

COMPARATIVE ANALYSIS OF RAMP-TYPE AND BUSEMANN INTAKES FOR HYPERSONIC AIR-BREATHING ENGINE

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ABSTRACT

Analytical results obtained through gas dynamics relations are conventionally used to generate preliminary designs of scramjet intakes. Ramp-type configurations (mixed compression type) are common among scramjet intake geometries. These are known to produce adequate thrust with minimum length/weight. However, there is a scope for improvement in total pressure recovery. The Busemann intakes have been shown to have much larger total pressure recovery values, thus being more efficient.

In present work, we take a two-ramp mixed compression scramjet intake designed for freestream Mach number 6.5 satisfying shock-on-lip condition. The isolator Mach number is 3.12 with a total pressure recovery of 0.52. A range of Busemann intakes are designed for the same free stream and isolator Mach numbers and varying truncation angles. The Busemann intake with truncation angle of 6° is considered for further analysis based on length and total pressure recovery criteria. The analytical results along with numerical simulations are compared for ramp-type and Busemann intakes.

INTRODUCTION

Scramjet is an air-breathing engine used in the hypersonic flights wherein the incoming air is compressed to high pressure due to the multiple shocks formed at the intake. This compressed air is fed to the combustor where supersonic combustion takes place and the exhaust gases exit through the nozzle at a very high speed. Scramjets are light in weight with high specific impulse and have greater maneuverability

compared to the rocket engines. The design of scramjets is mostly determined by their intakes. The primary purpose of the intake is to provide homogeneous high-pressure flow to the combustor with minimum aerodynamic losses. Scramjet intakes can be classified as: (i) external compression intake, (ii) internal compression intake, and (iii) mixed compression intake. The mixed compression intake is the most commonly used intake among the three due to its shorter length, higher pressure recovery and lower drag.

Recently, Busemann intakes have been the subject of substantial interest for hypersonic air-breathing propulsion applications. This is because of the low wetted-area to volume ratio. One such intake is the Busemann intake [1, 2]. Its flow-field is axisymmetric and produces uniform flow at the outlet. The intake comprises of isentropic compression of the flow through a series of weak compression waves followed by a conical shock wave which turns the flow into the isolator. Within the isentropic portion of the intake, the flow obeys the Taylor-Maccoll equations for supersonic conical flow.

Objective of this paper is to study the impact of free-stream Mach number and truncation angle on the Busemann intake flow-field and determine the advantages/disadvantages that Busemann intakes have against the conventionally utilized ramp-type intakes. The criteria chosen for this purpose are total pressure recovery and kinetic energy efficiency. A detailed analysis of the flow structure in the Busemann intake is carried out using numerical computations.

In the next section, design procedure for generating Busemann intake geometries is explained in detail. The concept of truncation angle is discussed with results. Subsequent section

contains the description on the starting condition of intake with its contraction ratio and the analytical results that are obtained by solving the Taylor-Maccoll equation in the intake domain. Further, simulation results are discussed with relevant contour plots to gauge the impact of free-stream Mach number and truncation angle on the Busemann intake flow-field. Next section contains a comparative analysis of ramp-type and Busemann intakes and discusses the advantages and disadvantages that the Busemann intakes have over ramp-type intakes.

BUSEMANN INTAKE

Busemann intakes have an axisymmetric internal compression design. They consist of conically symmetric isentropic compression of flow followed by a free-standing conical shock wave, which is cancelled at the corner of the intake surface. The flow in the intake is therefore conically symmetric and obeys the Taylor-Maccoll equation used to obtain the flow-field over a cone. Symmetric nature of the flow leads to Busemann intakes producing uniform flow for the combustor. Presence of a single conical shock wave ensures an irrotational flow with minimal production of entropy, ensuring high performance. For the spherical coordinate system as shown in figure 1, the non-dimensionalised Taylor-Maccoll equation [1] for a calorically perfect gas is given as

$$U_R'' = \frac{U_R'^2 U_R + 0.2(1 - U_R^2 - U_R'^2)(U_R' \cot \theta + 2U_R)}{U_R'^2 - 0.2(1 - U_R^2 - U_R'^2)},$$

where U_R is the radial velocity (non-dimensionalised by the maximum velocity which can be achieved by expanding the flow to a temperature of absolute zero). The primes represent differentiation with respect to θ . Velocity in the θ direction is given by the irrotationality condition

$$U_\theta = U_R',$$

where U_θ is non-dimensionalised by the maximum velocity.

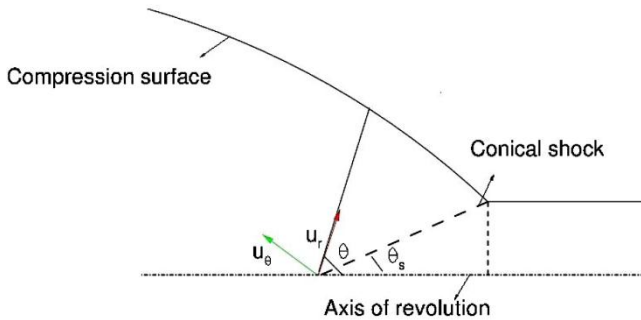


Figure 1: Schematic of Busemann intake

The flow-field in the intake is obtained through numerical integration of Taylor-Maccoll equation, starting from the downstream of the conical shock wave. The isolator Mach number (M_3) and the total pressure recovery (P_{t3}/P_{t0}) are specified beforehand. Subscripts 3, 2 and 0 stand for value of the parameter in the isolator (downstream of the conical shock wave), intake (upstream of the conical shock wave) and freestream respectively. The normal Mach number (M_{2n}) is a function of the total pressure recovery and we iterate to find $M_{2n} = f(P_{t3}/P_{t0})$ using

$$\frac{P_{t3}}{P_{t0}} = \left[\frac{(\gamma + 1)M_{2n}^2}{(\gamma - 1)M_{2n}^2 + 2} \right]^{\frac{\gamma}{\gamma - 1}} \left[\frac{(\gamma + 1)}{2\gamma M_{2n}^2 - (\gamma - 1)} \right]^{\frac{1}{\gamma - 1}}.$$

The conical shock wave angle is calculated as

$$\theta_s = \sin^{-1} \left(M_{3n} / M_3 \right),$$

where

$$M_{3n} = \left[\frac{(\gamma - 1)M_{2n}^2 + 2}{2\gamma M_{2n}^2 - (\gamma - 1)} \right]^{\frac{1}{2}}.$$

The total velocity downstream of the conical shock wave (non-dimensionalised by maximum velocity) is then obtained by

$$V_3 = \left[\frac{(\gamma - 1)M_3^2}{2 + (\gamma - 1)M_3^2} \right]^{\frac{1}{2}},$$

which is then used to find U_{R3} and $U_{\theta3}$ given by

$$U_{R3} = V_3 \cos \theta_s,$$

and

$$U_{\theta3} = -V_3 \sin \theta_s.$$

The Taylor-Maccoll equation is then integrated in the upstream direction with U_{R2} and $U_{\theta2}$ as initial values for U_R and U_θ respectively. U_{R2} and $U_{\theta2}$ are obtained just upstream of the shock, through the relations

$$U_{R2} = U_{R3},$$

and

$$U_{\theta2} = -V_3 \sin \theta_s \frac{(\gamma + 1)M_{2n}^2}{(\gamma - 1)M_{2n}^2 + 2}.$$

The angle formed by the freestream velocity vector and the local total velocity vector is called the truncation angle (denoted by δ). The numerical integration must be performed until the total velocity becomes equal to the freestream velocity i.e. δ becomes 0. The value of δ is calculated therefore at every step, with increasing values of θ (starting from θ_s), done through the following relation

$$\delta = \tan^{-1}(U_y/U_x),$$

where, U_y and U_x are the velocities in the y and x directions respectively in the Cartesian coordinate system. These are given in terms of U_R and U_θ as

$$U_x = U_R \cos\theta - U_\theta \sin\theta,$$

and

$$U_y = U_R \sin\theta + U_\theta \cos\theta.$$

Having obtained the velocities everywhere in the domain (the intake), we get the Mach number at all points through

$$M = \frac{V}{a},$$

where, V is the total velocity at a point and a is the speed of sound. Both are non-dimensionalised by the maximum velocity and are given as

$$V = [U_R^2 + U_\theta^2]^{\frac{1}{2}},$$

and

$$a = [(\gamma - 1)(1 - U_R^2 - U_\theta^2)/2]^{\frac{1}{2}}.$$

The value of Mach number when δ becomes 0 is the freestream Mach number (M_∞). To get the intake flow-field for the intended freestream Mach number, specific values for M_3

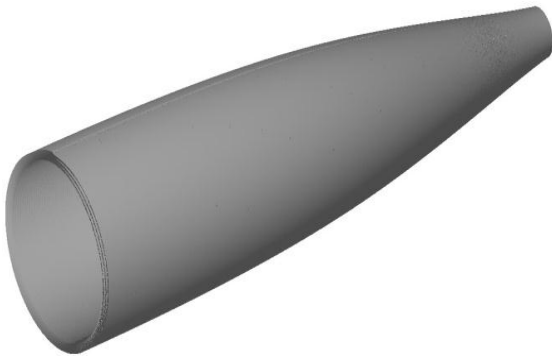


Figure 2: 3D Busemann intake geometry

and P_{t3}/P_{t0} must be found by carrying out the above exercise iteratively. Geometry of the Busemann intake, including the length and area ratio (A_3/A_0), however cannot be obtained through the Taylor-Maccoll equation alone. The following equation for r and θ when solved in conjunction with the Taylor-Maccoll equation will generate the geometry [3],

$$r = \frac{U_\theta}{U_R} \frac{dr}{d\theta}.$$

We therefore get a family of Busemann intakes, with varying M_3 , A_3/A_0 and P_{t3}/P_{t0} , for the same freestream Mach number. Suitable isolator Mach number can then be chosen to generate the geometry and flow-field for the Busemann intake for a given M_∞ . The resulting geometry would be similar to figure 2.

STARTING OF INTAKES

The starting problem is inherent to the internal compression scramjet engine. This is because the intake design does not allow the excess mass flow to spill overboard when necessary. For a fixed geometry and a set of operating freestream Mach numbers, an intake can have starting problem for certain contraction ratios. Kantrowitz criterion and isentropic limit are widely utilized to address the starting problem using the contraction ratio. The Kantrowitz criterion provides the minimum contraction ratio needed to achieve an unchoked flow for a given freestream Mach number. The self-start condition for a scramjet is achieved when the design contraction ratio is larger than the Kantrowitz limit, given by

$$\frac{A_i}{A^{**}} = \frac{1}{M_\infty} \left[\frac{(\gamma + 1)M_\infty^2}{(\gamma - 1)M_\infty^2 + 2} \right]^{\frac{\gamma}{\gamma - 1}} \left[\frac{(\gamma + 1)}{2\gamma M_\infty^2 - (\gamma - 1)} \right]^{\frac{1}{\gamma - 1}}$$

$$\left[\frac{(\gamma - 1)M_\infty^2 + 2}{(\gamma + 1)} \right]^{\frac{(\gamma + 1)}{2(\gamma - 1)}}$$

The relevant curve for this limit is shown in figure 3. Above this limit an intake will start spontaneously. The isentropic curve in figure 3 provides the corresponding contraction ratios which theoretically produce 100% total pressure recovery, and are given by

$$\frac{A^*}{A_i} = M_\infty \left[\frac{(\gamma + 1)}{2} \right]^{\frac{(\gamma + 1)}{2(\gamma - 1)}} \left[1 + \frac{(\gamma - 1)}{2} M_\infty^2 \right]^{\frac{-(\gamma + 1)}{2(\gamma - 1)}}$$

where A^{**} , A^* , A_e , A_i , represent sonic area, isentropic sonic area, exit area and intake entry's area respectively. An intake with the exit-to-entry ratio, A_e/A_i , lying in between these two curves will operate stably and supersonically, once it has been properly started.

Molder et al. [4] proposed a startability index - S_i , to measure the difficulty of starting an intake. It is the measure of the

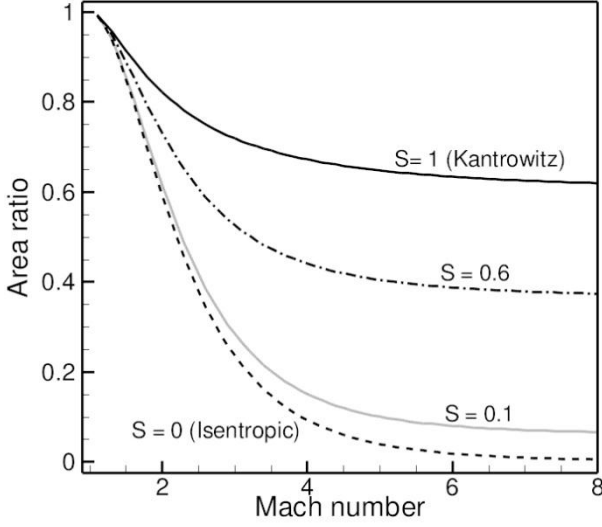


Figure 3: Plot of startability index, Kantrowitz limit and isentropic flow line

contraction ratio on the scale between the Kantrowitz and the isentropic contraction ratio's,

$$S_i = \frac{A_e/A^* - 1}{A^{**}/A^* - 1}$$

This index is a ratio of contractions and, with the presumption that startability increases with a decrease in contraction. The index takes on a value of 1 at the Kantrowitz condition and is 0 under the isentropic conditions, below which the intake will not remain started. The lower bound of the startability index is at the $S_i = 0.1$, where high-contraction intakes are indicated to start [5].

ANALYTICAL RESULTS

We intend to compare the performance of Busemann intake against the specified 2-ramp type configuration; hence we take the isolator Mach number as 3.12 from earlier paper [6] to generate the geometry and flow-field. We obtain the estimate of total pressure recovery (referred to as pressure recovery henceforth) corresponding to this isolator Mach number from the plot of family of Busemann intakes for freestream Mach number 6.5 (figure 4).

The pressure recovery value is 0.967 and the flow-field for the resulting intake is given in the figure 4. As expected, the flow is conically symmetric about the intake centreline ($y=0$). Compression waves enable isentropic compression of the flow up till the conical shock wave and the only discontinuity in flow is at this location. Flow turns across the conical shock wave to enter the isolator at design isolator Mach number.

The length of the intake is 6.987m and the area ratio is 15.236. The corresponding values for the 2-ramp configuration are 1.2m and 8.1 respectively [6]. This suggests that the

Busemann intake, even though more efficient in total pressure recovery for inviscid flows, is much longer than the 2-ramp configuration. It has been shown that the length of Busemann intakes can be reduced by significant margins without compromising considerably on the performance [7]. This is done by truncating the design before δ becomes 0 i.e. intended freestream conditions are attained. Hence, we generate the family of Busemann intakes for $M_\infty = 6.5$ for truncation angles 2° , 3° , 4° and 6° in order to improve upon the length criteria.

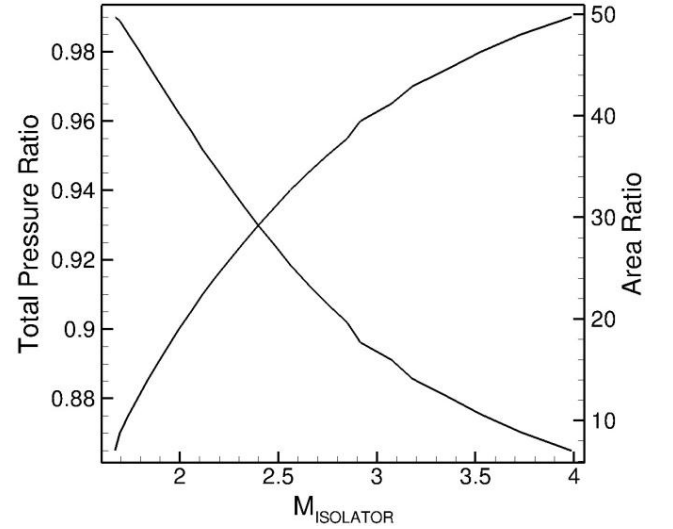


Figure 4: Family of Busemann intakes

For the isolator Mach number of 3.12, following table summarizes the essential parameters for truncated Busemann intakes.

Truncation angle δ (in degrees)	Length	Area ratio (A_i/A_e)	Startability index
0	6.987	15.236	0.085
2	5.113	14.328	0.092
3	4.510	13.530	0.099
4	4.030	12.663	0.100
6	3.265	10.796	0.128

Table 1 : Geometric details of the Busemann intake obtained by using analytical method. Figure 6 corresponds to these values.

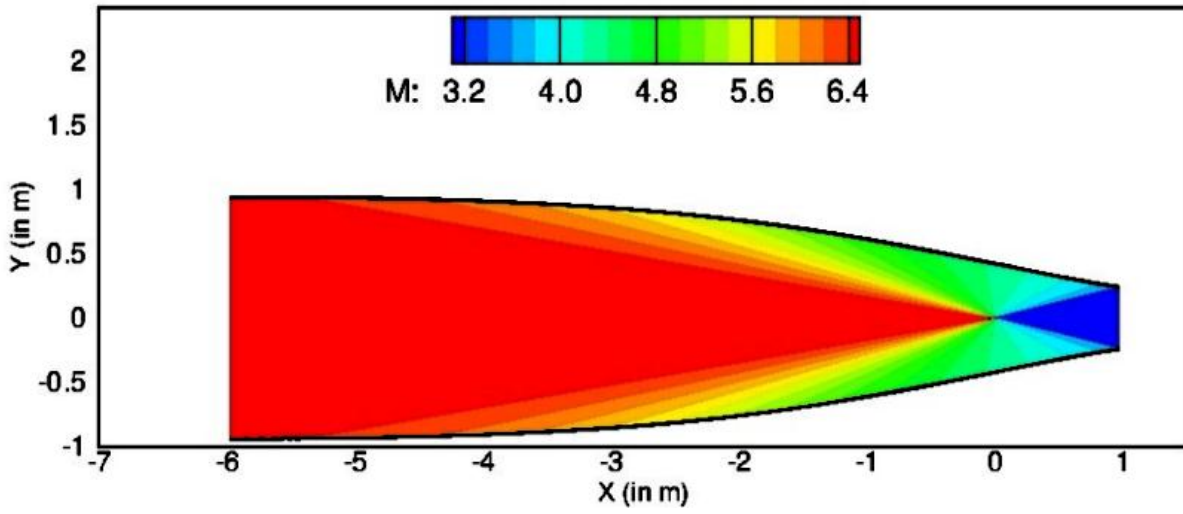


Figure 5: Analytical solution of Busemann intake with 0° truncation angle at Mach 6.5.

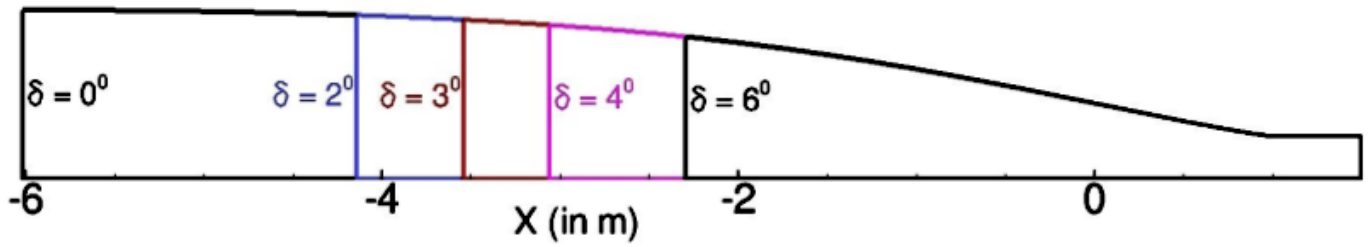


Figure 6: Busemann intake geometries with varying truncation angles

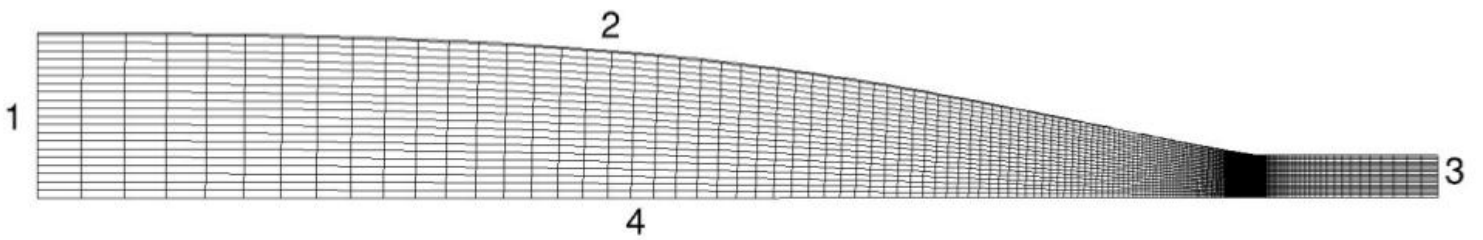


Figure 7: Grid structure and boundary conditions details

SIMULATIONS

Simulations are performed for inviscid-compressible flow governed by Euler equations. A well validated in-house code is utilised for flow-simulations [8]. The code is based on finite-volume formulation and a modified low-dissipation form of the Steger-Warming flux splitting scheme. The discretization method is second-order accurate in space. Implicit Data Parallel Line Relaxation (DPLR) method is used to integrate the equations in time and reach a steady-state solution [9].

Referring figure 7 for the grid geometry, the present study assumes freestream conditions (1) at an altitude of 26 km above the sea-level, where $T_\infty = 219.3$ K and $\rho_\infty = 0.03436$ kg/m³. The intakes are designed for $M_\infty = 6.5$ and simulations are done for design and off-design ($M_\infty = 7.5$ and $M_\infty = 5.5$) conditions with varying truncation angles (0° , 2° , 3° , 4° and 6°). Inviscid wall boundary conditions (2) are used for the intake surface. Isolator exit (3) utilizes extrapolation boundary conditions. Axisymmetry boundary condition is used at $y = 0$ i.e. the axis of symmetry (4).

The grid is exponentially stretched in the X-direction and is uniformly spaced in Y-direction. The grid density is high at the conical shock wave location. All the simulated cases are grid converged and have been carried out using 400X100 grid points. The pressure contours in figure 8 show the simulated intake flow-field at design freestream Mach number (6.5) for truncation angle $= 0^\circ$. A set of weak compression waves generated from the compression surface coalesce to form the conical shock wave which meets exactly at the shoulder of the intake, thereby cancelling the expansion fan.

Table 2 gives a comparison of inviscid numerical simulations for the $\delta = 0^\circ$ Busemann intake geometry against the corresponding analytical solution. A satisfactory match between the two is obtained.

Method	δ (in deg.)	M_∞	M_{ISO}	$P_{0,iso} / P_{0,\infty}$	P_{iso} / P_∞	T_{iso} / T_∞
Analytical	0	6.5	3.12	0.970	57.12	3.20
CFD	0	6.5	3.12	0.967	58.95	3.21

Table 2 : Physical properties of the Busemann intake obtained by analytical method and CFD simulations

Pressure contour of the flowfields for truncated Busemann intakes at $M_\infty=6.5$ is shown in figure 8. A distinct leading edge shock is seen for the truncated Busemann intakes when compared to un-truncated Busemann intake. The sharp leading edge shock is generated due to the change in geometric contraction which requires a larger turn in the flow at the intake. At the centerline, the leading edge shock adds to total pressure losses created by the conical shock wave. An increase in truncation angle makes the leading edge shock stronger, thereby enhancing the total pressure losses through the intake.

Strength of the conical shock is increased due to mismatch between the geometric contraction for the un-truncated and truncated Busemann intake, since the flow needs to take a sharper turn before the isolator. The conical shock wave does not meet the expansion fan exactly at the shoulder and a reflected shock is hence obtained. Once the flow passes the shoulder, a small expansion occurs and cancels the excess turning caused by the reflected shock.

The flow-fields of Busemann intakes at off-design condition of $M_\infty=7.5$ are shown in figure 9. The compression waves of un-truncated Busemann intake no longer produce a conical shock that exactly meets the expansion fan at the shoulder. Instead, the focal point moves downstream, making the conical shock wave impinge upon the isolator surface. The breakdown of the shock cancellation leads to a change in the shock cone geometry, leading to greater isolator Mach number and consequently increased kinetic energy efficiency. For the fixed freestream Mach number, the averaged throat velocity is high for the truncated intake compared to the un-truncated Busemann intake. It is noteworthy that an increase in kinetic efficiency at higher freestream Mach number does not necessarily mean better performance. It can be inferred from the figure 11 that at this condition, total pressure recovery reduces significantly, thus making design condition as the most favourable.

In contrast, figure 10 shows the pressure contour of the flow-fields for Busemann intakes at off-design condition of $M_\infty=5.5$. The reflected shocks in this case are significant and pressure gradients are high. The flow has to traverse through this shock structure for the intake to continue working, which becomes difficult when the flow does not have enough energy. Hence, we expect Busemann intakes to have starting problems at freestream Mach numbers that are lower than the design Mach number. Intakes unstart condition at lower Mach numbers can be addressed in two ways. Firstly, through the gas dynamic relations by plotting area ratio against Mach number. We note that for decreasing freestream Mach number, the lower bound for minimum contraction ratio (A_e/A_i) increases, shown in figure 3. This ensures that for a fixed geometry and a fixed contraction ratio, any reduction in freestream Mach number leads to the range of operation becoming narrower (region above the isentropic curve in figure 3). Theoretically, if the point of operation (Mach number, area ratio) is below the isentropic curve, the intake will be unstarted. Another way to look at this is from CFD point of view. For Mach 5.5 case, the apex of the conical shock moves upstream of the throat plane when compared to Mach 6.5 case and leads to change in shock structure. The conical shock no longer interacts with the shoulder and the impinging shock gets reflected. The reflected shock then penetrates through the throat plane leading to another conical shock. This pattern repeats throughout the isolator section. The reflected shocks in this case are significant and pressure gradients are very high. Further decrease in the Mach number can lead to unstart of the inlet. This has been reported in the literature [2].

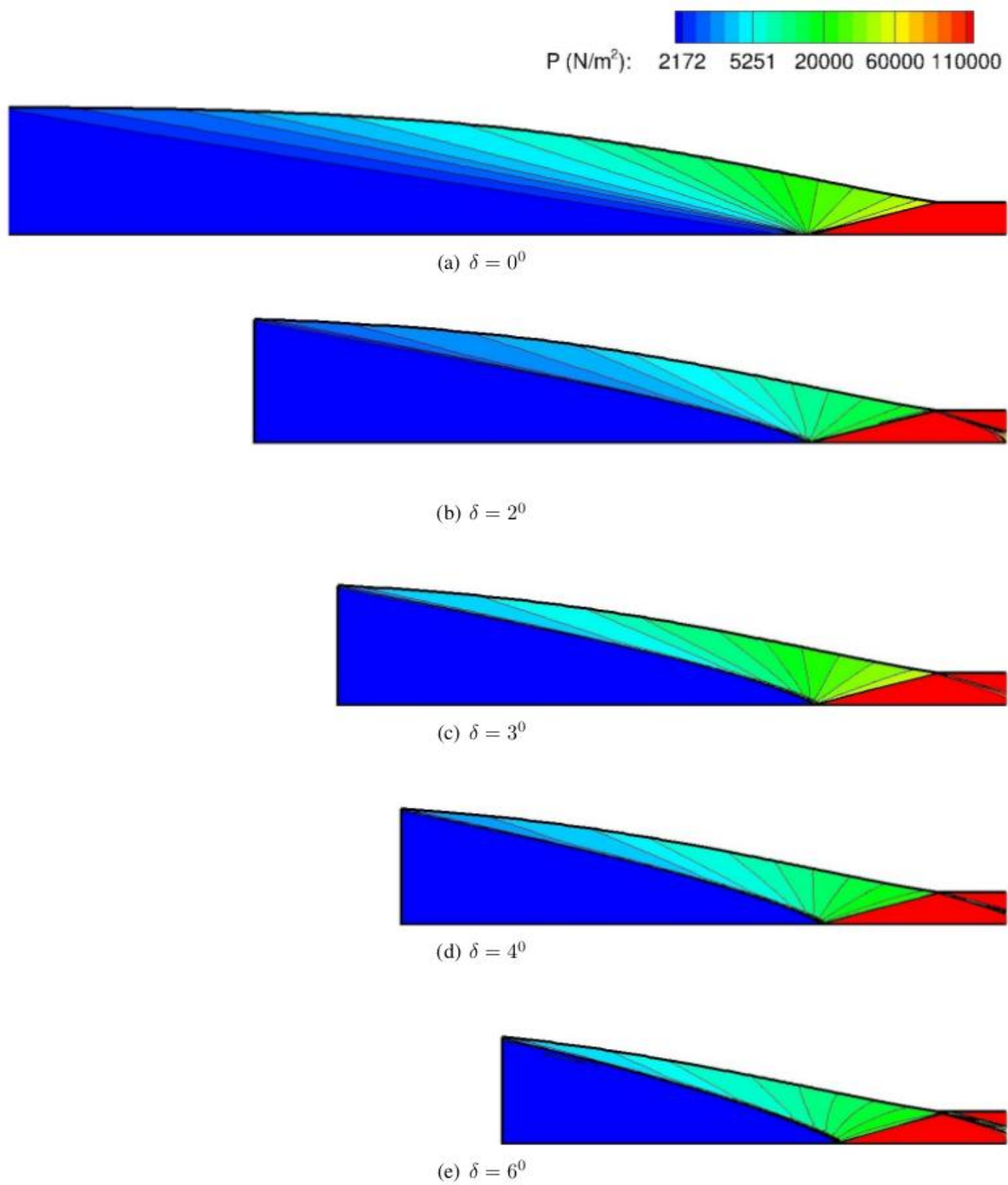


Figure 8: Pressure contour for Busemann intake with different truncation angle of Mach 6.5

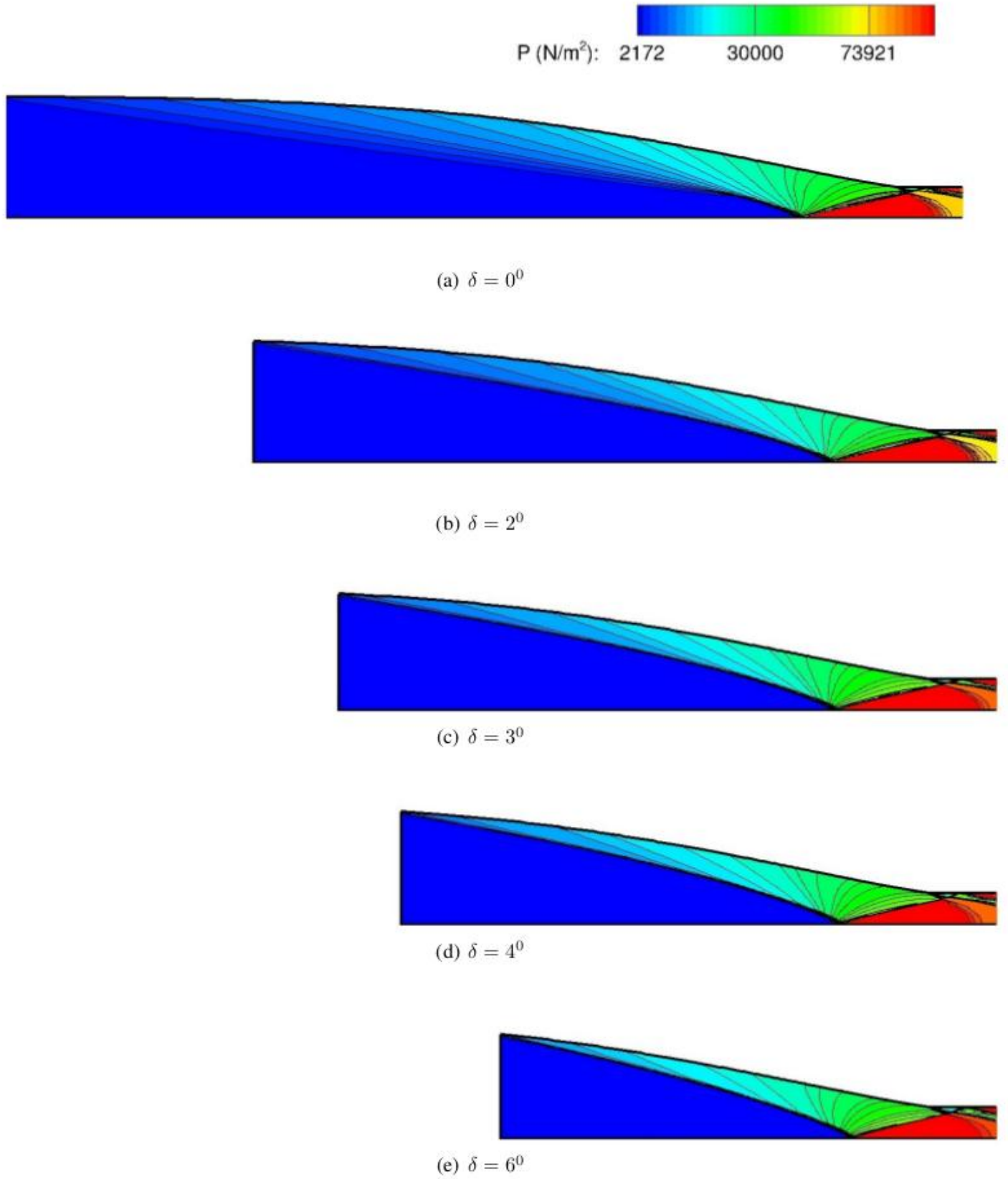


Figure 9: Pressure contour for Busemann intake with different truncation angle of Mach 7.5

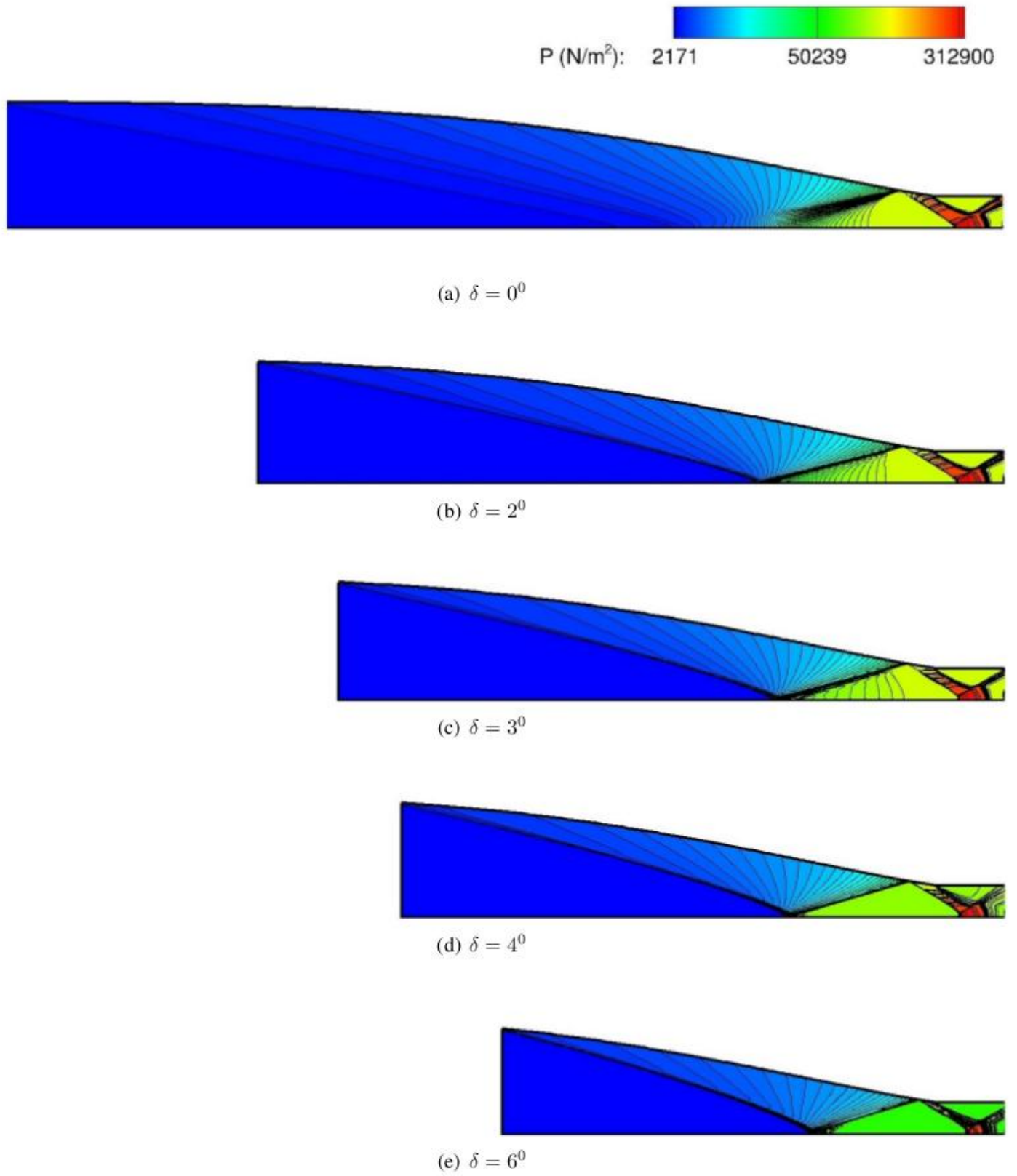


Figure 10: Pressure contour for Busemann intake with different truncation angle of Mach 5.5

With increasing truncation angles, the contraction ratio of the truncated intake approaches Kantrowitz limit and is shown in figure 3. In the design of the hypersonic intakes, one should strive to attain S_i to 0.1, which represents the highest contraction for which the intake remains started.

COMPARATIVE ANALYSIS OF RAMP-TYPE AND BUSEMANN INTAKE

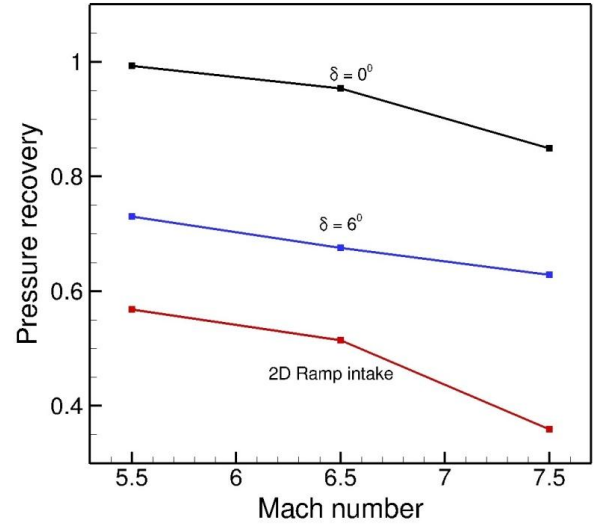
Pressure recovery, kinetic energy efficiency and length are chosen as criteria to compare ramp type intakes and Busemann intakes. Initial part of the Busemann intake comprises of isentropic compression followed by a single conical shock wave as opposed to a series of weak shock in ramp type intakes. Therefore pressure recovery for Busemann intakes at same free-stream and isolator Mach number is substantially high. Reduction in length through early truncation causes a drop in pressure recovery across the intake. The values obtained however are still comparatively high against ramp type intakes as shown in figure 11(a). As the freestream Mach number is increased, the Busemann intake is able to perform at levels similar to its performance at design freestream Mach number. In contrast, the ramp type intakes experience a considerable loss in pressure recovery due to an increase in the strength of the oblique shocks that the flow encounters.

The kinetic energy efficiency depends on the throat and freestream Mach numbers, it is highest at the design condition for both the intakes (Busemann and ramp type). As the Mach number increases the kinetic energy efficiency decreases because of the presence of stronger shocks in the isolator. At lower Mach numbers the kinetic energy efficiency for the Busemann intakes falls down. With increasing truncation angles the contraction ratio (A_e/A_i) increases and the reduction in throat Mach number is less. The ramp type intake continues to work at efficiency similar to the design conditions.

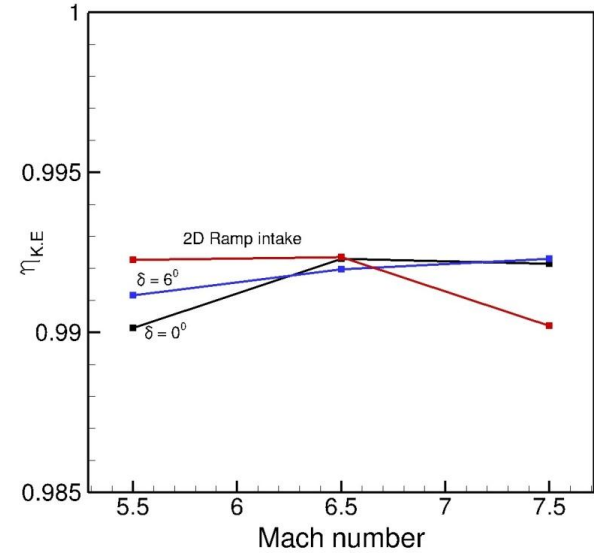
An increase in kinetic energy efficiency does not necessarily indicate better performance. Pressure recovery is the primary criteria for intake selection.

CONCLUSIONS

In this paper, conventional compression ramp intakes are compared with axisymmetric Busemann intakes for a design Mach number of 6.5. The conically symmetric Busemann flowfield is generated by solving the Taylor-Maccoll equations. Several truncated versions are proposed to reduce the length and weight of the intake. Numerical simulations of the whole Busemann intake as well as its truncated versions are performed to study the internal flowfield and its performance. Off-design conditions at lower and higher Mach number are also considered. It is found that Busemann intakes have much higher total pressure recovery at design and higher Mach numbers compared to conventional compression ramp type intakes, while also being longer in length. A reduction in length can be achieved without substantially compromising on the performance through early truncation of Busemann intake geometries.



(a)



(b)

Figure 11: Comparison of the performance parameters of ramp type intake against truncated and un-truncated Busemann intakes.

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