

# Effects of Mach Number and Angle of Attack on Mass Flow Rates and Entropy Gain in a Supersonic Inlet

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**Abstract**—A parametric study of a mixed-compression supersonic inlet is performed and reported. The effects of inlet Mach Numbers, varying from 4 to 10, and angle of attack, varying from 0 to 10, are reported for a constant inlet dynamic pressure. The paper looked at the variations of mass flow rates through the inlet, gain in entropy through the inlet, and the angles of the external oblique shocks. The mass flow rates were found to decrease monotonically with Mach numbers and increase with angle of attacks. On the other hand the entropy gain through the inlet increased with increasing Mach number and angle of attack. The variation in static pressure was found to be identical from the inlet throat to the exit for Mach number values higher than 6.

**Keywords**—Angle of attack, entropy gain, mass flow rates, supersonic inlets.

## I. INTRODUCTION

THE quest for the highest attainable speed by the aerodynamic industry is continuous. Much energy is focused on improving the design and efficiency of the different air-breathing propulsion engines in order to expand their Mach number range of operability. The inlet is the first component of an air-breathing propulsion system. The function of the inlet is to provide appropriate mass flow and velocity to the engine with high total pressure recovery, flow uniformity and flow stability, all of which are important to the overall engine efficiency. The leading edge shock system, the terminal shock boundary layer interaction, the decelerating subsonic flow and the associated rapidly growing boundary layers combine to form typical inlet flows. Analysis of supersonic inlet flows are complicated by the presence of mixed subsonic and supersonic flows, shock boundary layer interactions that may or may not cause separation [1].

Currently there are a number of supersonic inlet designs in various applications. Most of the inlets used in supersonic flight today are external compression inlets. This means that the terminal shock occurs at the entrance to the inlet and that the flow is subsonic throughout the inlet to the engine face. A classic example of this type of inlet is the sharp-edged air intakes on the sides of the fuselage of an F-18 fighter jet. A second type of supersonic inlets is the mixed-compression inlets. The name is derived from the fact that air compression process initiates outside of the inlet and continues inside. The terminal shock is located inside the inlet and the shape of the inlet can be changed by moving either the inner center body or the outer surface (cowl) to re-position the terminal shock for optimum efficiency in flight. As a result of this configuration mixed-compression inlets are capable of high Mach number flight and they are exceptionally efficient when operating at their design Mach number. Figure 1 shows the schematic of a typical mixed-compression supersonic inlet. The current study focuses on a mixed-compression supersonic inlet.

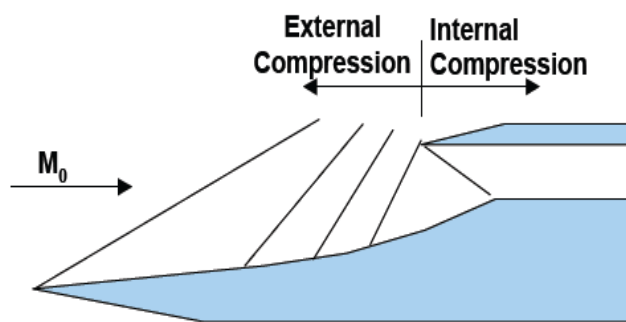


Fig. 1: Schematic of mixed-compression supersonic inlet

There is, however, numerous design issues that have plagued the mixed-compression design and these are responsible for the inlets being used only in missiles and in limited number of (primarily) military aircraft. For example, inlet unstart and buzz are several of the features of mixed-compression inlets that the scientific community has been wrestling with since the mid-1960's to bring this approach to

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regular commercial use. Typically, mixed-compression inlets perform poorly at subsonic speeds.

Flow in inlets of supersonic air-breathing propulsion systems possesses several characteristic features that make experimental investigation a challenging and often difficult task. Experimental investigations can highlight gross parameters, such as pressure recovery, mass flow rates, approximate shock location, etc. A Two-Dimensional Bifurcated (2DB) Inlet, which is a mixed compression inlet, was successfully tested in NASA Lewis Research Center's supersonic wind tunnel [2]. These tests were the culmination of a collaborative effort between the Boeing Company, General Electric, Pratt & Whitney, and Lewis. The results, which met or exceeded many of the High-Speed Research (HSR) program goals, were used to revise system studies within the HSR Program. Another experimental investigation was conducted at NASA Langley, Mach 4 Blowdown Facility [3].

However, in order to find the finer details, features such as flow reversal and separation, shock-boundary layer interactions and shock reflection, one needs to resort to detailed numerical simulation. The current work examines the effect of Mach number variation and the angle of attack on a fixed geometry, two dimensional, mixed-compression supersonic inlet through Computational Fluid Dynamic (CFD) analysis. The CFD simulations are performed using parallel computing on a Linux Cluster. The paper presents results detailing the variation on the flow field, oblique shock angles, entropy generation and exiting mass flow rates.

## II. METHODOLOGY

### A. Mixed Compression Inlet Geometry

The mixed compression inlet configuration chosen for the current study was based on the numerical simulation of a two dimensional mixed compression supersonic inlet carried out by M. K. Jain and S. Mittal [4]. This geometry presented the most comprehensive set of data readily available in the open literature. The details of the inlet, along with the dimensions, are shown in Figure 5.1. The geometric throat is located at 1.49 m (58.8 in.) from the leading edge of the intake. The first compression ramp is at an angle of  $7^\circ$  to the flow and is 0.71 m (28 in.) long. It is followed by the second ramp which is at an angle of  $14^\circ$  to the free-stream flow. The distance of the cowl tip from the leading edge of the intake is 0.772 m (30.40 in.). The overall axial distance of the inlet is 2.578 m (101.5 in.).

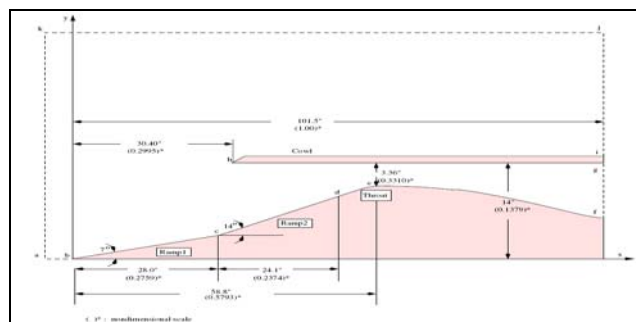


Fig. 2: Geometry of the Supersonic Mixed-Compression Inlet.

### B. Solution Algorithm

The CFD simulations of mixed compression supersonic inlet internal flow path were performed with CFD code CHEM. CHEM is the first application developed using the Loci framework [5]. CHEM is a full featured Navier-Stokes solver for non-equilibrium flows involving chemical reactions. The solver uses advanced generalized grid algorithms based on finite-volume methods and high resolution Riemann solvers. In the code, a finite-volume procedure is applied to discretize the flow equations. The governing equations are written in vector form for an arbitrary control volume for a three-dimensional flow with non-equilibrium chemistry and equilibrium internal energy. The finite-volume technique, implemented in CHEM, is frequently used because it can guarantee that numerical truncation errors do not violate conservation properties. In the current work the ideal gas air model (air\_1s0r) chemistry model is used. To limit *Muscl* extrapolation scheme Venkatakrishnan limiter is used.

### C. Grid Description

The grids for the CFD simulations were generated using the commercial code GRIDGEN. To obtain a grid independent solution several grid density parametrics were performed with the base line configuration.

The computational domain consists of a 2-D representation of the experimental hardware internal flow path and direct surrounding. The grid is created using unstructured Delaunay triangulation mesh. An *Unstructured Grid* has no inherent ordering of the cells, and so, the arrangement of cells must be specified explicitly. Unstructured grids allow greater flexibility in generating and adapting grids at the expense of greater storage of cell information. In this research a total of 127,012 triangular elements were used with nodes clustered in the critical flow path regions. This grid density was similar to the density of Jain et. al. [4]. The grids of the computational domain are shown in Figure 3.

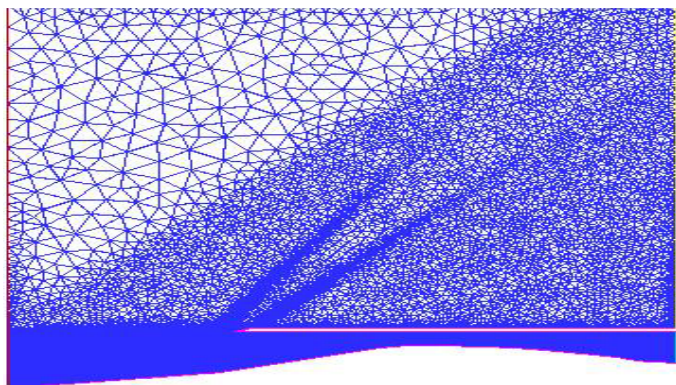


Fig. 3: View of the Finite Element Mesh With Triangular Elements

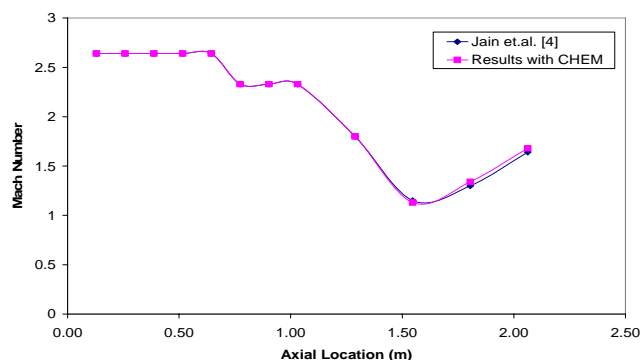


Fig. 4: Comparison of Mach Number Along the Ramp of the Inlet.

#### D. Boundary and Initial Conditions

The simulation conditions modeled in this analysis for benchmarking were extracted from the work of Jain et. al. [4] case R52.1. The computational line is shown via broken lines in Figure 2. The axial length of the inlet ramps is 1.323 m (52.1 in.) thus the name R52.1.

Inlet was supersonic flow with Mach number of 3, temperature of 229 K and a static pressure of 0.2975 atm. The no-slip adiabatic viscous wall condition was used for cowl and inlet surfaces. The upper boundary was considered farfield with the same conditions as inlet. The outlet was considered supersonic.

For the parametric study of the current work four different Mach numbers were used (4, 6, 8, and 10) along with five angles of attacks (0, 2, 4, 6, and 8). For every case an inlet temperature of 229 K and a dynamic pressure of 71,820.44 Pa (1500 lb/ft<sup>2</sup> (psf)) were used. This fixed dynamic pressure translated into different static pressures corresponding to the four Mach numbers. These inlet static pressures were 6,413 Pa, 2850 Pa, 1603 Pa, and 1026 Pa. For each case the initial conditions were set at the inlet conditions.

### III. RESULTS AND DISCUSSION

The CFD results were first validated by simulating the case R 52.1 of Jain et. al. [4] and comparing the results. This geometry is the base case geometry of the current work. The boundary conditions are those described in section II-D. Figure 4 shows the plot of Mach number distribution along the ramp of the inlet. The figure shows excellent agreement. The plots are almost identical with a slight over prediction near the exit. In order to study the effects of Mach number and angle of attacks, twenty cases were simulated with the inlet conditions as described in section II-D. In each case the inlet dynamic pressure was kept constant at 71,820.44 Pa (1500 psf). Figures 5 and 6 show the contour plots of Mach number and pressure of the base line case, which is the case with an inlet Mach No. of 4 and zero angle of attack. The Mach No. contour plot indicates that the flow remained supersonic on the entire simulation domain. Both the plots clearly show the locations of the oblique shocks in the flow field.

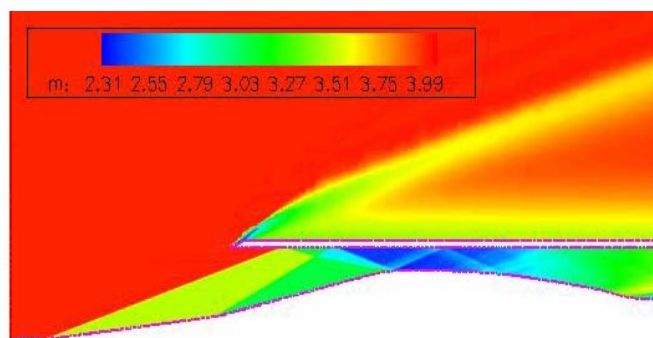


Fig. 5: Mach Number Contour Plot of Base Line Case (M=4 and =0°)

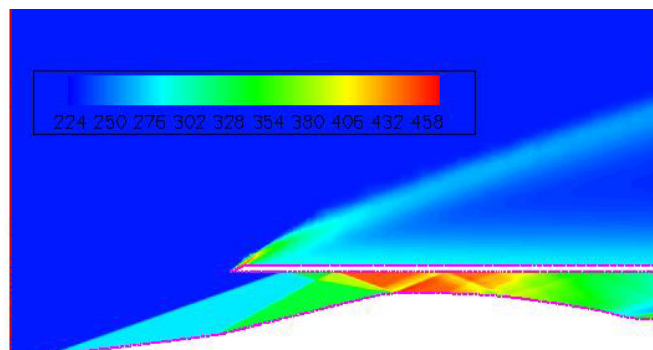


Fig. 6: Pressure Contour Plot of Base Line Case (M=4 and =0°)

For each simulation, the angles of the external shock were calculated. Figure 7 shows the variation of the external shock angle as a function of inlet Mach No. for zero angle of attack simulations. For an inlet Mach No. of 4, the first external oblique shock occurs at an angle of 14° from the inlet ramp. It reflects on the upper inside wall of the inlet, just past the cowl. As the inlet Mach No. increases to 10, the oblique shock angle decreases to 4° from the inlet ramp and merges with the second shock. Figure 8 shows the static pressure variation along the ramp surface as a function of inlet Mach No. for the cases of zero angle of attack. The sharp edges represent the locations where oblique shocks intercept the ramp surface.

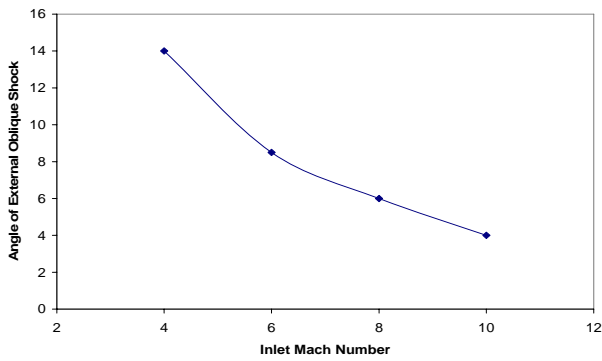


Fig. 7: Angle of External Oblique Shock With the Ramp as a Function of Inlet Mach Number.

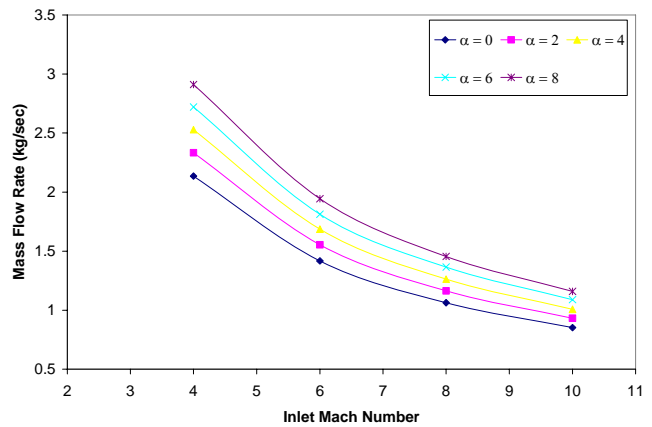


Fig. 9. Mass Flow Rate Through the Inlet as a Function of Mach Number.

With increasing inlet Mach No. the external oblique shock angle decreases, which pushes the axial location of the shock intercept location to the right. One interesting observation is that for inlet Mach Numbers of 6 and above, the pressure variation from the throat to the exit becomes identical.

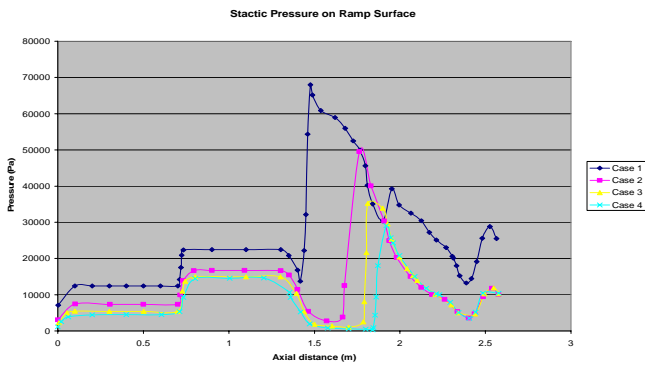


Fig. 8: Pressure Trend Along the Inlet Ramp Surface

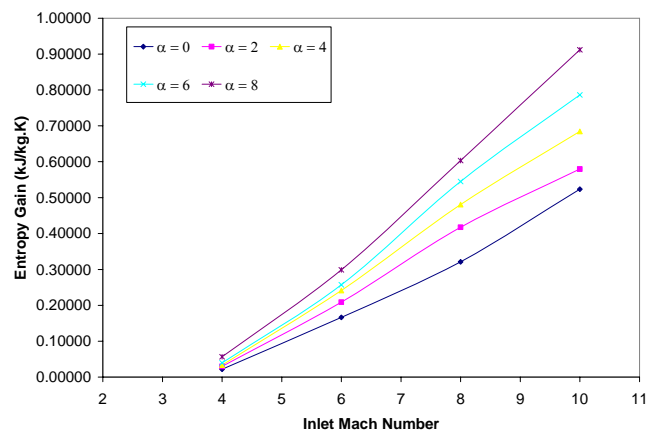


Fig. 10: Entropy Gain in kJ/kg.K as a Function of Inlet Mach Number.

Figures 9 and 10 show the plots of mass flow rate and entropy gain as a function of Mach number for different angles of attack for a length of ramp tip to cowl tip of 0.9246 m. The mass flow rate continuously decreases as the inlet Mach No. increases. This is because of keeping the inlet dynamic pressure constant which reduces the inlet static pressure. On the other hand as expected the mass flow rate increases with increasing angle of attack. The variation of the mass flow rate with angle of attack also decreases as the Mach number increases. The entropy gain for all angle of attack increases with Mach No. and at all Mach Numbers increases with angle of attack. But at higher Mach numbers the variation of entropy gain with angle of attacks become quite large.

#### IV. CONCLUSION

This work focuses on the parametric study of a supersonic inlet. This is the initial work of an overall effort to perform response surface based optimization of the inlet and determine the pareto optimal front.

#### ACKNOWLEDGMENT

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#### REFERENCES

- [1] D. Rozario and Z. Zouaoui, "Computational Fluid Dynamic Analysis of Scramjet Inlet", University of Wales, UK
- [2] *Two-Dimensional Bifurcated Inlet/Engine Tests Completed in 10- by 10-Foot Supersonic Wind Tunnel*. Research and Technology 1998. NASA TM-1999-208815, 1999, p. 107.
- [3] S. Emami, C.A. Trexler, A.H. Auslender and J. P. Weinder "Experimental Investigation of Inlet-Combustor Isolators for a Dual-Mode Scramjet at a Mach number of 4", NASA Technical Paper 3502, May 1995.
- [4] M. Kumar and S. Mittal "Euler Flow in a Supersonic Mixed-Compression Inlet", International Journal for Numerical Methods in Fluids, 2006; 50: 1405 - 1423.
- [5] E.A. Luke "CHEM: Computational Combustion Modeling", Mississippi State University, 2004.