Parameteric study of the performance of two-dimensional Scramjet Intake

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Abstract

Scramjets are air-breathing engines used in the propulsion of hypersonic vehicles. The design of scramjets mainly depend on the design of their intakes. Out of the various intake types, mixed compression intakes are commonly used because of their inherent advantages over other intakes. This paper discusses the design of a two-ramp variable area mixed compression intake with a free-stream Mach number of 6.5. Shock-on-lip condition required to obtain maximum capture of air entering the intake is satisfied in the design procedure. A detailed analysis of the performance of the intake due to variation of the flight conditions in terms of the free-stream Mach number, angle of attack and cowl deflection is carried out using inviscid numerical simulations.

Keywords : Scramjet, Mixed compression intake, Shock-on-lip, kinetic energy efficiency.

1 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 a minimum of aerodynamic losses.

Scramjet intakes can be classified as : (i) external compression intake, (ii) internal compression intake, and (iii) mixed compression intake [1, 2]. The mixed compression intake is the most commonly used intake among the three due to its shorter length, higher pressure recovery and lower drag. This paper discusses the design of a variable area mixed compression intake with two ramps. The design is based on a free-stream Mach number of 6.5.

The main objective of the paper is to study the effects of various parameters like the free-stream Mach number, cowl deflection and angle of attack on the performance of the intake. The performance

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criteria chosen are the total pressure recovery, kinetic energy efficiency, inlet mass flow rate and compression ratio. A detailed analysis of the flow structure in the intake and the isolator for the different cases considered is carried out using numerical computations. Two-dimensional planar geometry with calorically perfect gas and inviscid model for the airflow is considered for the numerical simulations.

2 Intake design methodology

The criteria for the design of the intake are chosen as (the geometry is made to satisfy these conditions) : (a) shock-on-lip condition which ensures maximum capture area and minimum intake length and (b) reflected cowl shock cancellation on the shoulder of the intake to ensure uniform flow in the isolator. The number of external and internal shocks has to be fixed for the design of the intake. In this work, number of external shocks are fixed to be two, i.e. two ramps, and one internal shock, i.e. cowl shock. The horizontal region between the cowl and the innerbody after the expansion corner is called as the isolator. There are no internal shocks in the isolator due to cowl shock cancellation at the expansion corner.

The intake geometry for the on-design Mach number of 6.5 is prescribed by a) the first ramp length, b) the distance of the cowl tip from the front leading edge, and c) the total intake height. Figure 1 shows the intake geometry with the values of different geometric parameters. The angles of the first and the second ramp are decided such that the shocks forming at the compression corners hits exactly at the cowl tip. This allows maximum mass flow to enter through the intake. The ramp angles are determined geometrically and using the gas dynamic relations by satisfying the shock-on-lip and cowl shock cancellation conditions.

3 Simulation methodology

The simulations are performed by assuming the fluid to be inviscid, compressible and the governing equations as two-dimensional Euler equations. In-house code based on finite-volume formulation of the governing equations and a modified low-dissipation form of the Steger-Warming flux splitting approach is used. The discretization method is second-order accurate in space. The implicit Data Parallel Line Relaxation method is used to integrate the equations in time and reach a steady-state solution. The code has been validated for several supersonic and hypersonic flow applications [3, 4].

For the present study, the design Mach number M_1 is taken to be 6.5 and the conditions at an altitude of 26 km (where T = 219.3 K, $\rho = 0.03436\ kg/m^3$) above the sea-level are taken as free-stream conditions

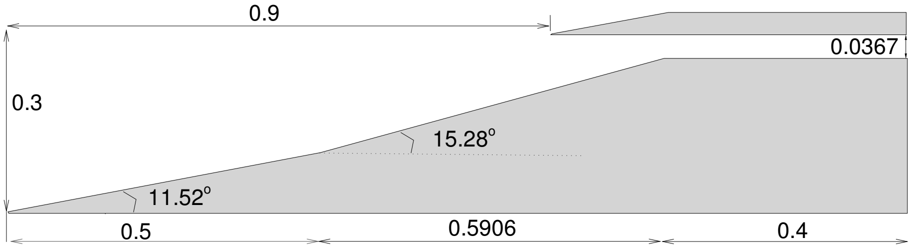


Figure 1: Details of scramjet intake geometry (All dimensions are in meters).

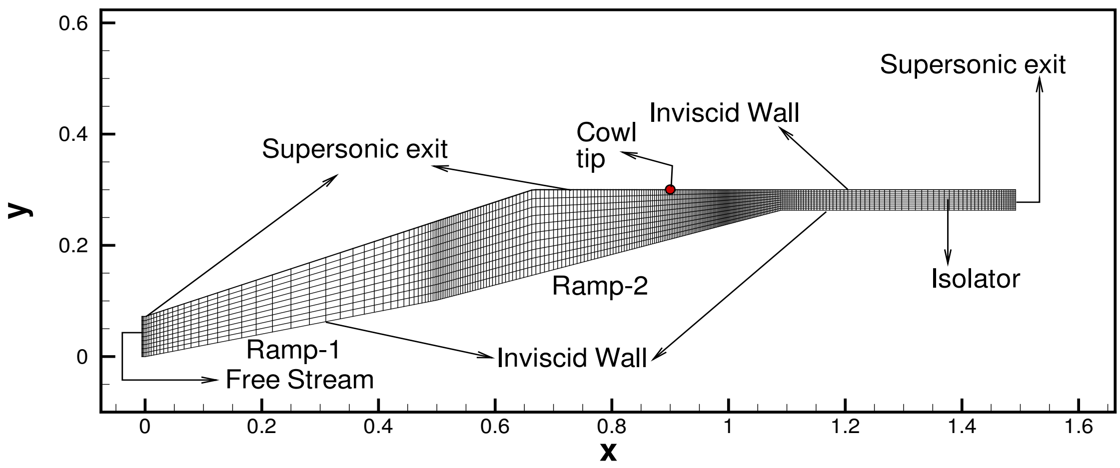


Figure 2: Grid structure and boundary condition details.

for the simulations. Inviscid wall boundary conditions are used on the two ramps, cowl and the innerbody wall. Extrapolation conditions are used at the isolator exit and on the top boundary up to the cowl-tip to avoid shock reflections. Figure 2 shows the grid used for the inviscid simulations. Exponential stretching has been used in the X-direction whereas the Y-direction grid lines are uniformly spaced. The grid is designed so as to keep more density of the points in the shock formation and interaction regions. The grid with 550 points in the X-direction and 250 points in the Y-direction has been found to be sufficient to get grid converged solutions for all the cases considered and hence is used for all the simulations.

4 Performance parameters

The static temperature and pressure ratios determine the amount of compression achieved in the inlet. The total pressure recovery, defined as the ratio of total pressure at the isolator exit to the free-stream total pressure, is a measure of how much entropy is generated by the inlet. It also is a measure to predict drag because increasing the pressure recovery factor without changing the compression ratio means increasing the exit Mach number. The capture area of the intake represents the proportion of air available to enter the isolator. It is measure of thrust; if more air is captured, and the pressure and temperature remain the same, we would expect the combustor to generate more thrust. Capture area is measured with respect to the limiting stream-line ending at the cowl leading edge. The kinetic energy efficiency is defined as the kinetic energy the compressed flow would achieve if it were expanded isentropically to free stream static pressure, relative to the kinetic energy of the freestream [5]. Empirically it is given by,

$$\eta_{K.E} = 1 - 0.2\left(1 - \frac{M_{exit}}{M_{inlet}}\right)^5 \tag{1}$$

where, M_{exit} is the Mach number at the exit of the isolator and M_{inlet} is the free-stream Mach number. It represents the amount of momentum available at the combustor inlet and is directly related to the thrust produced by the engine.

Table 1: Comparison of the analytical and numerical simulation results with respect to various parameters for scramjet inlet.

Mach	T_{iso}/T_{inlet}		$P_{0,iso}/P_{0,inlet}$		P_{iso}/P_{inlet}		M_{iso}	
	1D INV	2D INV	1D INV	2D INV	1D INV	2D INV	1D INV	2D INV
4.5	2.298	2.295	0.742	0.745	13.660	13.652	2.446	2.450
5.5	2.716	2.707	0.630	0.637	20.804	20.797	2.824	2.830
6.5	3.197	3.197	0.521	0.523	30.422	30.533	3.127	3.120
7.5	3.743	3.76	0.422	0.414	42.827	42.769	3.370	3.370

5 Results and discussion

The flow field characteristics of the designed scramjet inlet is studied numerically. The design Mach number of the scramjet inlet is considered as cruising flight Mach number. The effect of Mach number, angle of attack, α, and cowl deflection angle, θ_c, of the scramjet inlet is reported below.

The performance of the intake is evaluated by parameters such as kinetic energy efficiency, total pressure recovery, static temperature ratio, static pressure ratio and inlet mass flow rate which depends on the inlet capture area. Change in these parameters due to variations in flight conditions and change in the intake area is studied numerically. At on-design condition, the two compression corner shocks intersect each other exactly at the cowl leading edge, known as shock-on-lip condition, and the reflected cowl shock hits near the second ramp trailing edge, as shown in figure 3.

Table 1 gives the various performance parameters - static temperature ratio, static pressure ratio, stagnation pressure ratio and exit Mach number calculated after the cowl shock (isolator entrance). A comparison between numerical and analytical results obtained using numerical simulations (2D Inviscid) and the gas dynamic relations (1D Inviscid) for each Mach number is also shown in the table 1. The difference is within the ± 2 % error range for all parameters.

5.1 Effect of Mach number

Figure 4 shows the comparison of pressure contours of the scramjet intake for varying Mach number at the zero angle of attack and zero cowl deflection angle. For lower off-design Mach numbers, the shocks

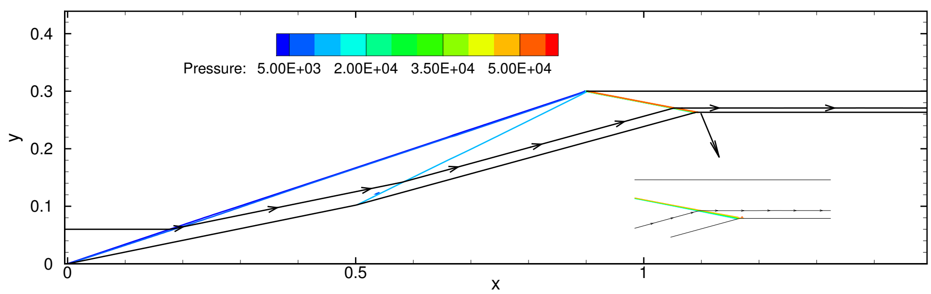
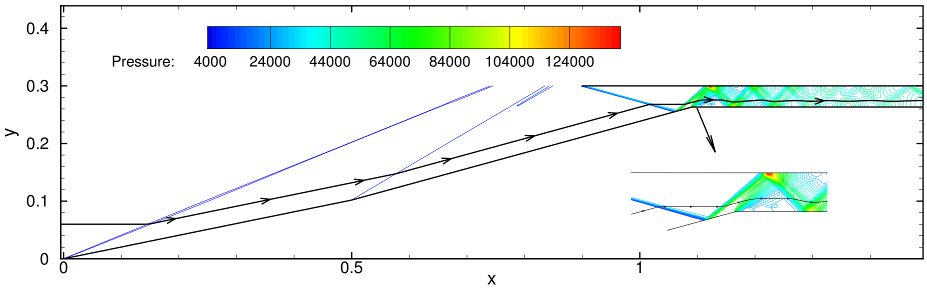
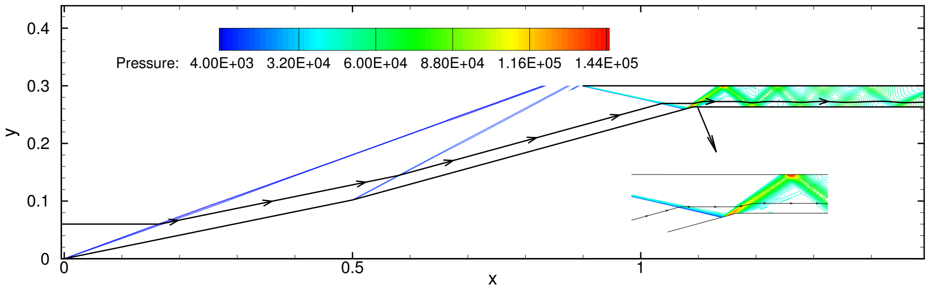


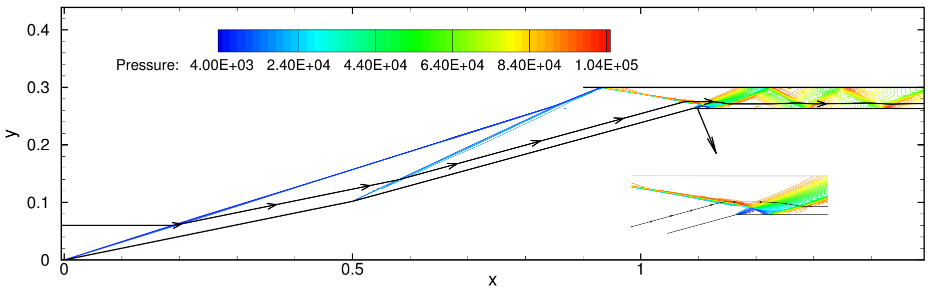
Figure 3: Pressure contour at on-design condition.



(a) Mach 4.5



(b) Mach 5.5



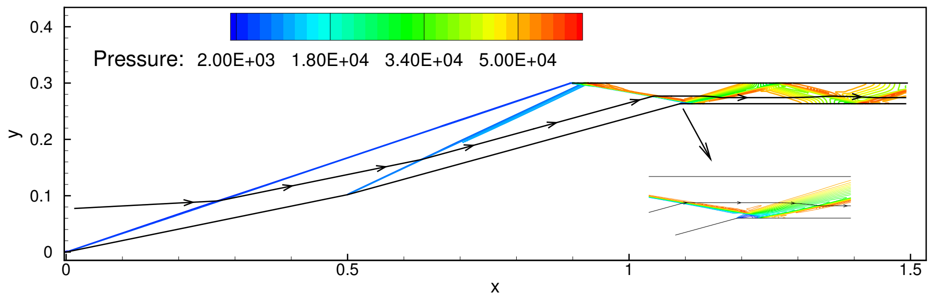
(c) Mach 7.5

Figure 4: Pressure contour for varying Mach number at $\alpha = 0°$ and $\theta_c = 0°$.

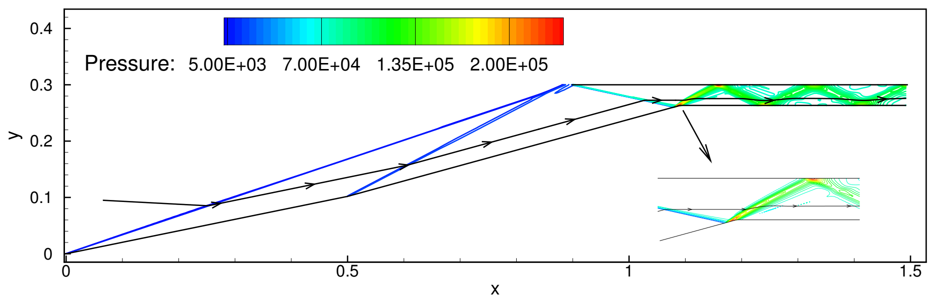
generated by two compression corners neither intersect each other nor hit the cowl wall. This leads to spillage of the air due to decrease in the capture area and the spillage would increase for further lower Mach numbers. At higher Mach numbers, the two compression corner shocks coalesce to form a single shock which hits the cowl wall and gets reflected. The reflected shock interacts with the expansion fan generated from the second ramp trailing edge and gets reflected at the isolator wall. This shock reflection continues through out the isolator and leads to the expansion and compression regions inside the isolator. This causes the static pressure at inlet exit to increase.

5.2 Effect of angle of attack

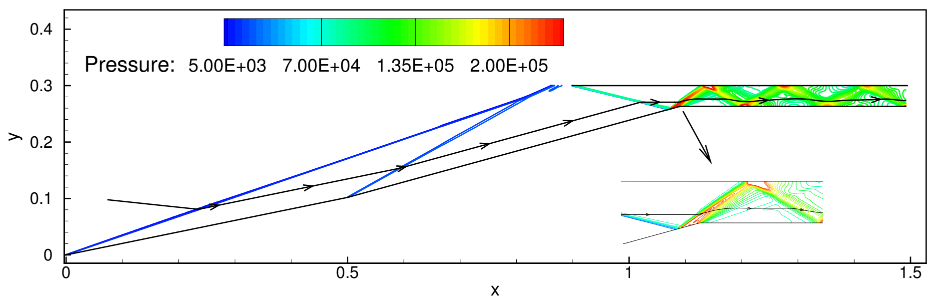
The pressure contour of the scramjet inlet and zoomed view of the shock structure at the expansion corner for the varying angle of attack, α, at the designed Mach number is shown in Figure 5. As the angle of attack increases, the point of intersection of the two external compression shocks moves upstream, away from the cowl leading edge. Whereas, for the negative angle of attack, the two external compression shocks hit downstream at the cowl wall without intersecting each other. Figure 6 represents the performance of the inlet with respect to various parameters, for varying Mach number and angle of attack. At zero angle of attack, as the Mach number increases from a lower value to design Mach number, the flow capture area of the inlet increases. At the design Mach number, it reaches to maximum value thereby



(a) $\alpha = -3^{\circ}$

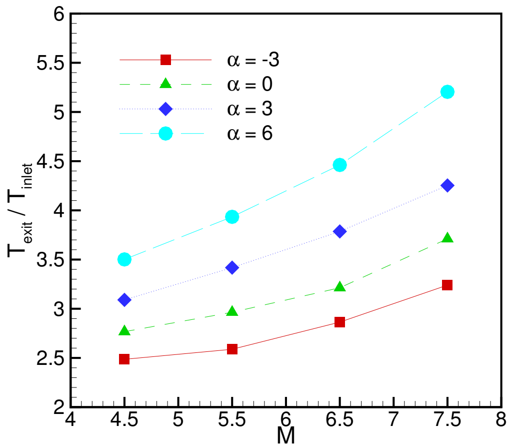


(b) $\alpha = 3^{\circ}$

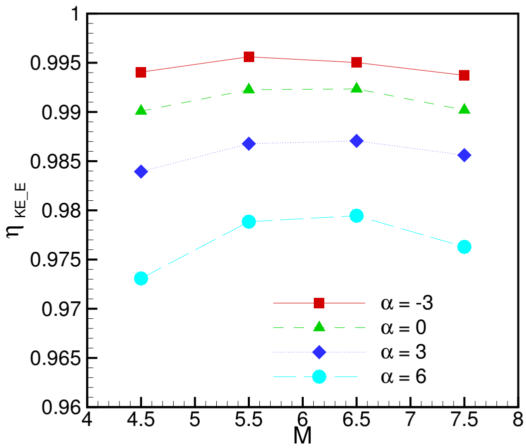


(c) $\alpha = 6^{\circ}$

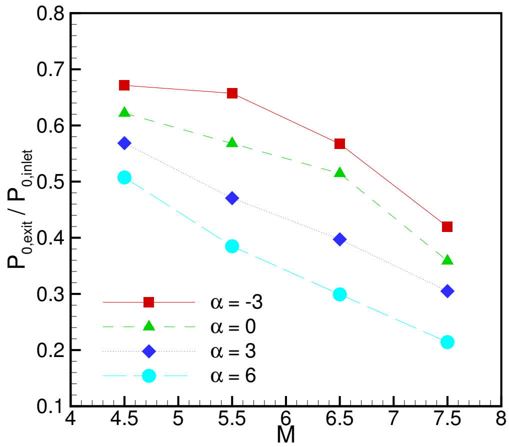
Figure 5: Pressure contour for varying α at Mach 6.5.



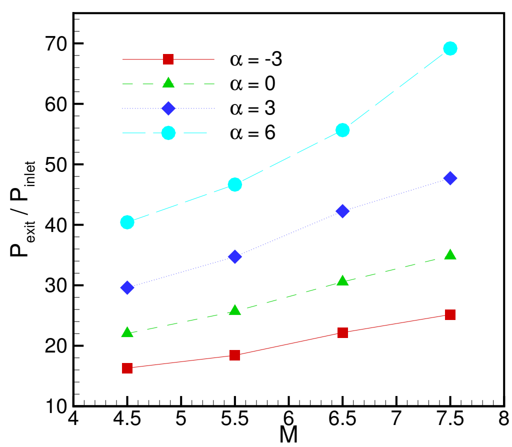
(a) Compression ratio



(b) η_{KE}



(c) Stagnation pressure ratio



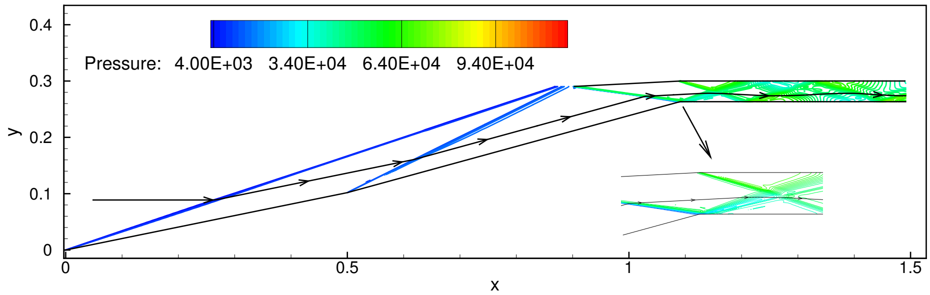
(d) Static pressure ratio

Figure 6: Effect of angle of attack for varying Mach number.

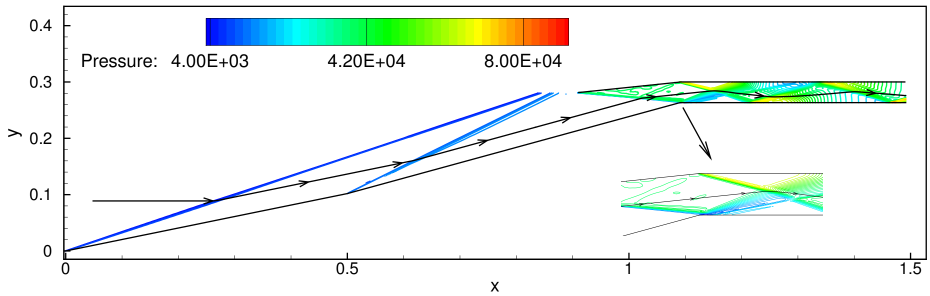
remaining constant for higher Mach numbers. For negative angles of attack and design Mach number, the captured mass flow rate decreases as compared to zero angle of attack, whereas for positive angles of attack, it increases. The shock strength increases with the Mach number and consequently the compression ratios, i.e., temperature and static pressure ratios, increases. For given angle of attack, the kinetic energy efficiency is maximum at the design Mach number ($M = 6.5$) and it reduces at the off-design conditions due to the spillage at the lower Mach number and high shock strength at higher Mach number. The maximum pressure recovery is achieved at the lower Mach number and decreases in proportion with increasing the shock strength at higher Mach numbers. For given Mach number, the pressure recovery decreases with increasing the angle of attack.

5.3 Effect of cowl deflection:

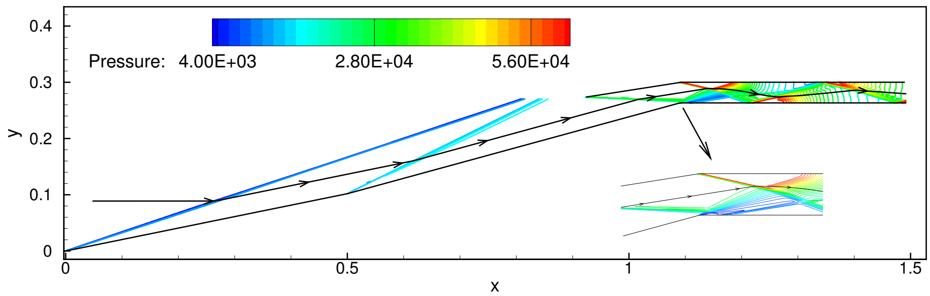
The pressure contours of the scramjet and shock structure at the expansion corner for the varying cowl defelction, θ_c, at the on-design Mach number is shown in figure 7. At zero cowl deflection angle ($\theta_c = 0$), the inlet satisfies the shock-on-lip condition, as discussed earlier. As cowl deflection increases, the two external compression shocks intersect away from the cowl leading edge at the upstream and this increases the spillage. Two internal compression shocks, generated from the cowl leading edge and the point of cowl deflection, interacts with the expansion fan and hits the isolator wall.



(a) $\theta_c = 3°$

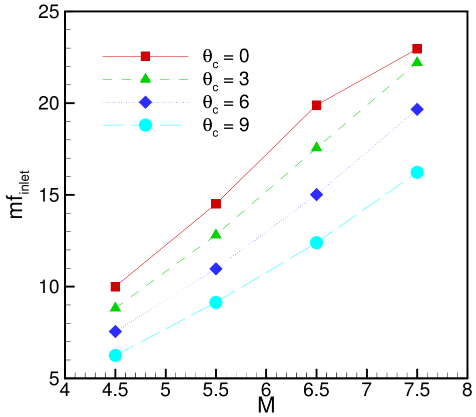


(b) $\theta_c = 6°$

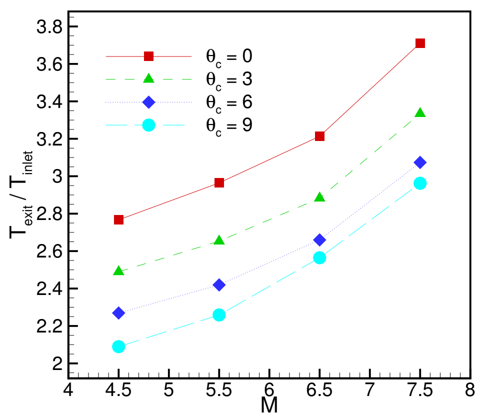


(c) $\theta_c = 9°$

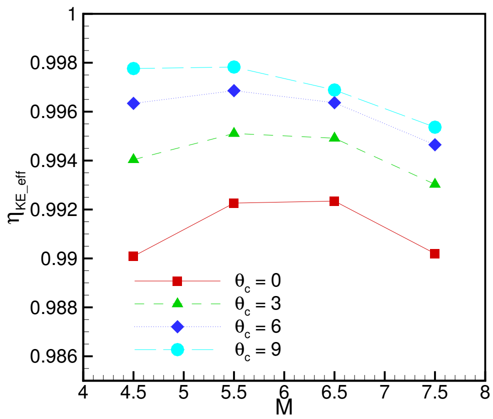
Figure 7: Pressure contour for varying θ_c at Mach 6.5.



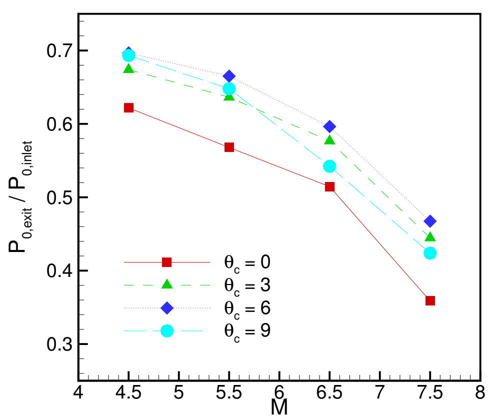
(a) Mass flow rate



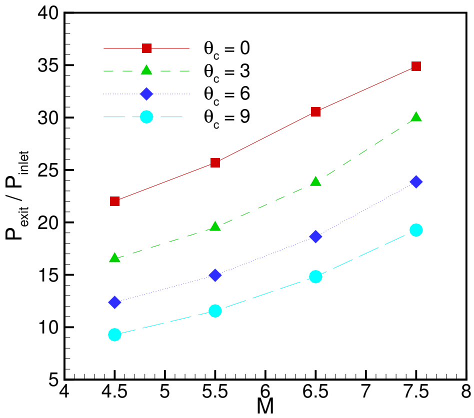
(b) Compression ratio



(c) η_{KE}



(d) Stagnation pressure ratio



(e) Static pressure ratio

Figure 8: Effect of cowl deflection for varying Mach number.

Figure 8 shows the effect of the cowl deflection on the performance parameters for the range of Mach number for the scramjet inlet at zero angle of attack. For the zero cowl deflection angle, the increment in Mach number shows a linear increase in the captured mass flow rate. By increasing cowl deflection angle, the capture area decreases, hence the mass flow rate reduces. The compression ratios increase in proportion with the Mach number for a given cowl deflection angle due to higher shock strengths, and for a given Mach number it decreases with increasing cowl deflection angle due to spillage. The total pressure recovery reduces with the increasing Mach number and increases with cowl deflection angle. At the zero cowl deflection, the maximum kinetic energy efficiency is obtained at on-design Mach number. Whereas, increment in cowl deflection angle shifts the maximum kinetic efficiency towards the lower Mach numbers.

6 Conclusion

In this paper, we perform inviscid numerical simulations of a typical mixed-compression scramjet intake, and study its performance for a range of Mach numbers, angles of attack and cowl deflection angles. The ramp angles and cowl placement are designed for shock-on-lip condition and to achieve uniform flow in the intake duct at Mach 6.5. At off-design conditions, a set of shock and expansion fans are generated in the intake duct, and they reflect between the duct walls. This degrades the flow quality at the intake/isolator exit. It is found that the maximum pressure recovery is obtained at lower Mach number with weaker shock waves, and the capture mass flow rate is maximum at higher Mach numbers. The maximum kinetic energy efficiency is obtained at intermediate Mach number, close to the design point. Cowl deflection is also found to affect the performance adversely. As the cowl angle is increased, the maximum kinetic energy efficiency is obtained at Mach numbers lower than the design point.

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