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Modeling & Numerical Analysis of Supersonic Combustor with Double Inclined Ramp-Cavity Fuel Injector

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ABSTRACT

Sustaining the Supersonic Combustion in Scramjet engine is a very challenging topic of research nowadays. 'Single-stage-to-orbit' aerospace vehicles incorporating scramjet engine, is being contemplated to cut down space transportation costs. Propulsion and airframe unit integration, where the vehicle body adds to the thrust generating capacity of the engine besides providing aerodynamic lift, forms an integral part of the design philosophy. This Paper describes some challenges in the modeling of the Supersonic Combustor for proper mixing of air-fuel. Fuel Injectors are a critical component and their design has important effects for sustaining the flame in supersonic combustion as well as overall performance of the engine. Ramp injectors are considered to be a key feature to generate axial vortices. Generation of acoustic oscillations by the cavity injector is also considered to be a better candidate to achieve optimum mixing. Improvement in the performance of ramp and cavity injectors can be improved overall, by combining these injectors properly. Generation of turbulence and 3D flow field for better mixing and proper combustion relies on the combination of cavities and ramps. Ramps will improve the penetration of fuel in to the core and cavities will improve the flame holding characteristics. The ramp generated axial vortices can be utilized to scoop out the hot gases generated at cavities to improve the combustion efficiency. Thus Ramp and cavity combination shows promising characteristics for better scramjet combustor performance. Instead of having a long single inclination in the ramp, two short double inclinations can be made. By this we can prevent the sudden loss of energy. This in-turn increases the flame stabilization during Combustion.

K**eywords:** Fuel Injector, Vortices Generation, Optimum Mixing, Flame holding

1 INTRODUCTION

A scramjet (supersonic combustion ramjet) is a variant of a ramjet air breathing jet engine in which combustion takes place in supersonic airflow. As in ramjets, a scramjet relies on high vehicle speed to forcefully compress and decelerate the incoming air before combustion (hence ramjet), but whereas a ramjet decelerates the air to velocities before combustion, airflow in a scramjet is supersonic throughout the entire engine. This allows the scramjet to efficiently operate at extremely high speeds: theoretical projections place the top speed of a scramjet between 12 and Mach 24. The fastest air-breathing aircraft is a SCRAM jet design, which reached Mach 9.8. For comparison, the second fastest air-breathing aircraft, the manned, has a cruising speed of Mach 3.2.

The scramjet is composed of three basic components: a converging inlet, where incoming air is compressed and decelerated; a combustor, where gaseous fuel is burned with atmospheric to produce heat; and a diverging nozzle, where the heated air is accelerated to produce. Unlike a typical jet engine, such as engine, a scramjet does not use rotating, fan-like components to compress the air; rather, the achievable speed of the aircraft moving through the atmosphere causes the air to compress within the inlet. As such, nothing is needed in a scramjet. In comparison, typical turbojet engines require inlet fans, multiple stages of rotating, and multiple rotating stages, all of which add weight, complexity, and a greater number of failure points to the engine. Due to the nature of their design, scramjet operation is limited to near-hypersonic velocities. As they lack mechanical compressors, scramjets require the high of a hypersonic flow to compress the incoming air to operational conditions. Thus, a scramjet-powered vehicle must be accelerated to the required velocity by some other means of propulsion, such as turbojet or rocket engines. In the flight of the experimental scramjet-powered, the test craft was lifted to flight altitude by a before being released and accelerated by a detachable rocket to near Mach 4.5.

While scramjets are conceptually simple, actual implementation is limited by extreme technical challenges. Hypersonic flight within the atmosphere generates immense drag, and temperatures found on the aircraft and within the engine can be much greater than that of the surrounding air. Maintaining combustion in the supersonic flow presents additional challenges, as the fuel must be injected, mixed, ignited, and burned within milliseconds. While scramjet technology has been under development since the 1950s, only very recently have scramjets successfully achieved powered flight. Mixing, ignition and flame holding in combustor, ground test facilities and numerical simulation of Scramjet engine are the critical challenges in the development of scramjet engine. Supersonic air breathing propulsion systems are crucial for the demands of today's defense industry and future's high speed civilian transportation vehicles. On the other hand, as a direct consequence of high flow speeds, time necessary for injection, mixing, and subsequent combustion is minimal, and is typically around 1ms. This makes significant challenge in the design of such propulsion systems. In order to successfully develop advanced air breathing propulsion systems capable of high speed flight it is necessary to understand the fundamentals of mixing and combustion processes within the combustor.

2 METHODOLOGY

This paper aims to design a supersonic combustor intended for the use over a wide range of flight Mach number, operating in supersonic combustion mode. The major focus is made around ramp-cavity flame holder geometry, which incorporates the shockwave interaction to produce region for stable flame. The analysis will be performed on the designed geometry for various inlets conditions at different altitude at 12 Mach. Design of the Ramp-Cavity Supersonic Combustor is made. Theoretical Calculation of flow properties aft the oblique shock is done. Optimizing the design using the analytical values calculated. Analysis of the design under various inlet conditions using computational methods. Performance of the combustor is depicted. Study of the shock wave interaction for various ramp angles is made and a best suited value is selected for modeling the design. Model of the axi-symmetry combustor is done by using CATIA V5R16 with double inclined ramp and swept ramp. Analysis of the modeled design at supersonic flow field with shockwaves, combustion is made. Performance of the swept ramp and double inclined ramp is compared. Modeling of the SCRAM jet combustor with Ramp and Cavity fuel injector is designed in CATIA V5. The width, lengths are assumed and ramp angles are calculated numerically for desired Mach number. The cavity length and width are also assumed for the desired Mach number. The design of the combustor put in CATIA V5 is imported in GAMBIT. The meshing of the combustor is done in GAMBIT. The meshed design is imported in FLUENT. Fluid analysis is made.

2.1 Literature Survey

Kyung and Seung (2003) described the numerical investigation concerning the enhancement of combustion efficiency by creating re-circulation zone. Eklund and Burton (2005) analyzed the supersonic combustion studies by employing swept ramp Injectors. They concluded that ramp design is efficient in mixing and compared with experimental data.

Pandey and Siva (2011) carried out CFD Analysis of Mixing with Planar Strut Injector. They concluded that the flame is attached in the downstream of strut but it creates only small re-circulation zones and Weak Shock waves. Kyung Moo et al. worked on the topic of cavity based fuel injection and their findings describes when the wall angle of cavity increases, the combustion efficiency is improved but total pressure loss is increased pre dominantly.

Jeyakumar et al. (2014) investigates the experimental study on Ramp Cavities and concluded that mixing is superior and ramp angles also enhance the pressure rise.

2.2 Conceptual Design of Double Inclined Ramp-Cavity Fuel Injector

The combination of cavities and ramps generate a three dimensional flow field and turbulence for better mixing and combustion. Ramps will enhance the fuel penetration in to the core and cavities will enhance the flame holding characteristics. The ramp generated axial vortices can be utilized to scoop out the hot gases generated at cavities to improve the combustion efficiency.

Double inclined swept ramp injector is a combination of ramp with double inclination followed by cavity of filleted corners made for transverse fuel injection. The length of the scramjet combustor is a function of shockwave interaction and magnitude of turbulence. The ramp acts a corner which at supersonic speeds generates oblique shocks. The shock angle is direct function of inclination angle. From the compressible flow theory, relation between θ-β for the given Mach number could be established.

For the initiation of design, shock angle to be taken under consideration which acts as primary design driven. The values of shock angle for various ramp angles are to be studied carefully. From the literatures available, it is clear that length (L) and width (D) of the combustor also have an impact on performance.

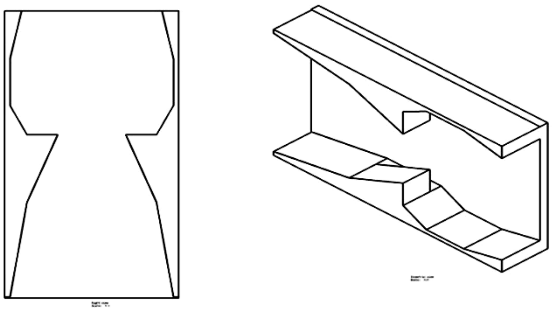

Figure 1 Double Inclined Ramp and Cavity design -2D cut section view

2.2 Computation of flow properties using compressible flow theory: (Calculations)

The oblique shock relation for a supersonic flow over a inclined surface is studied. The pressure and temperature values are found using isentropic relations. The Mach number after the oblique shock can be found by

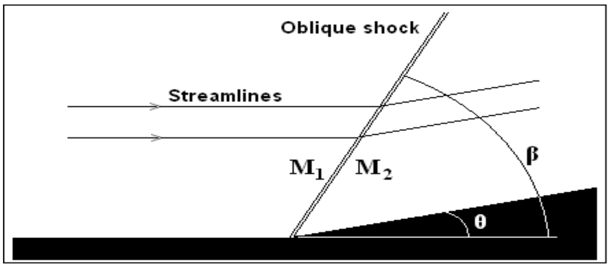

Figure 2 Formation of Oblique Shocks

$$M_2 = \frac{1}{\sin(\beta-\theta)}\sqrt{\frac{1+\frac{\gamma-1}{2}M_1^2\sin^2\beta}{\gamma M_1^2\sin^2\beta-\frac{\gamma-1}{2}}}.$$

The shock angle for various inclinations can be found from

$$\tan\theta = 2\cot\beta\frac{M_1^2\sin^2\beta-1}{M_1^2(\gamma+\cos 2\beta)+2}$$

Free stream conditions at 30 km altitude are

- Temperature – 231.83 K
- Pressure – 1.1514 e+3 N/m^2
- Density – 1.7302 e-2 Kg/m^3

After a complete analysis of shock angles for various angle inclinations, the best suited values for our design is selected. As our design is double inclined, there are two inclination angles selected for optimizing turbulence for better mixing for air and fuel. $M_\infty = 12$

Ramp-1 (Unswept)

- Inclination Angle Θ – 18.7
- Shock Angle β = 23.79

Properties after Shock

- M_2 =4.7
- T_2/T_1 = 5.496
- P_2/P_1 = 27.18
- P_{02}/P_{01} = 0.0698

Ramp-2 (Swept)

- Inclination Angle Θ – 26.5
- Shock Angle β = 38.48

Properties after Shock

- M_3 =2.34
- T_3/T_2 = 5.496
- P_3/P_2 = 27.18
- P_{03}/P_{02} = 0.0698

3 COMPUTATIONAL MESHING & ANALYSIS RESULTS

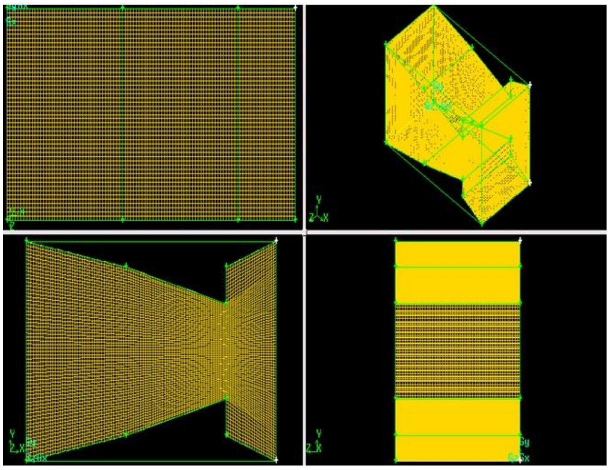

Figure 3 Different Views of Mesh

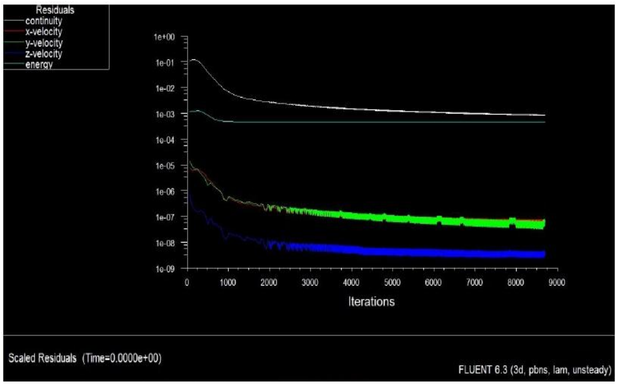

Figure 4 Iteration - Convergence

Model designed in CATIA is imported to Gambit and meshed. Mesh Shape: Tetra head/Hex; Mesh Interval: 2; Mesh Type: Cooper. The Fig.4 shows that the results of consecutive iterations satisfy the Convergence criteria.

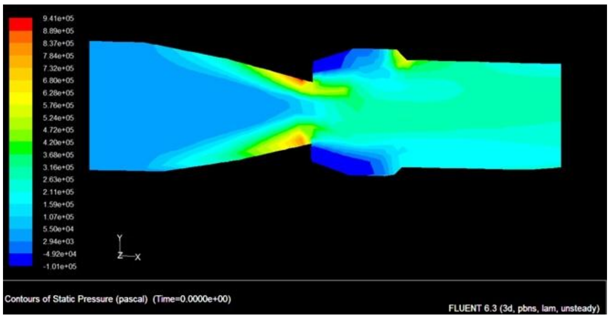

Figure 5 Static Pressure Contour

From the Fig.5 it is observed that the serious of oblique shocks are generated which is responsible for consecutive static pressure inside the Combustor.

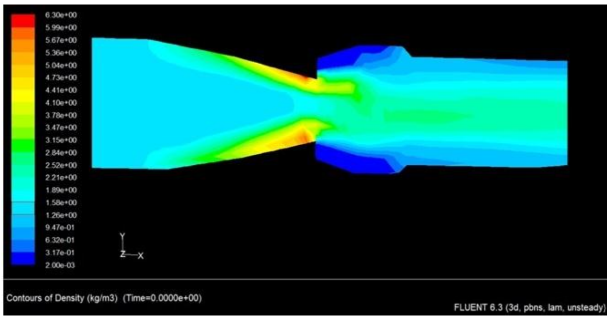

Figure 6 Density Contour

The Fig.6 shows that there is a significant rise in density gradient in the recirculation zone where the fuel mixes well with highly pressurized incoming air, which drops the velocity to zero at the recirculation zone. From the Fig.7 it is observed that the Mach number achieved in the combustor section is fully Supersonic which ranges from 1.04 to 2 – Satisfies the Supersonic Combustion Criteria.

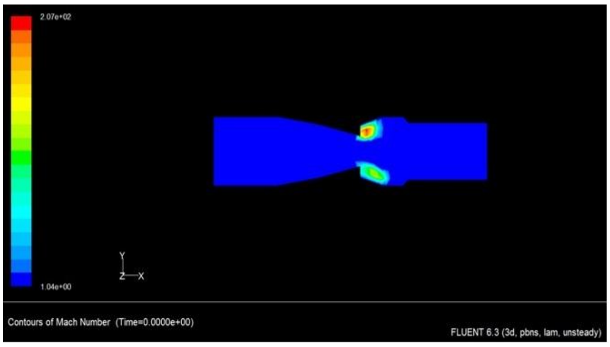

Figure 7 Mach number Contour

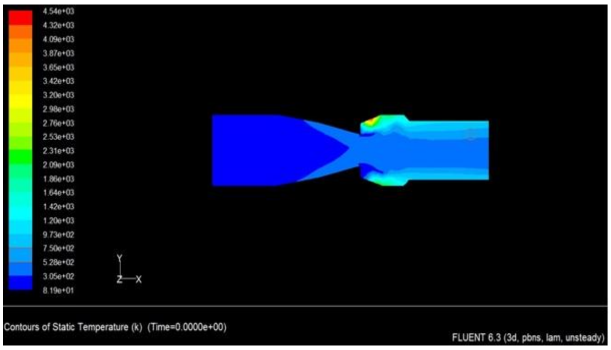

Figure 8 Temperature Contour

4 CONCLUSION

The design and analysis of double inclined swept ramp combustor is done. It has clearly observed that pressure and temperature profile of the combustor is favorable for the stable combustion. The combustor exit Mach number is 0.41(subsonic). The combustor exit temperature is 3.41e+03K (@ mean line). Thus this type of fuel injection has generated higher temperature and pressure rise. The combustor exit pressure is 6.62bar. The variable cross section combustor reduces the interaction between the inlet and the combustor due to fuel injection. This flow interaction can be further minimized by staged fuel injection. For these conditions the flame can be anchored at the cavity inside the combustor. Thus the flame holding characteristics of the combustor of SCRAM jet has been improved by incorporating the ramp and cavity fuel injector. Further studies are also required to design an optimal cavity shape for flame holding. Ideally a cavity would not only sustain a stable but at the same time should have minimum drag penalty.

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