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Investigation of Corner Rounding Effects on the Performance of a Supersonic Air Intake

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Abstract

In this research, flow is simulated numerically through and around a mixed-compression intake to investigate effects of corner rounding on intake performance at free stream Mach numbers of 1.8, 2 and 2.2 and at zero degrees angle of attack. Furthermore, effects of different Mach numbers and back pressures are studied. Total Pressure Recovery (TPR), Flow Distortion (FD), Mass Flow Ratio (MFR) and drag coefficient (C_D) are chosen as the intake performance parameters. CFD results are validated with experimental data. Results showed that increment of back pressure generally can improve the performance while increasing Mach number has unfavorable effects on TPR. Also applying fillet can significantly improve performance parameters of FD and MFR. However it doesn't TPR and C_D.

Keywords: *"Supersonic intake", "Intake performance", "fillet radius of curvature", "Mach number"*

1. Introduction

Air intakes play an important role on performance, maneuvering and as a result general efficiency of air-breathing engines [1]. The main task of intakes is to supply sufficient amount of air through combustion [2]. Therefore, design of proper geometry for the intake can improve performance of supersonic air-breathing vehicles. As a result, many studies have been performed to investigate effects of various geometry parameters on performance of the intakes.

Holland [3] conducted a computational parametric study to investigate influence of some geometric parameters including leading edge sweep angle and leading edge position of cowl on performance of a 3-D, sidewall scramjet intake. Hongjun and Dimitri [4] presented a method for preliminary design of a mixed-compression supersonic air intake in order to maximize TPR while providing required mass flow rate. After validating the results of on-design condition with CFD data, they extended their method for off-design condition. Xiong, et al. [5] numerically analyzed the effects of different shapes of cowl leading edge on intake performance of ramjets. They simulated different types of cowl leading edge at various free stream Mach numbers, angles of attack and outlet static pressures. They showed that choosing sharper cowl leading edge reduces intensity of the bow shock and normal shock location is approached to exit of intake. CFD methods were used by Xu, et al. [6] to optimize intake geometry of a scramjet. Geometry parameters including length and angle of each wedge were considered to maximize TPR. Using CFD methods, Mohamed, et al. [7] presented a method to calculate intake TPR as a function of geometry parameters, including intake lip position on x-axis and intake height. They showed that increment of mentioned parameters lead to TPR decrement. Applying bleed to mitigate destructive effects of shock wave boundary layer interaction and flow separation have been investigated by Soltani, et al. [8], Wan and Guo [9] and Hirschen, et al. [10]. Results indicated that applying this tool increases performance and stability of intakes.

To summarize, many studies have been done to investigate effects of geometric parameters on aerodynamic performance of supersonic air intakes. Corners in some of them were sharp while in the others were rounded. However, in reality, cowl lip radius has significant effects on the intake performance and starting problem [11]. Therefore, Singh, et al. [12] studied effects of corner rounding on performance of double offset Y-shaped aircraft intake duct. They showed that by rounding sharp corners, performance and flow characteristics improve significantly. To the author's knowledge, there are not enough researches which focus on influences of corner rounding in intake. As a result, the main objective of this paper is to study effects of using fillet at sharp corners on performance of a mixed-compression supersonic air intake. Simulations are performed numerically in different radius of curvatures at different free stream Mach numbers and TPR, MFR, FD and C_D are considered as performance parameters.

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2. Numerical Methods and Code Validation

In the current study, an axisymmetric mixed-compression intake with design Mach number of 2 is simulated. In this intake which is shown in Fig. 1, oblique shocks are created inside and outside of intake which finally lead to a normal shock inside the intake.

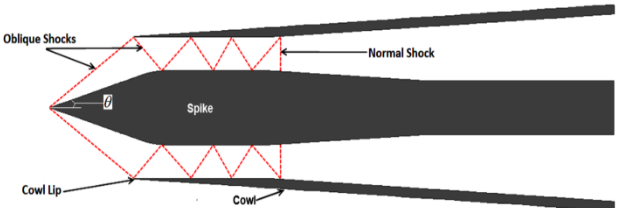


Fig. 1: Intake geometry and shock pattern

Operating conditions of a supersonic intake are supercritical, critical or subcritical. As represented in Fig. 2, when the normal shock is placed upstream of throat, it is called 'subcritical'. Conversely, in supercritical condition, normal shock will be placed downstream of throat and in critical condition, it is very close to the throat section.

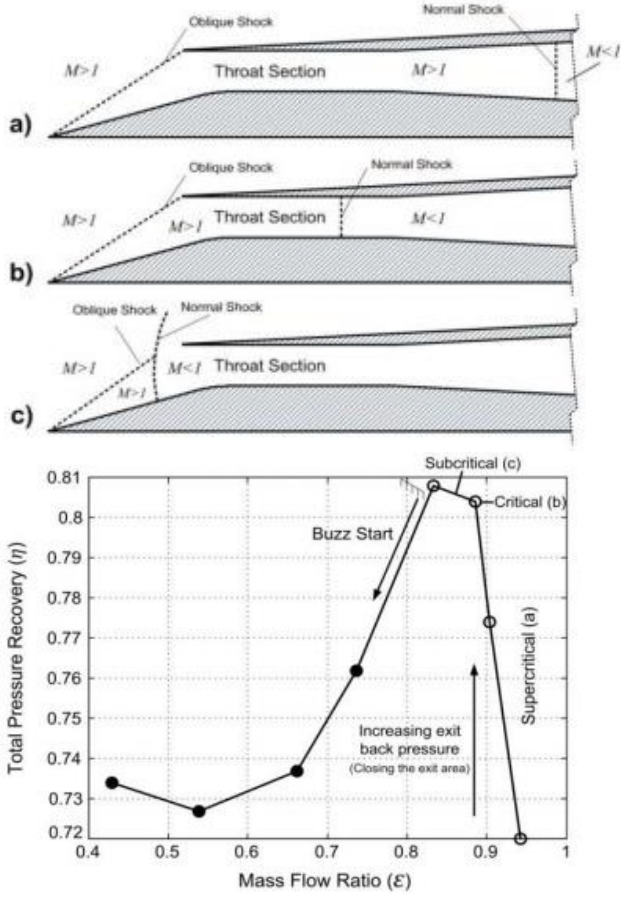


Fig. 2: Performance of a mixed-compression intake, (a) supercritical (b) critical and (c) subcritical

Grid solution study has been performed to ensure independency of the results from mesh. Finally a mesh with about 90000 cells was chosen as the most optimum grid. In addition the first node (or cell centroid) was chosen at y^+equal to unity. Final mesh has been shown in Fig. 3. To generate high quality structured mesh inside and around the intake, physical domain is divided into three blocks which are presented in Fig. 4.

In order to investigate effects of fillet on performance of supersonic intake, TPR, FD, MFR and C_D are analyzed in various conditions.

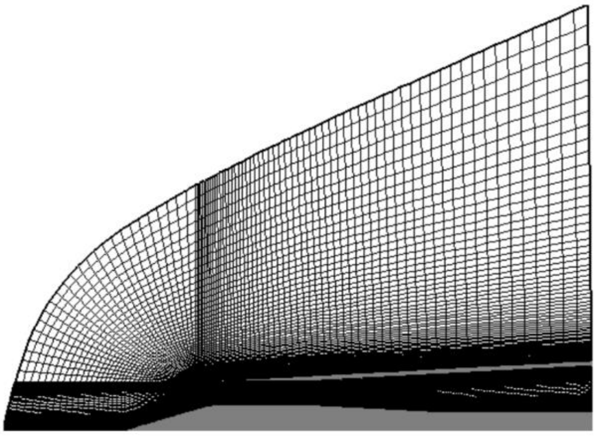


Fig. 3: Grid generated inside and around the intake

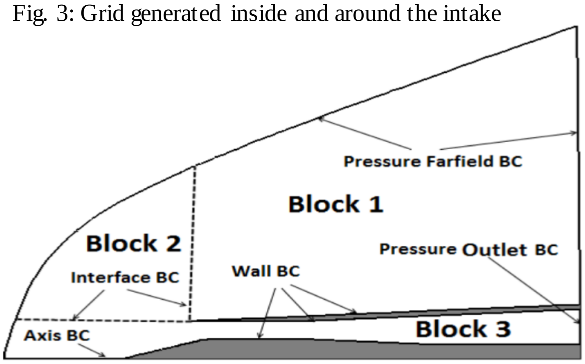


Fig. 4: Computational blocks and boundary conditions.

TPR is defined as the ratio of total pressure at exit face to total pressure of free stream:

$$TPR = \frac{P_{0e}}{P_{0\infty}} \qquad (1)$$

Total pressure at exit face, P_{0e}, is calculated by the area weighted averaging of the total pressure at outlet.

MFR is defined as the ratio of intake actual mass flow rate to its maximum value:

$$MFR = \frac{\dot{m}_i}{\dot{m}_\infty} = \frac{A_i}{A_\infty} \qquad (2)$$

Flow uniformity is measured by FD at the exit face:

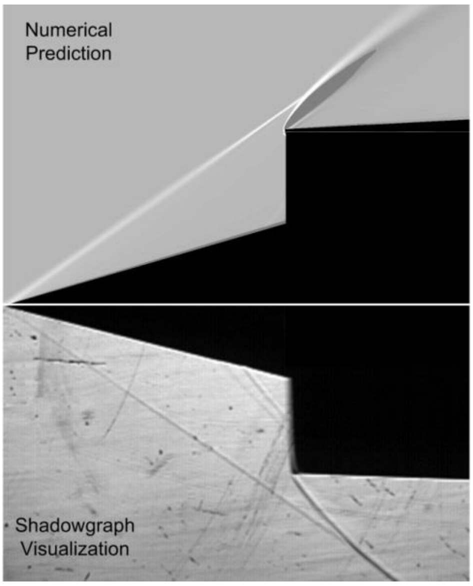
$$FD = \frac{(P_0)_{max} - (P_0)_{min}}{(P_0)_{avg}} \qquad (3)$$

High values of TPR and MFR and Low values for FD and Cd are favorable for intake operation.

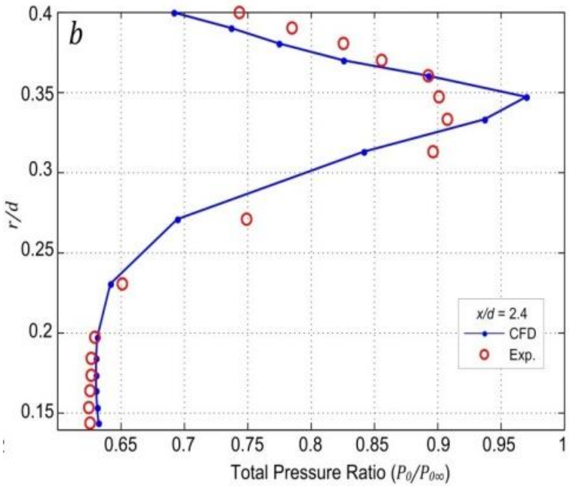
A CFD solver was used in this research to simulate the flow inside and around the intake. In this code, Reynolds-averaged Navier-Stocks (RANS) equations are discretized using an explicit finite volume method. The convective fluxes are computed by the second order accurate Roe scheme.

Laminar viscosity coefficient has been calculated using Sutherland relation. The turbulent viscosity coefficient, however, has been calculated by the k-ω SST turbulence model.

To validate the numerical methodology, static pressure distribution over the spike and total pressure profile at the end of intake are compared with experimental data of Soltani, et al. [13] obtained from the wind tunnel testing of the present intake. According to Fig. 5, acceptable agreement is observed between the numerical and experimental results.



(a)



(b)

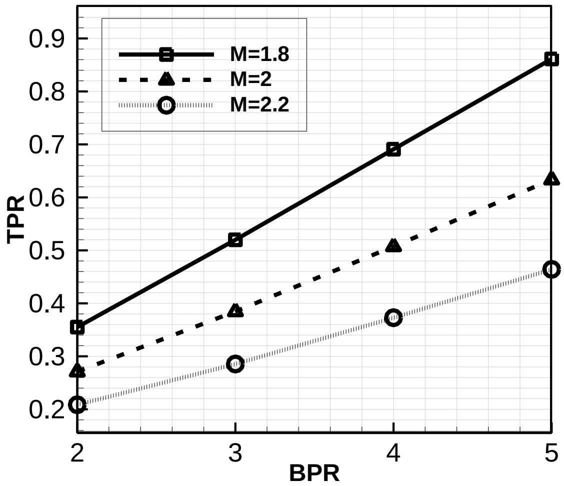
Fig. 5: Comparison of the numerical and experimental results for $M_\infty = 2$ and $\alpha = 0$ a) shadowgraph picture against present numerical simulation (b) radial distribution of total pressure ratio at $^{x}/_{d} = 2.4$ (d is the maximum intake diameter).

3. Results and Discussion

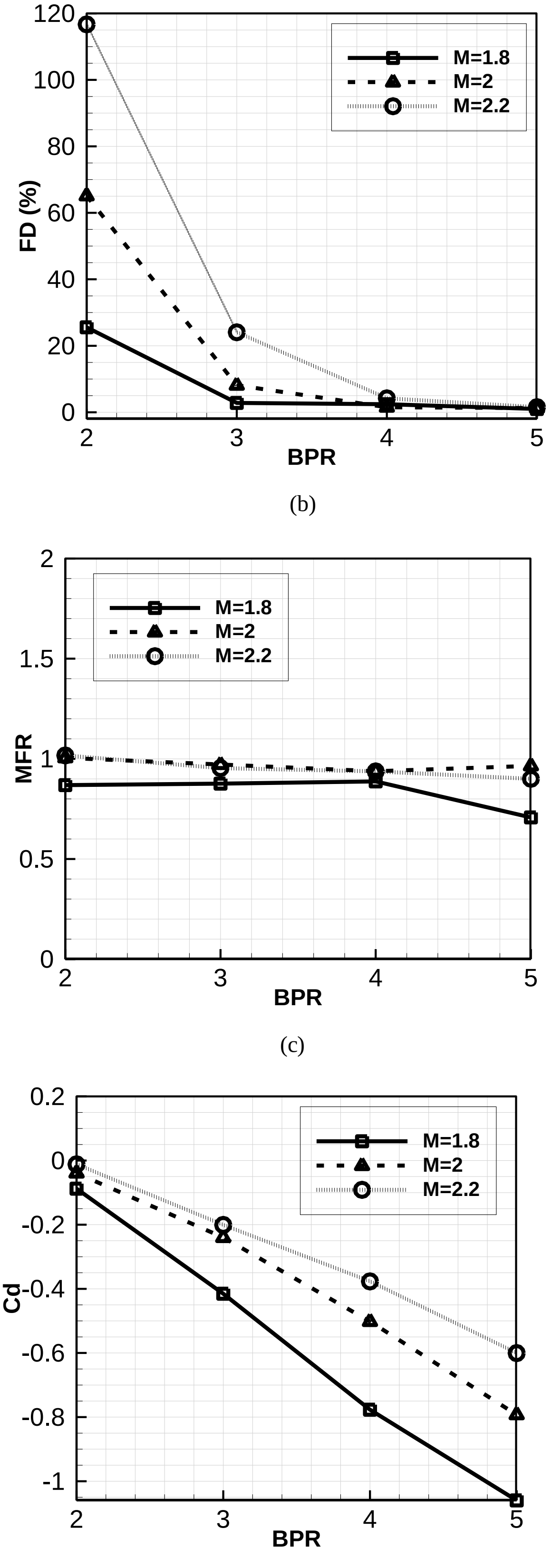
3.1. Effects of Back Pressure and Mach number

The simulations are done in supercritical operating condition and therefore increasing the back pressure causes movement of the normal shock toward upstream. Back pressure is normalized with free stream static pressure and is expressed by Back Pressure Ratio (BPR). By movement of the normal shock toward the throat and standing in a position with smaller area, its strength is reduced and as a result the TPR increases (Fig. 6(a)). However, according to this figure, TPR is reduced by increasing Mach number. That is due to the stronger shocks at higher Mach numbers. As shown in Fig. 6(b) increment of back pressure can reduce FD while it is increased by Mach number increasing. First is because of the movement and weakening of the inside normal shock by increasing back pressure and second is due to the strengthening of shocks that causes the flow to separate seriously and create a non-uniform flow. As shown in Fig. 6(c), there is not significant alteration in MFR by increment of back pressure because the intake operating condition is supercritical in these back pressures and changing the back pressure has no effect on the shock pattern ahead of the intake. This is in agreement with the performance curve illustrated in fig. 2. Fig. 6(c) also shows a reduction in MFR for M=1.8. This is due to this fact that the starting Mach number of the present intake is about 1.95 and as a result the intake has not been started at M=1.8 and the normal shock is outside the intake.

The isolated supersonic intake can have a negative drag force in supercritical and critical operating conditions. As seen from Fig. 1, at these conditions there is a normal shock inside the intake that significant increase of static pressure behind this shock and divergent duct of subsonic diffuser cause a considerable force in opposite direction of the drag force. As the BPR increases, normal shock moves toward throat and as a result this propulsive force increases. However, when the free stream Mach number increases the internal normal shock moves downstream and the magnitude of the propulsive force decreases. Obviously, when the intake is installed on an engine the total drag will be positive.



(a)



(b)

(c)

(d)

Fig. 6: Variations of performance parameters of no fillet intake for different back pressures and Mach numbers, (a) TPR (b) FD (c) MFR and (d) C_d

3.2. Effects of Fillet Radius of Curvature

Fillet radius of curvature, r_f, is normalized with radius of cowl, r_c, which is demonstrated in Fig. 7.

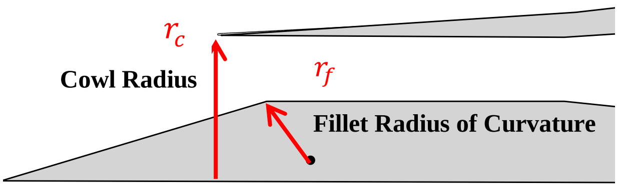
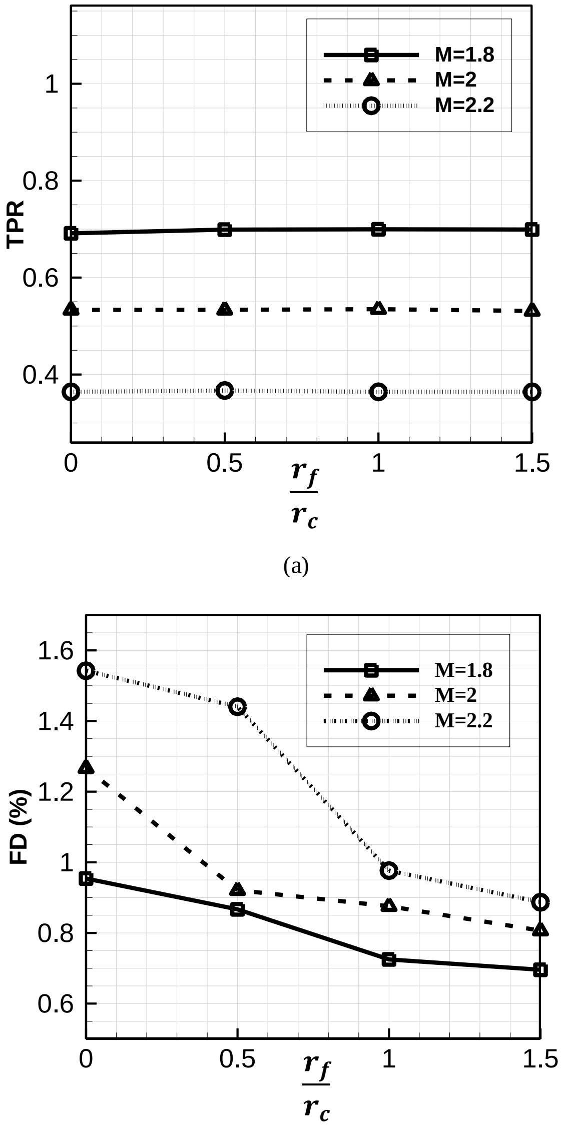


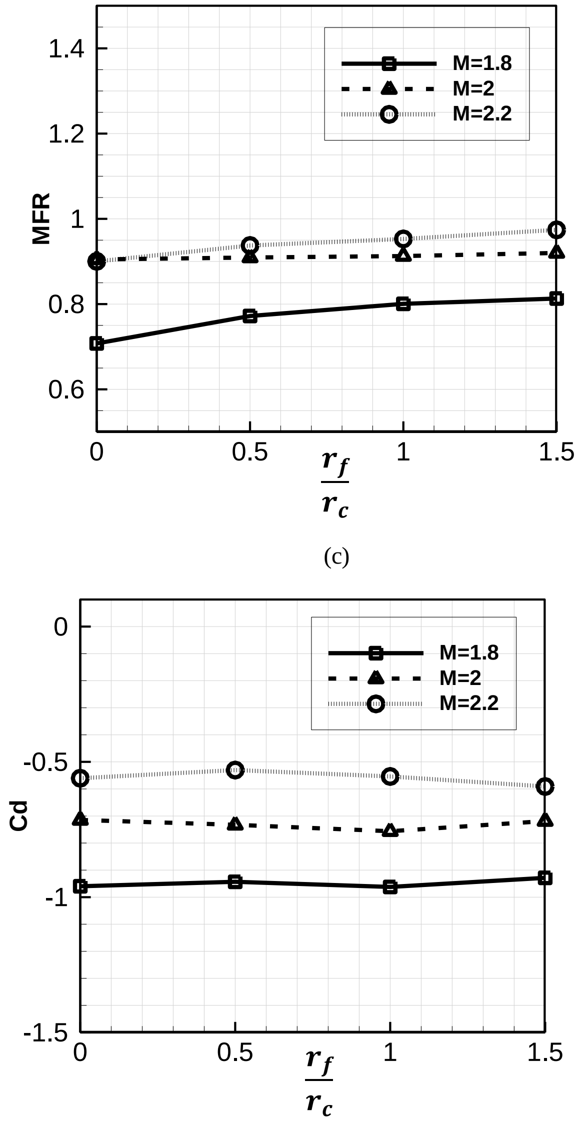
Fig. 7: Fillet radius of curvature and cowl radius

As illustrated in Fig. 8(a and b), $C_D$and TPR are not changed by different fillet radiuses of curvature because these parameters are integral quantities and are not affected by alteration of radius of curvature.



(a)

(b)

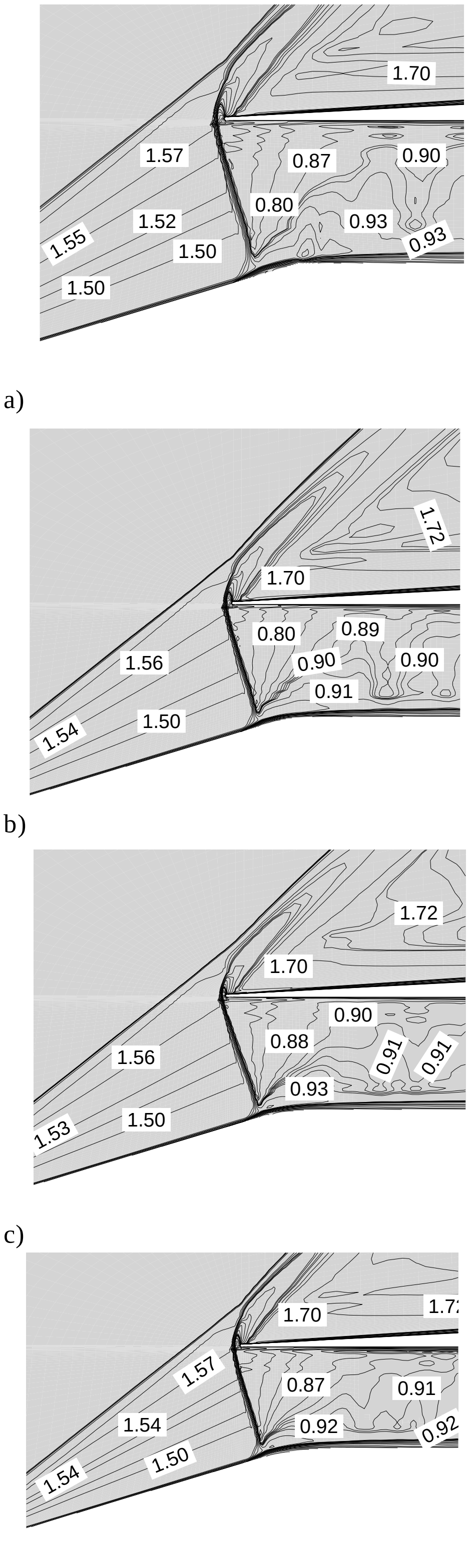


(c)

(d)

Fig. 8: Variations of performance parameters for various fillet radiuses of curvature at $BPR = 4$, (a) TPR (b) FD (C) MFR and (d) C_d

As seen from Fig 8. (c) MFR is almost constant for various radiuses of curvature at free stream Mach numbers of 2.0 and 2.2. However, it has small variations for M=1.8. As mentioned earlier, this intake is started for M=2.0 and 2.2 and as a results, SOL (Shock on Lip) is obtained, i.e. the spike conical shock collides with the cowl lip for these Mach numbers. The amount of spillage flow around the cowl lip is minimum in SOL for various radiuses of curvature. At M=1.8 the normal shock is outside the intake and as the radius of curvature increases from rf=0 to greater values, the normal shock stands closer to the cowl lip (Fig. 9) and reduces spillage that causes an increase in MFR.



a)

b)

c)

d)

Fig. 9: Contours of Mach number for different fillet radiuses of curvature at $M = 1.8$ and $BPR = 4$, (a) No Fillet (b) $r_f/r_c = 0.5$ (c) $r_f/r_c = 1$ (d) $r_f/r_c = 1.5$

Figure 8 (b) shows that the major effect of applying filleted corner instead of a sharp one is on the intake flow distortion that is an important parameter for proper operation of fan, compressor or combustion chamber after intake. As seen from Fig. 9 the flow separation is reduced by increasing the radius of fillet that in turn decreases FD.

4. Conclusion

In this research, flow at free stream Mach numbers of 1.8, 2.0and 2.2 and at zero degrees angle of attack was simulated numerically through and around a mixed-compression intake. The purpose of current study was to investigate effects of corner rounding, back pressure, and free stream Mach number on intake performance. Results indicated that by increment of fillet radius of curvature, FD and MFR are improved. However, TPR and C_d are almost constant due to their integral inherent. Also by increasing back pressure, performance generally improves in supercritical conditions while increment of Mach number has reversed impacts on TPR.

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