in the flow. This type of flow phenomenon will lead to a catastrophic effect on the scramjet performance.

The unstart of the intake is due to numerous reasons, such as over contraction, off-design conditions, fluctuations in operation of the combustor, and back pressure, or maybe because of the combined result of these factors. One of the major causes for unstarting is flow separation due to shock wave-boundary-layer interaction and develops the boundary-layer thickness in the isolator duct. Generally, supersonic intakes use a bled system, and varying intake geometry by cowl angle is used to start intake. Because of high enthalpy and total temperature in hypersonic flows, the mechanical designed control methods have to sustain severe structural problems and need cooling techniques.

## 2. Design of hypersonic intake

The design of hypersonic intake is a very complex method because of multiple shocks in the intake. So, the design procedure should consider the adoption of oblique shock relations. The subsequent intake geometry has to undergo the possibility of starting flow characteristics. If the intake fails to start, then the design has to be changed.

The design of hypersonic intake has to consider the following points:

1. The starting Mach number of intake should be less than the cruise Mach number, and the flow should be uniform while entering into the combustor over a wide range of flight envelope.

2. The intake has to satisfy Oswatitsch and Kantrowitz criteria.

3. The shocks from ramps should be of equal strength with minimum total pressure loss.

4. The design should be flexible to have good performance in off-design conditions also.

5. The geometry has to be easily analyzed using analytical and computational methods.

6. The mass flow spillage should be minimum without affecting starting of intake.

7. The design of intake has to ensure minimum external drag.

8. The aerodynamic stability of intake depends on the forces generated in all directions due to changes in the angle of attack. So, these forces must be as small as possible.

9. The designed intake has to sustain extensive acceleration, large internal pressure, and huge heat transfer without varying geometry of intake.

The known fact is that a better range of intake starting is attained with a less Mach number and has low efficiency with adequate thrust designed for the missile/vehicle to launch from its parent engine than an intake starts with a high Mach number for high efficiency. This emphasizes the efficiency of the intake and its performance parameters will not be the deciding negotiators in the selection of intake for a definite mission. A detailed study of these negotiations and trade-offs should be analyzed along with other engine parameters for designed conditions, which does not lead to the finest performance but somewhat needs design negotiations to enhance the scramjet mission requirements.

The intake is made into three divisions and named ramps, cowl, and isolator. In intake, the compression process taken due to ramps by shocks is known as external compression and compression due to cowl, and isolator by the reflection of a series of shocks is known as internal compression. The isolator is a constant area duct that functions to reduce the disturbances in the flow caused due to combustion process and mitigates it to further propagation toward the cowl and forebody of intake. So, the design of three components fulfills the design of intake.

The design of the intake gives the efficiency and performance of the intake. The design starts with requirements of scramjet for combustion process, such as the amount of pressure, that is, compression with minimum total pressure loss and drag. Michel K Smart has stated a minimum of 50 is required for scramjet to attain hypersonic speeds [2]. Thus, as this amount of compression cannot be achieved by a single ramp, the number of internal and external shocks will decide the number of ramps for the design of intake. This illustrates the dependence of intake performance on the number of shocks, but the isentropic condition restricts the number of shocks. Furthermore, the number of shocks will increase the number of ramps with lower deflection angles and increase the length of the intake adding drag and weight to the scramjet. Considering above points to simplify the design of intake, it is divided into two sub-steps, (i) deflection and shock wave angles, and (ii) intake geometry.

## 2.1 Deflection angle ($\theta$) and shock wave ($\beta$) angles

The Oswatitsch criterion says to improve the efficiency of the intake and the shocks should be of equal strength to generate an equal pressure ratio throughout multiple shocks [3]. So, the intake compression efficiency depends on deflection and shock wave angles, which are by using gas dynamic relations with the following iterative procedure.

The free-stream Mach number of the scramjet intake is $M_1$ and the throat Mach number should not be less than half of the free-stream Mach number to evade the flow separation as given by Mahoney [4].

The two stages of intake, external compression and internal compression corresponding flow deflection angles, are calculated separately. The design of both stages is independent excluding the static pressure ratio, which is the combined effect of the compression process in both stages. To attain minimum total pressure loss across a shock, weak shocks with a low static pressure ratio are preferred. This leads to low deflection angles. So, in this iterative procedure, the initial static pressure ratio ($P_2/P_1$) assumed is 0.01 and total pressure ratio ($P_{t2}/P_{t1}$) is 1.0, and the respective shock wave angle, deflection angle, and Mach number across the shock wave are found with the input of the free-stream Mach number using the following oblique shock relations.

The pressure ratio is given by:

$$\frac{P_2}{P_1} = 1 + \frac{2\gamma}{\gamma + 1}\left(M_{n1}^2 - 1\right) \tag{1}$$

$$\mathrm{Mn1} = \mathrm{M1}\sin\ \beta \tag{2}$$

Substitute Eq. (2) in Eq. (1).

$$\beta = sin^{-1}\left[\sqrt{\frac{\left(\frac{P_2}{P_1} - 1\right)\left(\frac{\gamma+1}{2\gamma}\right) + 1}{M_1^2}}\right] \tag{3}$$

Eq. (3) gives shock wave angle for a given Mach number.

To find the deflection angle the θ-β-M relation is used.

$$tan\theta = 2cot\beta\left[\frac{M_1^2 sin^2\beta - 1}{M_1^2\ (\gamma + cos^2\beta) + 2}\right] \tag{4}$$

The static pressure ratio from Eq. (1) for the former shock wave is fixed with reference to the Oswatitsch criterion and further used for the subsequent shocks and the properties across each shock wave are calculated by using the above oblique shock relations. This procedure is repeated for all the shocks in the external compression. Once all the calculations for each and every shock wave are done, the Mach number behind the last external shock wave is compared with the defined Mach number after the external compression, that is, $M_e$. If both are not matching, then the above procedure has to be iterated continuously by step-by-step increase in the static pressure ratio till the Mach number after external compression matches with $M_e$. The turning angles for the external compression are concluded if the above condition is satisfied.

Similarly, the turning angles of the internal compression are also calculated using the same iterative procedure assuming the static pressure ratio obtained after external compression as the initial guess. This iteration process is repeated continuously to match the exit Mach number of internal compression to half of the free-stream Mach number by an increase in the static pressure ratio. The actual static pressure ratio and total pressure ratio of the intake are obtained by multiplying the properties considering all the shock waves of both internal and external compressions. Optimum turning angles are generated for maximizing the total-pressure recovery for given operating conditions.

Now, the second step in the design process of intake is to find the linear dimensions of intake, such as lengths of the ramps and height, which fixes the location of the shocks for the compression. While calculating the lengths, shock-on-lip condition is to be considered, which means the shocks from ramps have to impinge on the cowl at the same point as shown in **Figure 5**. In the **Figure 6**, points a, b, and c are for the external

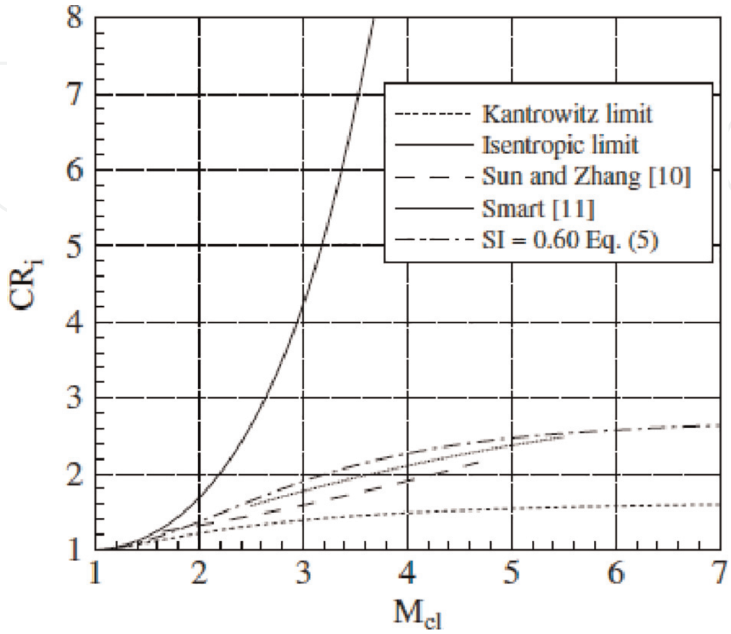

**Figure 5.**
*Plot against internal contraction ratio and cowl Mach number using empirical relations [5].*

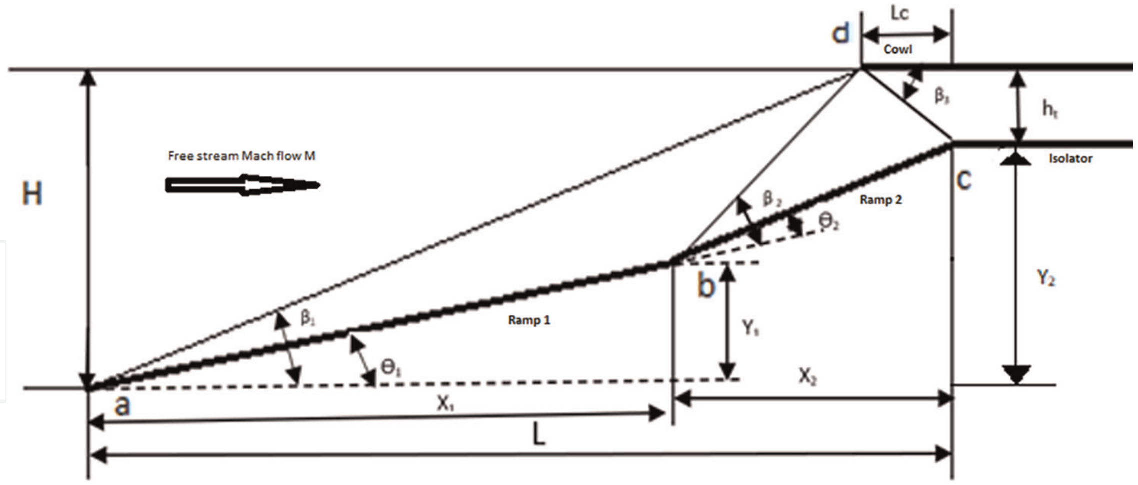

**Figure 6.**
*Schematic diagram of scramjet intake with geometrical parameters.*

ramp, and points d and e are for the cowl. The ramps and cowl together will generate two external shocks and one internal shock. However, the number of shock waves is of any number of combinations with respect to external/internal compression satisfying the pressure requirement for combustion.

Deflection angles for first, second ramps, and cowl are denoted by $\theta_1$, $\theta_2$, $\theta_{3,}$ and shock wave angles are $\beta_1$, $\beta_2$, $\beta_3$, respectively, which are calculated using oblique shock relations as stated in the design procedure.

## 2.2 Linear dimensions of scramjet intake

In the performance of intake, drag estimation is an important parameter and the length of the intake leads to skin friction drag, and also, the external/internal oblique shocks have to intersect at the cowl leading edge point to avail maximum capture area to reduce the spillage drag or losses satisfying shock-on-lip condition. Point d is the leading-edge point of the cowl known as the cowl lip at which the external shocks meet. To reduce the intake length, point d is chosen as the point where the first external oblique shock meets the horizontal line drawn from e. Similarly, all the internal shocks meet at shoulder point c. The trigonometric relations are used to calculate the length of ramps, cowl, and coordinates of the intake geometry, and the procedure is as follows:.

From the isentropic limit of contraction ratio, that is, $CR_{isen}$.

$$CR_{isen} = \frac{A}{A^*} = \frac{1}{M}\left[\frac{2}{\gamma+1}\left(1+\frac{\gamma+1}{2}M^2\right]^{\frac{\gamma+1}{2(\gamma+1)}} \tag{5}$$

From Kantrowitz limit the contraction ratio is $CR_{kantr}$.

$$CR_{kantr} = \frac{A}{A^*} = \left[\frac{(\gamma+1)M^2}{(\gamma-1)M^2+2}\right]^{0.5}\left[\frac{(\gamma+1)M^2}{2\gamma M^2-(\gamma-1)}\right]^{\frac{1}{(\gamma-1)}} \tag{6}$$

In the intakes, the external compression considers the overall contraction ratio with respect to free stream Mach number, and for the internal contraction ratio, Mach number close to cowl is chosen. The internal contraction is given as the ratio of the cowl cross stream area to the throat area and variation of $CR_i$ with respect to Mach number is shown in **Figure 5**.

$$CR_i = \frac{A_{cl}}{A_t} \tag{7}$$

Kantrowitz criterion gives an important design parameter of intake, that is, the isolator height using the above relations. It has been categorized into three regions based on the contraction ratio values as follows:

i. If $CR > CR_{isentr}$ in which the starting of intakes is impossible;

ii. If $CR < CR_{Kantr}$ in which the self-starting of intakes is possible according to the Kantrowitz theory;

iii. The intakes work efficiently once it is started and this is a critical region.

Based on the above CR value for a given Mach number for a 2-dimensional design CR can be considered with respect to height at the respective locations.

$$CR_i = \frac{A_{cl}}{A_t} = \frac{h_{cl}}{h_t} \tag{8}$$

The length of the cowl is given by the following:

$$\tan(\beta_3) = \frac{h_t}{L_c} \tag{9}$$

Assume the value of the length of intake L, and calculate the height H using the following relation:

$$\tan(\beta_1) = \frac{H}{L - L_c} \tag{10}$$

$$x_1 = \frac{H - (L - L_c) * \tan(\beta_2 + \theta_1)}{tan\,\theta_1 - \,tan\,(\beta_2 + \theta_1)} \tag{11}$$

$$y_1 = x_1\,tan\,\theta_1 \tag{12}$$

$$x_1 + x_2 = L \tag{13}$$

$$\tan(\theta_1 + \theta_2) = \frac{y_2 - y_1}{x_2} \tag{14}$$

$$y_2 = y_1 + x_2 * \tan(\theta_1 + \theta_2) \tag{15}$$

With the above relations, we can calculate the first and second ramp points, that is, $(x_1, y_1)$ and $(x_2, y_2)$.

## 3. Performance of scramjet intake

Scramjet intake performance is evaluated with respect to its total pressure ratio and kinetic energy efficiency. These two are the performance parameters derived based on quasi-one-dimensional flow through the Intake. In **Figure 1**, the free-stream flow is indicated by station 0, that is, the captured free-stream flow before the compression, and station 3 in the figure indicates the downstream flow through the internal compression of intake and followed by the isolator connecting to the combustor. The flow properties at all stations are used to calculate performance parameters.

### 3.1 Total-pressure recovery, $\pi_c$

Total-pressure recovery, $\pi_c$, is defined as the ratio between the total pressure at station 3 to the total pressure at station 0. It establishes the loss in total pressure due to shock waves in the internal and external compression process. The total pressure recovery parameter indicates the sum of total pressure loss due to each shock wave. Total-pressure recovery is also severely inclined by shock wave-boundary-layer interactions, and to a slighter range by the viscous loss as the flow deteriorates due to the no-slip state at the surface of the ramps, isolator, or cowl walls. The following equation is used to calculate $\pi_c$:

$$\pi_c = \frac{p_{t3}}{p_{t0}} \tag{16}$$

### 3.2 Kinetic energy efficiency, $\eta_{KE(ad)}$

Kinetic energy efficiency, $\eta_{KE}(ad)$, is defined as the ratio of the kinetic energy of the flow at station 3 to the kinetic energy of the free-stream flow, if it stayed to be expanded isentropically to free-stream pressure. This parameter quantifies the productivity of the compression process with respect to energy supervision. In scramjet engine, the kinetic energy possessed at hypersonic speeds is enough to produce the required thrust by enhancing the flow velocity through the nozzle. The loss in kinetic energy due to compression will obviously affect the thrust and efficiency of the engine. The equation for calculating $\eta_{KE}$ is:

$$\eta_{KE} = 1 - \left(\frac{2}{\gamma - 1}\right)\left(\frac{1}{M_0^2}\right)\left[\left(\frac{T_x}{T_0}\right) - 1\right] \tag{17}$$

$$T_x = T_{03}\left(\frac{p_0}{p_{03}}\right)^{\frac{\gamma-1}{\gamma}} \tag{18}$$

### 3.3 Compression process efficiency, $\eta_{C(ad)}$

The overall efficiency and specific impulse of the engine depend on the efficiency of the compression process, $\eta_{C(ad)}$. The overall compression efficiency gives the amount of energy used up during the compression process. It is defined as the ratio of the total energy of the flow at station 3 to the initial energy of the flow captured at station 0 from free stream. This value of $\eta_{C(ad)}$ is calculated by:

$$\eta_{c(ad)} = 1 - \frac{(\gamma - 1)M_0^2}{2}\left(\frac{1 - \eta_{KE(ad)}}{\frac{T_3}{T_0} - 1}\right) \tag{19}$$

## 4. Challenges in scramjet intake at off-design conditions

The scramjet intake works efficiently at designed conditions but the major challenges that come across at off-design conditions are shock wave-boundary-layer interactions (SBLI), flow spillage, etc. Out of these problems SBLI is very harmful to the structure of intake and starting of intake. So, in this section, a detailed explanation about the formation of SBLI and the methods are suggested to mitigate the flow separation due to SBLI.

### 4.1 Shock wave-boundary-layer interactions

Shock wave-boundary-layer interactions are a phenomenon when a shock wave meets a boundary layer and it can be found in most of high-speed flows. The typical case of SBLI is when a generated shock wave impinges on a surface where the boundary layer is developed as shown in **Figure 7**. As a result, the shock imposes a severe adverse pressure gradient toward the boundary layer causing it to eventually thicken and creating the possibility of separation. In most cases, SBLI also causes flow unsteadiness. The consequences of the phenomena are found to be detrimental, especially in high-speed flows. In hypersonic flows, SBLI causes intense localized heating due to high Mach numbers that can be severe enough to destroy the body of the aero vehicle.

### 4.2 SBLI control mechanisms

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 stabilize the oscillating shock. The momentum of the turbulent boundary layer appears to be an important factor affecting the upstream turbulence of the shock as well as the resistance of the boundary layer toward 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.

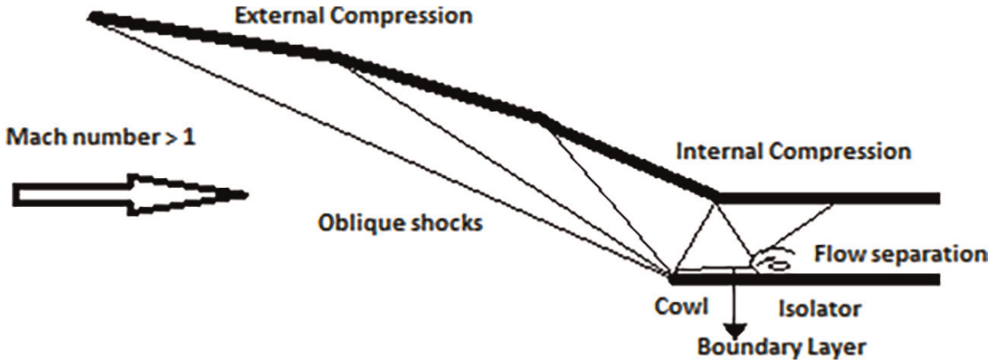

**Figure 7.**
*Schematic diagram of shock wave-boundary-layer interactions in a typical hypersonic inlet [1].*

### *4.2.1 Bleed system*

Currently, this is one of the most popular techniques due to its effectiveness. The introduction of the bleed system is aimed to suppress the boundary-layer separation induced at the impinging of shock wave with boundary layer by removing the low momentum portion of the boundary layer as shown in **Figure 8**. 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 in which SBLIs are likely to occur. The locations are along the compression ramp, cowl, and sidewall of the intake (**Figure 8**).

Numerical investigation of different bleed models for a mixed compression inlet has been reported by Mizukami et al. [6] and Vivek and Mittal [7]. Gawienowski conducted a series of experiments with different bleed slot sizes and mass flow rates to assess the performance of an external compression intake at supersonic speeds [8]. 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. The selection of bleed hole geometry and its inclination for an effective and efficient bleed system are reported by Syberg et al. [9]. The effect of the different bleed systems at various locations on hypersonic intake is studied by Pandian et al. [10]. Shock wave-boundary-layer with bleed slot interaction studies were reported by Hamed et al. [11]. The bleed system can be introduced in the following ways:

- Mass injection

- This is done by applying fluid injection through a porous plate or several slots positioned upstream of the shock impingement location.

- Distributed suction

- This is applied at a certain distance upstream (usually specified in the scale of the boundary-layer thickness,) of the shock impingement. This will lower the shape parameter; hand produces a fuller velocity profile and a more robust boundary layer toward separation.

- Localized suction

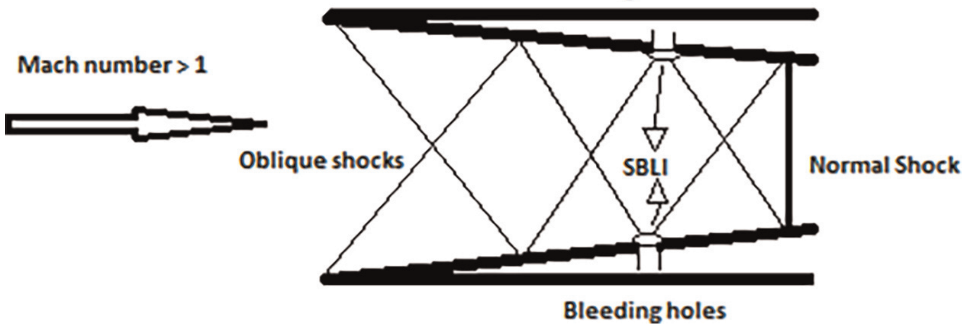

**Figure 8.**
*Internal compression inlet with bleed holes.*

- This type of suction is applied locally inside the interaction region or in the immediate vicinity. It is done by drilling holes perpendicularly to the surface.

#### *4.2.2 Cowl bending*

The cowl of intake is deflected to attain a variable intake geometry angle to enhance the operating range of intake as analyzed by Das and j. k. Prasad [12]. The analysis is carried out to understand the flow phenomenon and performance characteristics of intake with permissible exit flow and back pressure. For permissible exit flow, increasing the deflection angle of the cowl will increase the performance, but due to pressurized flow at the exit, a small change in the angle of the cowl in the direction of 2° enhances the performance. But for subsequent flow separation in the bigger region of the intake because of back pressure, the flow will be distorted at the intake exit.

#### *4.2.3 Vortex generators*

The vortex generator devices are placed upstream of the shock and produce counter-rotating vortices that transfer high momentum flow from the outer region into the low momentum flow near the wall. This will produce a more energize boundary layer and high resistance to an 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 and Surendra Bogadi [13]. There was little variation in the flow field results between inviscid and laminar flows and it was due to the low molecular viscosity at the altitude considered and consequently a thin boundary layer. The line and contour plots presented in the report have given a 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 the mixed inlet with MVG. The amount of pressure is also gaining in the case of MVG and thereby proper compression for efficient combustion (**Figure 9**).

#### *4.2.4 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 adverse

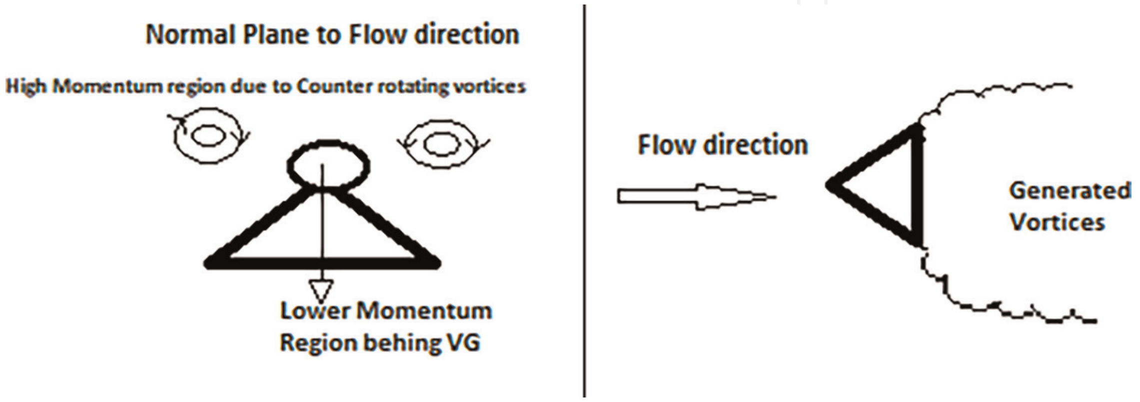

**Figure 9.**
*Flow over vortex generators in normal plane and along flow direction.*

phenomena. The term micro relates to the device having a height less than the boundary-layer thickness. In most present literature, the height range of the micro-ramp is between 30% and 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 with the conventional full-size vortex generator.

The study on the effect of the micro-ramp height was done by Babinsky et al. [14]. It was shown that the height has little effect on the fundamental flow development specifically in 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 a real most 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 however similar but still vary with height. Ashill et al. [15] also agree with this conclusion and stated that flow by smaller devices develops and evolves more quickly than larger devices. Hence, high momentum fluid is moved to the near-wall regions in a shorter period of time. Therefore, practically it would be beneficial to locate smaller devices in certain regions that require more flow control.

### *4.2.5 Stream-wise vortices*

Shock wave-boundary-layer interaction control by air jet stream-wise vortices was studied by Ryszard Szwaba [16]. This shows that stream-wise vortices influence the static pressure level downstream of the shock wave, which implies the reduction of separation. The vortices cause the entertainment of higher momentum fluid into the lowest sub-layers of a boundary layer, which counteracts separation.

## 5. Conclusions

This chapter explains the importance of intake to achieve hypersonic speeds by a scramjet engine. Scramjet is the only air-breathing engine, which mostly depends on the quality of air given for combustion by intake to achieve hypersonic speeds. So, the major focus is given on the design of hypersonic intake for scramjet engine with an analytical method for preliminary design. The chapter also emphasizes on the performance parameters of a scramjet. The importance of shockwave-boundary-layer interaction and its effects on starting of intake are explained with methods to control it.

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## Appendices and nomenclature

| | |
|---|---|
| M | Mach number |
| p | Pressure (Pa) |

| | |
|---|---|
| T | Temperature (K) |
| $\beta$ | Shock wave angle relative to flow direction upstream of shock |

## Degrees

| | |
|---|---|
| $\gamma$ | Air-specific heat ratio |
| $\eta_{C(ad)}$ | Compression process efficiency |
| $\eta_{KE(ad)}$ | Kinetic energy efficiency |
| $\pi_c$ | Total-pressure recovery |
| $\theta$ | Flow turning angle relative to initial flow direction (degree) |
| H | Height of intake |
| L | Length of intake |
| $h_t$ | Height of isolator |
| $L_c$ | Length of cowl |
| $A_{cl}$ | Area near cowl |
| CR | Contraction ratio |
| SBLI | Shock wave-boundary-layer interaction |

## Subscript

| | |
|---|---|
| t | Stagnation flow condition |
| x | x-coordinate |
| y | y-coordinate |
| 0 | Station 0 at free-stream |
| 3 | Station 3 at isolator exit |
| * | Entrance of isolator |

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