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Computational Analysis of Scramjet Inlet

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Abstract- A numerical study of a hypersonic inlet with varying ramps and different cowl deflections has been made in this paper. This variable geometry inlet has a notable influence in shape and position of the front and cowl shock. Optimising the performance of the inlet is to operate over a range of Mach numbers at the concerned angle of attack. It is to be noted that the flow in hypersonic air-breathing engine is still supersonic at the end of the inlet and before the combustor. The interaction of oblique shock by the inlet ramp in hypersonic flow is observed. This shock may force the boundary layer to separate from the wall, resulting in pressure losses and a reduction of the inlet efficiency. Variable geometry inlets can be used over a relatively wide range of Mach numbers than the fixed geometry inlets. The numerical results are validated here by simulating the flow through a 2-D mixed-hypersonic inlet.

Keywords- hypersonic inlet, ramp, cowl deflection, oblique shock

I. INTRODUCTION

The supersonic combustion ramjet (scramjet) inlet remains a key design challenge in hypersonic flight regime. The design of this type of critical inlet component alters the overall performance of the engine. The major purpose of the air inlet is to compress the supersonic flow into subsonic flow and to diffuse the condition such that proper combustion takes place. Also to provide required amount of air to engine ensuring a stable flow and to keep the total pressure loss minimum. In hypersonic case inlets are often called as Inlet diffusers.

The wedges or compression surfaces generate shock wave resulting in compression of flow. Depending upon the type of compression the inlets are classified into three categories- internal compression, external compression and mixed compression inlet. In internal compression type the compression is carried by the flow turning in one direction by shock waves. The external compression type is best suited when operated below the design Mach number. Whereas in the mixed compression inlet the compression is done by both external and internal shocks. This produces infinitely large number of weak oblique shock waves which compresses the supersonic air stream.

It is necessary to simulate the inlet design to obtain the appropriate inlet performance. Computational Fluid Dynamics (CFD) is used to study flight simulations in both steady and un-steady flow. A time-averaged, viscous, 2 Dimensional, CFD scheme used to compute aero-thermo dynamic quantities including boundary layer effects. A variety of turbulent models available ranging from one to three equations transport models. Oblique shock waves, expansion waves and shock wave interactions are mainly considered. Accuracy of the solution is dependent on many parameters like size of the control volume, orientation of boundaries, discretization and its order of accuracy.

II. SHOCK WAVE THEORY

A. *Oblique Shock Relations*

When an object is greater than a point, shock wave is generated greater than Mach wave called oblique shock. The oblique shock relations are governed by the equations of continuity equation, momentum equation in tangential and normal direction, the energy equation and equation of state.

Continuity Equation:

$$\rho_x u_x = \rho_y u_y \tag{1}$$

Momentum Equation:

$$\rho_x + \rho_x u_x^2 = \rho_y + \rho_y u_y^2 \tag{2}$$

Energy Equation:

$$C_P T_x + \frac{u_x^2}{2} - C_P T_y + \frac{u_y^2}{2} \tag{3}$$

Equation of state:

$$PV = mRT \tag{4}$$

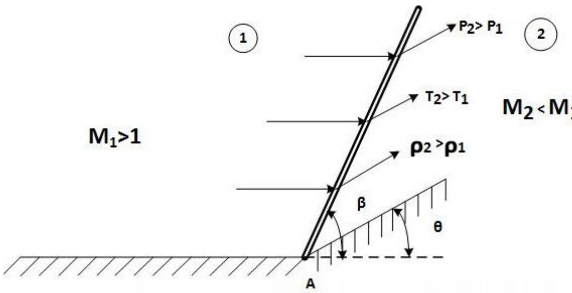


Fig 2.1 Oblique flow pattern

In oblique shock wave relations it is assumed that gas as calorically perfect. It is to be noted that in hypersonic relations if wedge angle (θ) is small then shock angle (β) also remains small.

$$\frac{P_2}{P_1} = 1 + \frac{2\gamma}{\gamma+1}(M_1 \sin^2\beta - 1) \quad (5)$$

$$\frac{\rho_2}{\rho_1} = \frac{(\gamma+1)M_1 \sin^2\beta}{(\gamma-1)M_1 \sin^2\beta+2} \quad (6)$$

$$\frac{T_2}{T_1} = \frac{P_2/P_1}{\rho_2/\rho_1} \quad (7)$$

The hypersonic pressure coefficient can be written as:

$$C_p = \frac{(P_2-P_1)}{q_1} = \frac{2}{\gamma M_1^2}\left(\frac{P}{P_1} - 1\right) \quad (8)$$

$$C_p = \frac{4}{\gamma+1}\left(\sin^2\beta - \frac{1}{M_1^2}\right) \quad (9)$$

When the flow is slowed by viscous effects inside the boundary layer loss in kinetic energy obtained due to viscous dissipation. The shock layer interacts with the boundary layer and becomes fully viscous thereby altering the shape of shock wave and pressure distribution. Supersonic diffusers produce non-uniform flow as a result of skin-friction creating boundary layer or non-uniform compression produced by the compression surface. The Euler's equation and Navier-strokes equation both admit shocks produced.

B. Prandtl-Mayer Expansion Relation

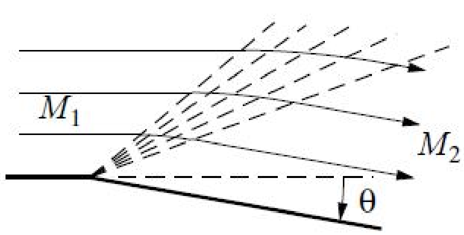


Fig 2.2 Expansion flow pattern

An expansion wave is often called as Prandtl-Mayer expansion wave. It consist of infinitesimal number of Mach waves. To analyse this particular change we must consider the flow angle θ, and flow variables like M and *v*.

$$v(M) = \sqrt{\frac{\gamma+1}{\gamma-1}}\arctan\sqrt{\frac{\gamma-1}{\gamma+1}(M^2-1)} - \arctan\sqrt{M^2-1}$$

Where *v* (M) is called Prandtl-Mayer Expansion function.

III. DESIGN SPECIFICATIONS

In mixed compression inlet the external flow is being compressed in a series of oblique shocks attached to the front ramp and extended till the cowl lip. Interaction of oblique and normal shocks create flow separation with the boundary layer. This type of inlet best suited for stagnation pressure recovery. Inlet generally consist of compression surface, cowl, throat and a diffuser shown below.

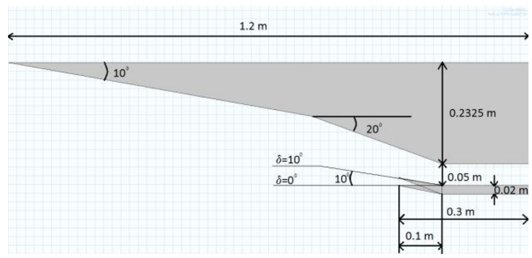


Fig 3.1 Double Ramp inlet geometry

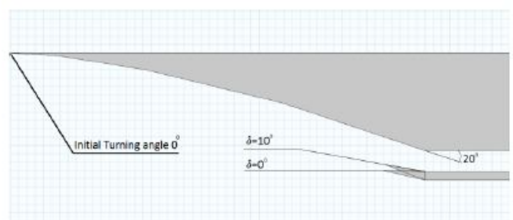


Fig 3.2. Single ramp inlet geometry

Double ramp model with a cowl deflection of 0^o and 10^o created to analyse the inlet performance. Also Single ramp model analysed with and without cowl deflection. Influence of cowl deflection studied in this paper as the cowl lip turns the incoming flow and divides into internal and external component. It is necessary to design the cowl angle in slender profile to compensate the wave drag. The flow path is changed accordingly to ensure high performance at range of Mach numbers. Throat area remains constant as 0.05m. Thrust is measured according to capture area, if more air is captured then pressure and temperature remain same. This helps in greater thrust at combustor part.

IV GRID GENERATION

A structured mesh with quadrilateral elements better suited for well resolved high Reynolds number flow. Rectangular grid generated with 5 times the length of the inlet model. Around 15 boundary layers created around the geometry which can capture the shock on lip condition. Applied mesh generated with evenly spaced structural quadrilateral cells for computation of complete grid.

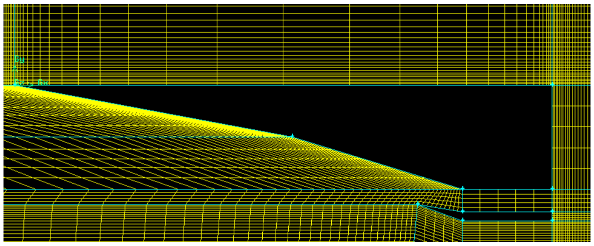


Fig 4.1 Boundary layer mesh

V. INLET BOUNDARY CONDITIONS

In a hypersonic inlet flow the flow variables like free-stream stagnation pressure, static pressure, stagnation temperature and static temperature are accounted. Pressure far-field boundary condition best suited for inlet in which gauge pressure and Mach number specified. Pressure outlet condition selected for outlet phase. Ramp, cowl, upper and lower portion of model chosen as wall.

Gauge Pressure	2511.023Pa
Mach number	5
Reference temperature	221.65K
Turbulent Viscosity	0.01
Turbulent Ratio	10
Altitude	20km

Table 5.1 Boundary condition details

The turbulence quantity is mentioned as free stream turbulence viscosity 10 (Tu_∞) i.e $k_\infty = 1.5(Tu_\infty u_\infty)^2$. Numerical Simulation carried out in FLUENT software. Calculations initially carried out in 33800 quadrilateral cells. Grid Independence study allows refinement of cell sizes in the boundary layer region without affecting other mesh areas. Later grid is then refined to 28300 cells after grid independence study.

VI. RESULT ANALYSIS

Results are concerned with the internal flow and interaction of cowl. The shock interaction generates an expansion fan. The benefit of variable- geometry inlet analysed by considering ramp and cowl deflection angles. To obtain suitable results four different geometries developed according to the dimensions in section III. The investigation carried out approximately 1,05,000 iterations. Each of which taken one second for 3.3GHz processor.

Model 1: Double Ramp without cowl deflection

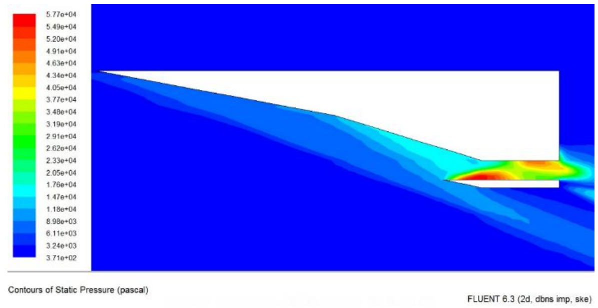


Fig 6.1 Pressure Contour

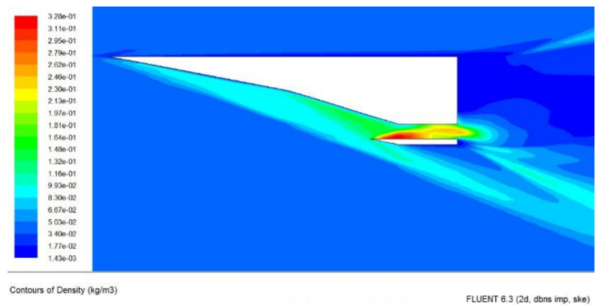


Fig 6.2 Density Contour

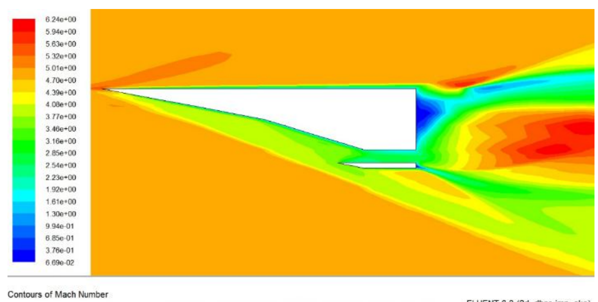


Fig 6.3 Mach Contour

Model 2: Double Ramp with cowl deflection

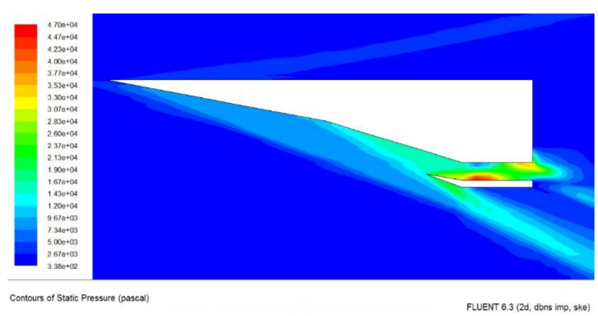


Fig 6.4 Pressure Contour

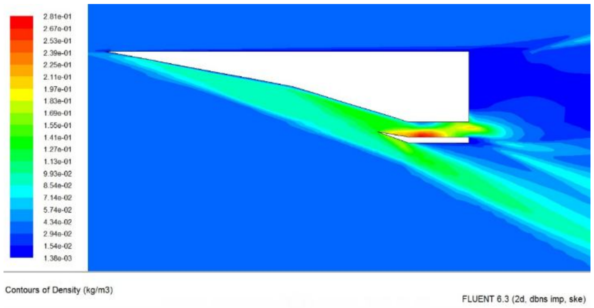


Fig 6.5 Density Contour

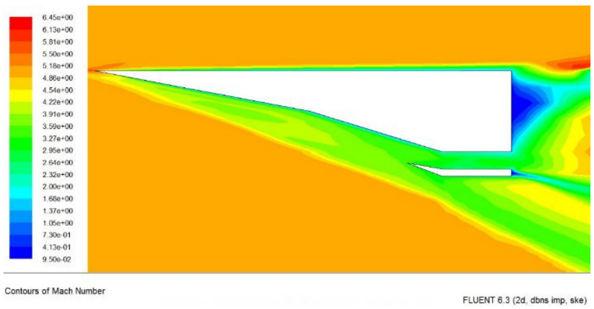


Fig 6.6 Mach Contour

Model 3: Single Ramp without Cowl Deflection

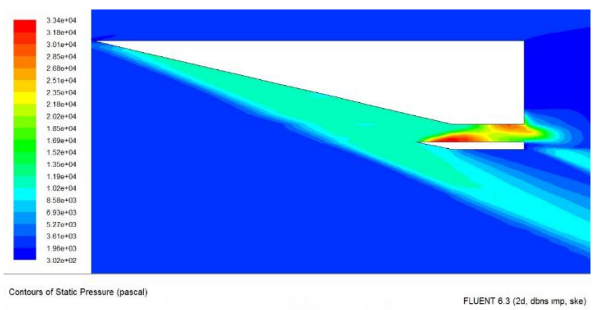


Fig 6.7 Pressure Contour

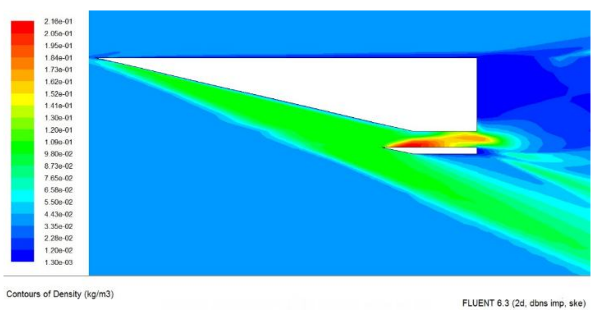


Fig 6.8 Density Contour

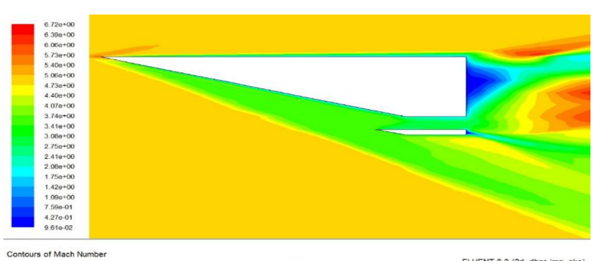
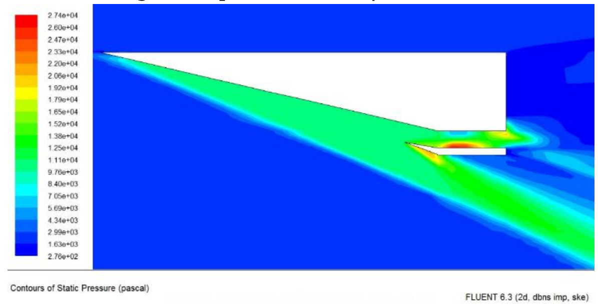


Fig 6.9 Mach Contour

Model 4: Single Ramp with Cowl deflection



6.10 Pressure Contour

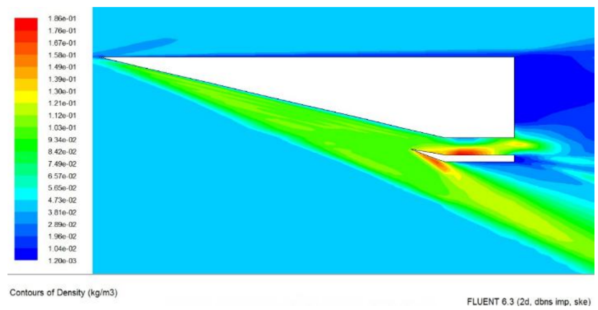


Fig 6.11 Density Contour

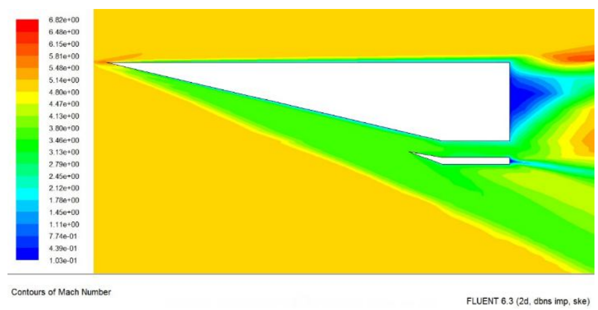


Fig 6.12 Mach Contour

VII. CONCLUSION

The simulation contours obeys the flow pattern which analysed here as plots to compare the performance of the models with respect to cowl deflection. Double ramp inlet without cowl deflection gives better increase in pressure and temperature ratio at the outlet while comparing with the single ramped inlet case.

A. Double Ramp Results

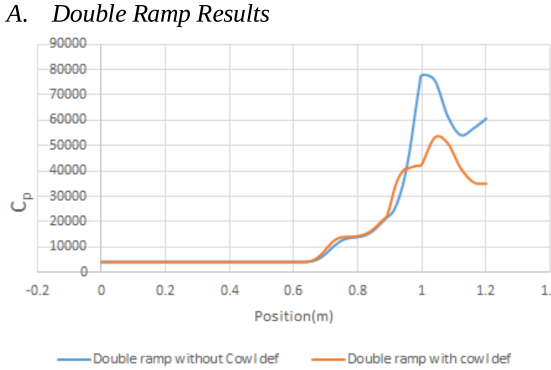


Fig 7.1 Double ramp Comparison plot

B. Single Ramp Results

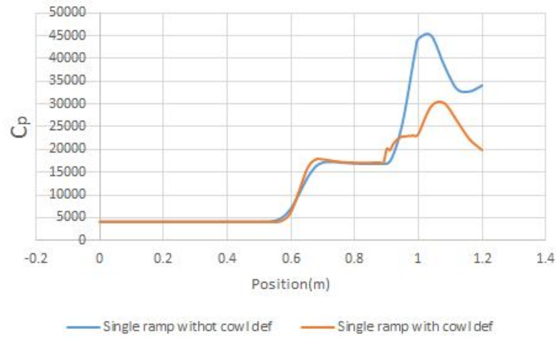


Fig 7.2 Single Ramp Comparison plot

C. Comparison between Double and Single ramp without cowl deflection

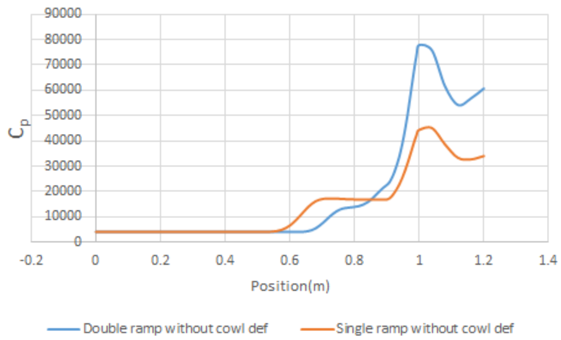


Fig 7.3 Pressure distribution in double and single ramp plot

In fig 7.1 Pressure distribution plot of double ramp model with and without cowl deflection compared. Results indicates that the model without cowl deflection gives more advantage in increasing the pressure, temperature and density parameters at the outlet. The higher pressure and temperature gas then expands to very high velocity in the nozzle. Similarly in fig 7.2 the pressure distribution plot for single ramp model also indicates that the model with 0^o cowl angle give more advantage in increasing outlet pressure. To analyse the advantage of ramps the double ramp and single ramp without cowl deflection is compared in fig 7.3. It clearly indicates that double ramped inlet gives higher peak pressure than the single ramped inlet. This paper is concentrated only the simulation of inlet.

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