Design and Performance Analysis of Rectangular Ramjet Intake At Mach 2.2

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Abstract: The design of supersonic intakes ensuring maximum performance is a highly challenging task for engineers. The present study incudes a systematic design methodology and geometric optimization for a three-ramp, mixed compression supersonic rectangular intake at M_∞=2.2 operation. In this work, we have followed the on-design condition to estimate the three ramp angles for maximum total pressure recovery. Then numerical simulations are carried out for the preliminary design at different exit blockage ratio to obtain the complete performance characteristics. The numerical simulation (computational fluid dynamics) model comprise of shear stress transport with two equation k-ω turbulence model and advection scheme. The results show a MFR of 0.963 for the preliminary design at supercritical operation. It is observed from the 2D results, the design with cowl opening angle of 10^0, cowl height of 6 mm without accounting the effect of side plate has 3.79% of the improved mass flow rate through the inlet and it has more uniform flow at the throat section. We have observed from 3D results that, the swept side plate shock bends the ramp shocks upstream resulting in reduced velocity, followed by a separation bubble that blocks the isolator inlet. Finally, we concluded that the mass flow rate highly influenced by shock-shock, shock-boundary layer interaction and flow separation.

Keywords: Supersonic intake, On-Design, Turbulence, Shock

1 Introduction

An air-breathing engine takes in air from its surrounding in order to burn fuel. All practical air breathing engines are internal combustion engines that directly heat the air by burning fuel, with the resultant hot gases used for propulsion via a propulsive nozzle [4]. To expel the gases from the nozzle at high velocity, the air entering the combustion chamber of the engine is compressed. Thrust produced by a typical air-breathing engine is about eight times greater than its weight. Intake performance is a critical point in the design of air breathing mission. The intake of an air breathing vehicle is required to capture and efficiently compress requisite quantity of air for engine operation [5]. Carsten D. Hermann et al. [6] are numerical shows that, the back pressure of the scramjets isolator highly influenced on its length. Experimentally they have proven that after a certain length the back pressure does not change. Mohammad Reza Soltani et al. [2] are shows that, a big buzz forms due to air flow through the narrow bleed system. The application of bleed improves the intake capacity by minimizing the buzz fluctuations. Y.P.Goonko et al. [3] are done the research on the hypersonic air intake systems with considering the effect side compression plates. Their result confirms that, the expansion shocks and vertex cause non-uniformity in the flow field at the engine front and exit.

The present research work is motivated to design a rectangular intake at M_∞=2.2 and geometrically optimize it to maximize the performance.

2 Methodology

2.1 Design procedure

The design cycle of supersonic inlets is usually a complex process involving the geometric design for each component and their optimization to maximize the performance. Hence, in the present study the intake has been designed using a 1D optimization method, and then the performance evaluation and optimization has been carried out using CFD. The dimensions for the intake with a scaling parameter are shown in Fig. 2.1.1. The detailed design procedure is given in ref. [1].

The preliminary design of intake involves the following steps,

- Selection of supersonic compression structure
- Obtaining the ramp angles for maximum Total Pressure Recovery at the on-design conditions
- Selection of Throat length and subsonic diffuser divergence angle from experimental correlations
- Obtaining the preliminary dimensions for the required mass capture

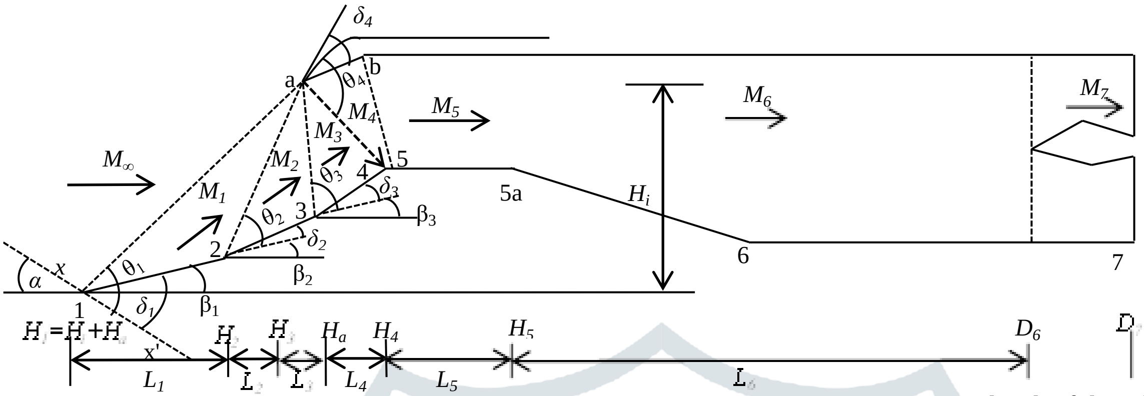

Fig. 2.1.1Sketch of the inlet system with on-design shock positions

2.2 Intake Performance Parameters

The estimation of intake performance is very crucial because it involves many complexities. Following are the important parameters which are used for the estimation of performance of a supersonic intake.

2.2.1 Mass Flow Ratio [MFR]

Mass flow/capture ratio is a characteristic parameter used in prediction of effectiveness of mass capture in ramjet engine. Here, the surrounding medium (air) acts as working fluid. It is important to capture the maximum amount of air at the inlet portion (see fig. 2.2.1). When the ramp shocks are within the cowl lip the free-stream air is completely captured and if the shocks are diverged some amount of surrounding air that would have captured into the diffuser now overflows around its cowl lip [10]. Hence, MFR is defined as below.

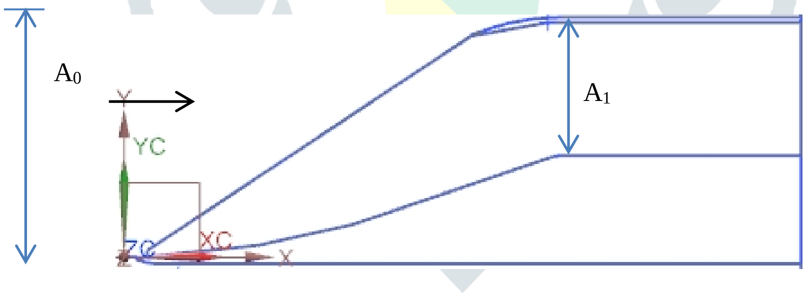

Fig. 2.2.1Air flow direction

$$Mass\ Flow\ Ratio = \frac{m_1}{m_0}$$

2.2.2 Total Pressure Recovery [TPR]

Total Pressure Recovery is another performance parameter for intakes. It is defined as the ratio of combustor face total pressure of air to the free stream total pressure. It strongly depends on the losses across the oblique shocks, viscous BL, flow separation happening inside the intake.

$$Total\ Pressure\ Recovery = \frac{P0_{avg}}{P0_{max}}$$

2.2.3 Distortion Index [DI]

The distortion index represents the flow uniformity at the intake exit face, and it must be as low as possible for an efficient combustion process [9]. The distortion index can be calculated in terms of total pressure profile.

$$Distortion\ Index = \frac{(P0_{max}) - (P0_{min})}{P0_{avg}}$$

2.2.4 Exit Blockage Ratio [EBR]

Exit Blockage Ratio is defined to include effects of the plug movement. This parameter is defined as the ratio of the exit duct area blocked by the plug to the total area of the exit duct. Thus, an EBR of 100% indicates, the exit area of the intake is completely closed, and when it is 0%, it means that the exit area was fully open.

$$Exit\ Blockage\ Ratio = \left(1 - \frac{A_{e2}}{A_{e1}}\right) \times 100$$

2.3 Design Calculations at M_∞=2.2

Here the results of 1D optimization for design at M_∞=2.2 are presented. The shock angles are then used to obtain the geometrical dimensions.

The on-design conditions are as follows:

Given: M_∞ =2.2, F=8km.

$\alpha=0^0$

$M_7 = 0.4$

Ramp system – 3 external ramps

The variation of TPR with a range of assumed Mach numbers upstream of the normal shock are given below. The Maximum TPR is about 0.89. The optimized ramp angles are then used to obtain the dimensions of the intake. The cowl tip height and width are decided based on the mass flow requirement [7]. For design privacy the detailed data are not given here. The throat length used is about 2 times the throat height and the subsonic diffuser divergence angle used is about 6 degree.

3 Numerical Approach

We generated the high quality structured mesh using ICEM software. The numerical simulations are done using a density based-CFX tool at steady state conditions.

3.1 Boundary Conditions

Similar to the actual altitude conditions of 8 Km, the static temperature of 236K is imposed at the supersonic inlet and at the subsonic outlet, 35650Pa static pressure is prescribed. Adiabatic and free wall conditions are imposed for top wall and bottom wall. At solid walls, no-slip conditions are prescribed by setting the velocity components to zero. Here we used high resolution difference-splitting scheme for simulation. SST with two equation k- ω turbulence model is used to capture the boundary layer behaviour at wall side and centre portion [8]. At the symmetry plane of the half-configuration, the conservation variables are mirrored onto the ghost cells to ensure symmetry.

3.2 Grid Independence study

To solve the partial differential equations numerically, a continuous physical domain needs to be specified with high number of discrete positions known as nodes [11]. Fig. 3.2.1 and table 3.2.1 represent the y^+ value for ramp wall surface. A maximum value of $y^+= 2$ realized at the main portion of the wall flow region to ensure the precision of the turbulent flow solution. The static pressure value increases when the flow hits the ramp wedges. Compared to fine grid, small differences observed in intermediate grid solution, hence the fine grid solutions are considered as accurate for numerical simulations.

Level of Resolution	Cells [millions]	First cell distance y [mm]	Max. Wall y^+
Coarse, G1	0.064	0.01	11
Intermediate, G2	0.156	0.005	5
Fine, G3	0.238	0.001	2

Table 3.2.1Grid independence value

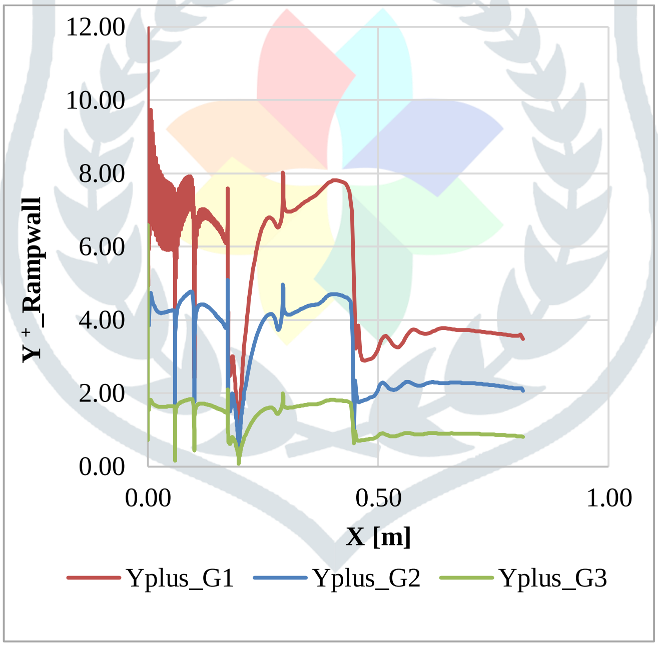

Fig. 3.2.1Ramp wall y^+ value

4 Results and Discussion

4.1 Analysis of Preliminary Design (PD)

The internal flow field of the intake at M_∞=2.2 for different modes of operation are studied. In below figure 4.1.1 we have shown the shock positions at supercritical operation. For different throttle conditions, a normal shock is formed in the subsonic diffuser across which the supersonic flow becomes subsonic. For EBR – 30.7%, as the normal shock is formed close to a Mach number of 1.7, instead of a single normal shock a normal shock train is formed.

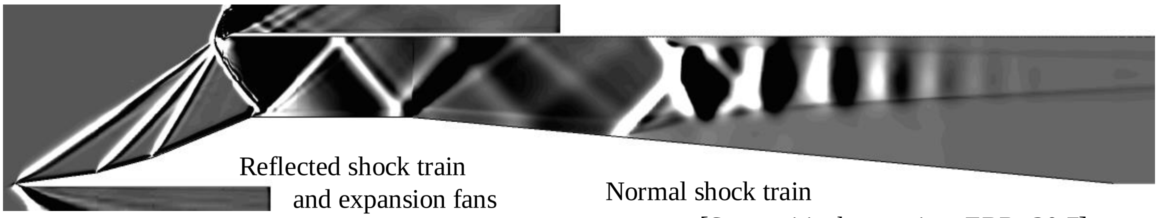

Fig. 4.1.1 Numerical schlieren image at EBR-30.7

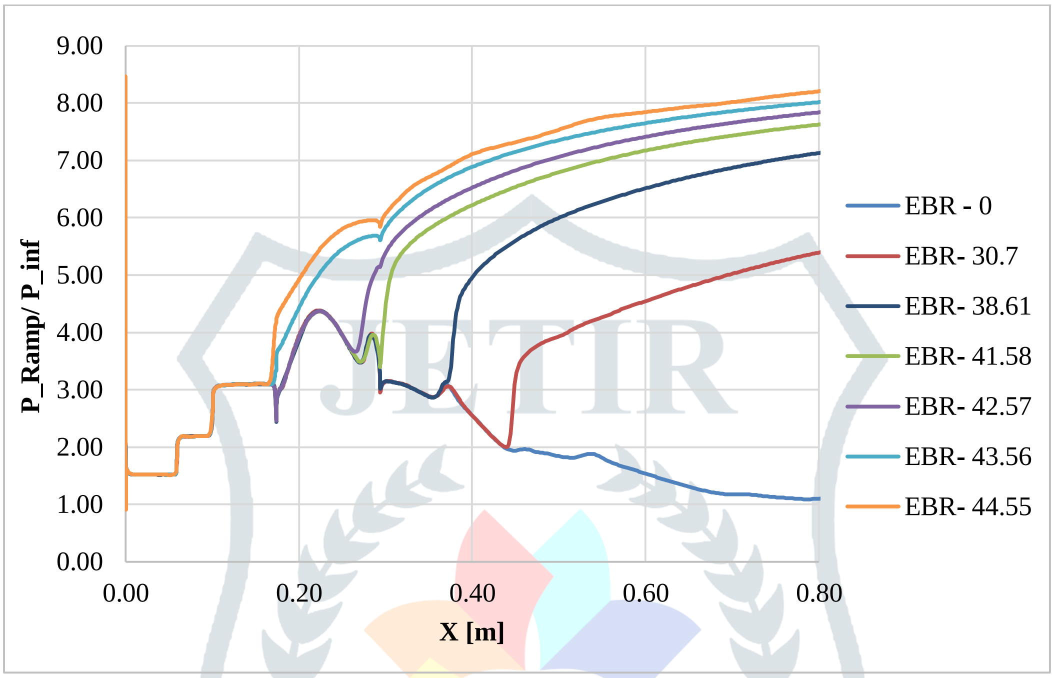

Fig. 4.1.2Wall static pressure at ramp for different operating conditions

We have done the analysis at EBR of 0, 30.7, 38.61, 41.58, 42.57, 43.56 and 44.55 for detailed flow field study. At EBR – 0%, the ramp wall pressure clearly indicates, the initial sharp pressure rise occurs across the bow shock formed ahead of the ramp lip, followed by three step increase in pressure at the ramps. There exists a dip in pressure due to flow expansion at the throat corner, and then the pressure again starts to increase across the reflected shock from the throat. There after the mean wall pressure keep decreasing with intermediate peaks across the repeatedly reflected shocks. At different throttle conditions, the upstream flow/pressure variation remains same till the position of normal shock, where there is a step increase in pressure. After the normal shock the subsonic flow diffuses till the end of the intake, showing a steady rise in pressure. The intake at subcritical operation (EBR of 44.55) has the sustainable peak pressure close to 8.3 [see fig. 4.1.2].

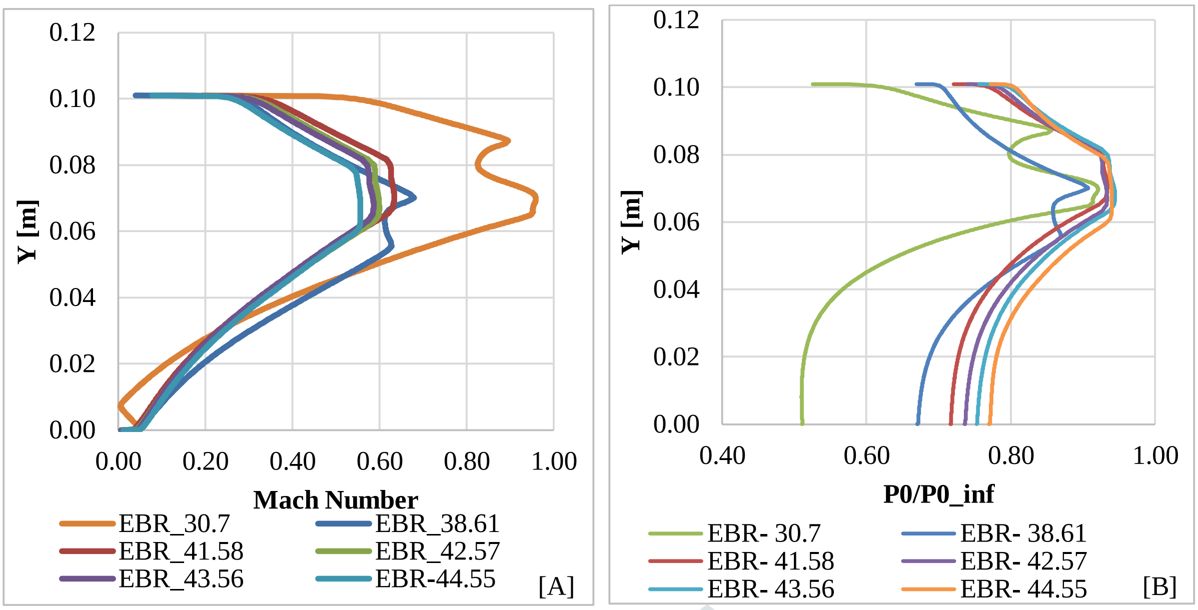

Fig. 4.1.3[A&B] Distribution of exit Mach number and stagnation pressure for different EBR [x=0.82 m]

In fig. 4.1.3 [A], clearly shows that the Mach number is highest for the super-critical operation at EBR of 30.7% because the normal shock stands far away from exit of the inlet. In fig. 4.1.3 [B], the stagnation pressure at the exit of the inlet portion is the highest for EBR of 44.55% indicates the subcritical operation. The variation in total pressure and Mach number clearly indicates non-uniformity in the flow field. Close to ramp wall the Mach number is lower compared to the core because of the flow separation in the diverging portion.

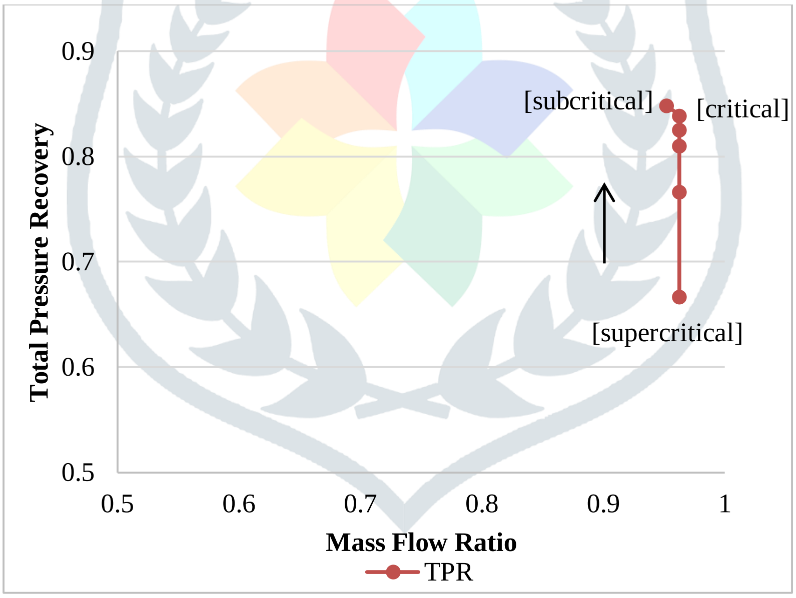

Fig. 4.1.4Intake performance curve for different operating conditions

Fig.4.1.4 shows the variation of total pressure recovery with respect to mass flow ratio. When the exit back pressure is low, a relatively strong normal shock wave is present downstream of the throat, hence the TPR is low (super-critical condition) [12]. When the normal shock placed close to the throat section (critical condition), a maximum recovery in total pressure is achieved. According to the intake performance curve, the critical total pressure ratio is about 0.856 for the preliminary design.

4.2 Improvements (2D and 3D)

To improve the performance parameters, many different design modifications without considering the effect of swept side plate and three dimension designs with swept side plate effect have been studied. In the following section we mentioned the best optimized design from both two dimensional and three dimensional.

4.2.1 Case 1: 10^0 Cowl Opening Angle, 6 mm Cowl Height without Swept Side Plate Effect

Fig. 4.2.1Contour of Mach number

Figure 4.2.1clearly shows that the flow separation is reduced at the cowl shoulder and the shock is pushed further inside. This design has higher mass flow ratio of 0.998 which is about 3.93% more, the total pressure recovery of 0.895 which is about 0.73% higher as well as a distortion index of 0.690 which is 3% less than preliminary design. Therefore, the ramp BL correction, a lower cowl opening angle of about 10^0, 6 mm cowl height improves the performance of intake over the base design. Following this, to reduce the flow separation at throat the effect of side plate has been studied in next simulation.

4.2.2 Case 2: 10^0 Cowl Opening Angle, 6 mm Cowl Height with Swept Side Plate Effect

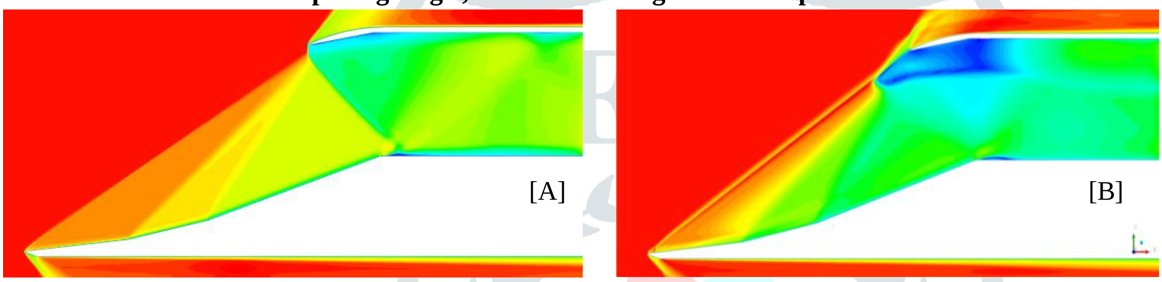

Fig. 4.2.2Contours of Mach number

Figure 4.2.2 [A, B] shows the contours of Mach number at two sectional planes Z = 0 and -52 mm. In case 1, the cowl shock impinges slightly downstream of the throat corner but in presence of the side plate the shock moves upstream and is close to the corner. Hence, the configuration is able to capture the maximum possible free-stream mass. The performance parameters show that, this design has a higher mass flow ratio of 0.986 which is about 2.62% more, the total pressure ratio of 0.867 which is about 3.88% less compare to preliminary design. Also, for this case the distortion index of 1.415 which is 54.22% more than preliminary design.

Hence, finally a MFR of 0.986 and TPR of 0.967 are obtained of the optimized geometry at M_∞=2.2.

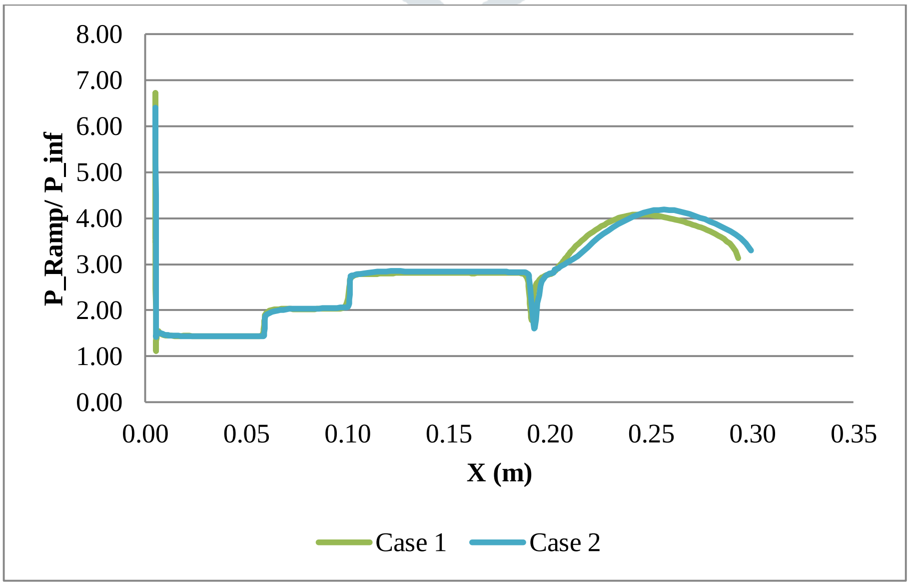

Fig. 4.2.3Comparison of ramp static pressure for 2D and 3D at M_∞ =2.2

Finally, the ramp wall static pressure profile are studied for final optimized design and plots for the 2D case 1 and the corresponding 3D case 2 are shown in fig. 4.2.3. It is clear from the figure, the static pressure increases sharply at initial stage across the bow shock occurs near to ramp tip then it shows stepwise increase as explained before.

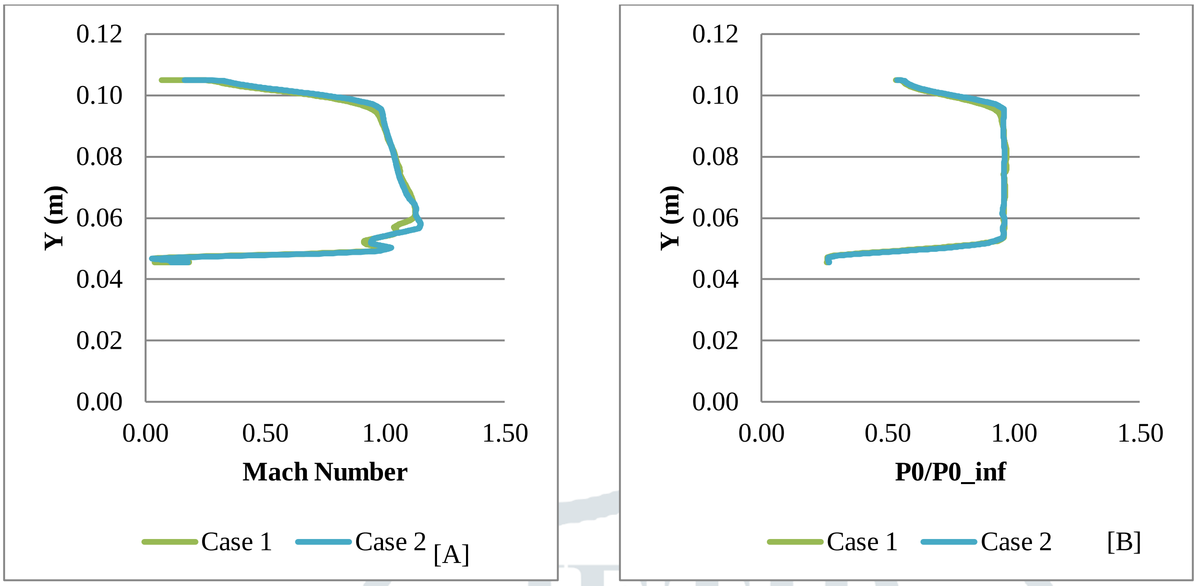

Fig. 4.2.4[A&B] Comparison of Mach number and stagnation pressure for 2D and 3D at M_∞ =2.2

The fig. 4.2.4 [A&B] shows the comparison of throat Mach number and throat stagnation pressure with and without side plate. The Mach number close to the cowl wall is low and it gradually increases at ramp wall surfaces. But in presence of side plate the Mach number is slightly slower due to higher compression. The stagnation pressure at the throat is almost similar and uniform for all designs.

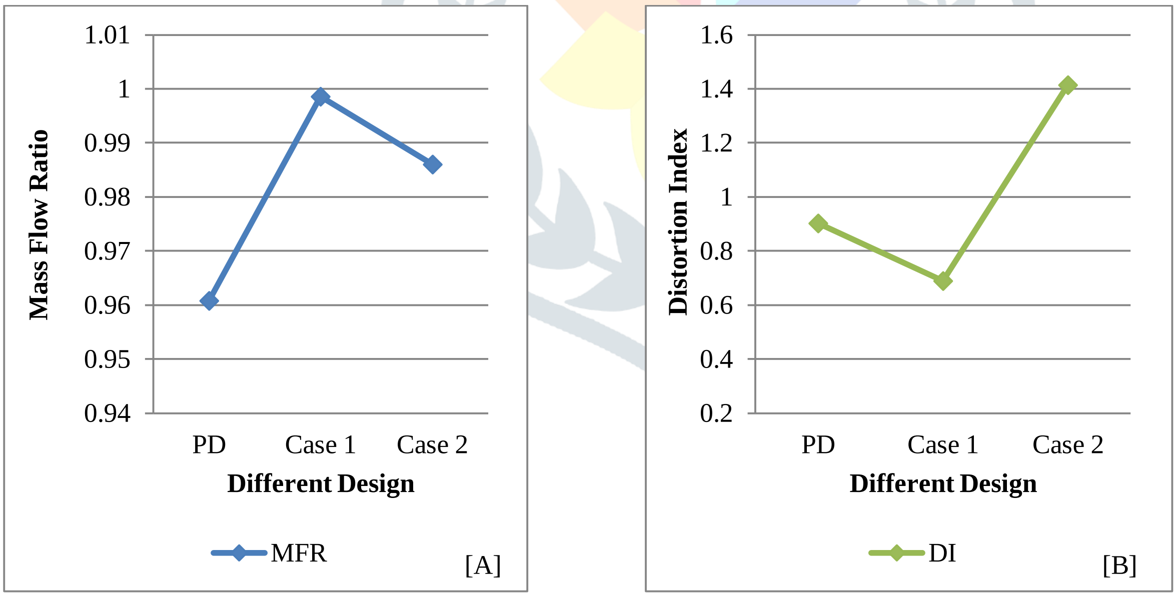

Fig. 4.2.5[A, B] Study of performance parameters for different design

Fig. 4.2.5 [A, B] represents the MFR and DI for the preliminary design and the optimized design with and without side plate respectively. The mass flow ratio for the case 2 [3D] is 0.989 and for PD is about 0.963. So that, the mass capture capacity of the optimized design is clearly improved compare to the PD. Similarly, the flow non-uniformity for the case 2 is higher than the PD. Hence, the optimized geometry is superior in performance at On-design M_∞=2.2.

5 Conclusion

In modern propulsion technology the intake systems play typical role in vehicle performance. Hence, the rectangular ramjet intake performance study is considered for our research work. Here, we have done the design and conducted numerical simulations for preliminary design to evaluate its performance.

The results of the present study can be concluded as below.

- The two dimensional design with cowl opening angle of 10^0, cowl height of 6 mm and 2 mm shorter throat height without side plate effect is better one to get maximum mass flow rate through the inlet and it has more uniform flow. This design has mass flow ratio of 0.998, total pressure recovery of 0.901 and distortion index of 0.665.
- By conducting 2D analyses, we have obtained an improved the mass flow rate about 3.79% compared to preliminary design at zero-degree angle of attack (cowl is parallel to the ramp surface).
- Finally, we concluded that the design with cowl opening angle of 10^0, cowl height of 6 mm without swept side plate effect is best one to get better performance quality. Also, the mass flow rate highly influenced by shock-shock, shock-boundary layer interaction and flow separation.

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