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Computational Analysis of Scramjet Combustor Using Ramp Injector for Supersonic Applications

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This work discussed about computational analysis of ramped injector based scramjet combustor for supersonic applications. Hydrogen is injected through ramp injector and it is successfully used to model the turbulent reacting flow field. Combustion is achieved through the continuous injection of hydrogen into the supersonic flow of air. Finally the combustible flow is expanded via the nozzle. This serves mainly two purposes; one is allowing the flow to accelerate to the external speed and to provide a mechanism by which the increase in pressure can be converted into forward thrust. The supersonic combustion is governed by both mixing and chemical kinetics. In supersonic combustors, the shear losses can drastically reduce the engine performance, thus rendering the trade-off studies very complex for attaining high combustion efficiency. From the analysis it is evident that the maximum temperature of 2910K is produced in the recirculation areas.

***Keywords*:** CFD, combustion efficiency, Mach number, ramp injector

1. Introduction

Increasing the demand for affordable access to space and high speed terrestrial transport has increased research interest into various air-breathing hypersonic propulsion systems which is key importance to the ultimate success of an air-breathing concept is the ability to efficiently mix the fuel with atmospheric air. The comparison of conventional ramps and cantilevered ramps for hypervelocity flow is we discussed by Heise and Pratt. Scramjet engine composed of four main sections: the inlet, isolator, combustor and exhaust (Heise and Pratt, 1994).

1.2. Mixing Enhancement Strategy

Mixing enhancement strategies are sought to improve the mixing of fuel and air over simple parallel injection relying on shear-layer mixing. Mixing augmentation usually has an associated total pressure loss, however, which must be weighed against the gain in performance. Mixing enhancement can be achieved by judicious design of devices which introduce the fuel into the airstream. These fuel injection devices or injectors can be classified into two main categories: non-intrusive injectors such as wall orifices. These categories are not mutually exclusive or exhaustive but provide a suitable framework for an introduction to the most commonly utilized mixing enhancement techniques.

1.3. Ramp Injector

A fuel injection system that has received growing interest is the ramp injectors which are either mounted on a wall surface or become an integral part of the wall contour and inject fuel at low angles or parallel to the surrounding airflow from a downstream facing step or ramp. A variety of intrusive fuel injector designs have been proposed but the most promising of these devices are those which employ axial vortices to mix the fuel and air. These vortices have been shown to be effective for high Mach number flows which make them ideally suited for hypersonic mixing applications. Ramp fuel injectors which exploit axial vortex generation techniques show great potential for enhanced fuel-air mixing. The aim of these injectors is to convert a small fraction of the free-stream momentum into angular momentum to produce axial vortices in the interest of mixing enhancement. A ramp injector design which employs axial vortices is the so-called ‘conventional’ ramp fuel injector, shown in figure 1. This type of fuel injector was first introduced by Marble, and has subsequently been the focus of considerable research. This type of injector is the predecessor of the cantilevered ramp injector.

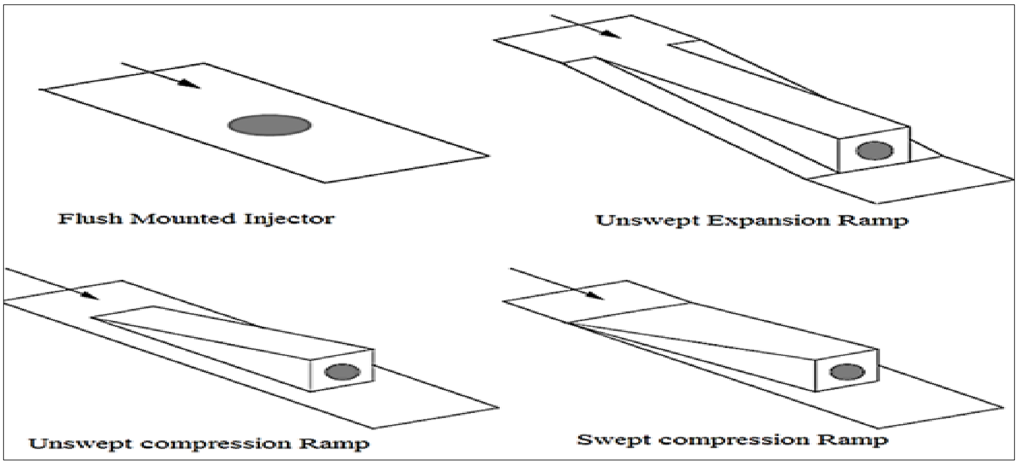

Fig. 1. Types of ramp injector

2. Historical Background

The fuel using in scramjets is usually either a liquid or a gas. The fuel and air are essential to be mixed about stoichiometric proportions for effective combustion. The key problem of scramjet fuel injection is that the air flow is quite fast which shows that there is minimal time for the fuel to mix with the air. Fuel injection may have a normal component into the flow from the inlet, but at higher Mach numbers. The injector cannot result in too several local flow disturbance, that could result in locally high wall static pressures and temperatures (Pandey et al., 2014, 2015). Some traditional methodologies for injecting fuel are: parallel injection, normal injection, transverse injection, ramp injector, strut injector, diamond shaped strut injector, wedge shaped strut injector etc. "Thrust losses in hypersonic engines–Part-1" and "Thrust losses in hypersonic engines–Part-2" has been carried out by (Riggins et al., 1997) and it is observed that the shock waves, incomplete mixing and viscous effects are the main factors are leading to the thrust loss in supersonic combustors. When the flight Mach number goes above the range of 3 to 6, the use of supersonic combustion allows higher specific impulse. These elevated temperatures are sufficient enough to melt down most of the known materials (Andreadis, 2004).

3. Material and Methods

3.1. Physical Model

The design of computational model is derived by Schumacher (2000) as Air inlet edge = 60 mm, Fuel inlet edge = 20 mm, Pressure outlet = 100 mm, Length of the ramp = 320 mm, Length of the combustion chamber = 600 mm, Angle of expansion (α_e) = 6^o, Angle of compression (α_c) = 6^o.

Table. 1. Specifications of the grid for the ramp injector

Refining levels	No. of nodes	Max. static temperature (K)
1	85816	1020
2	98462	1281
3	99927	1865
4	100537	3072
5	122319	3074
6	186754	3075

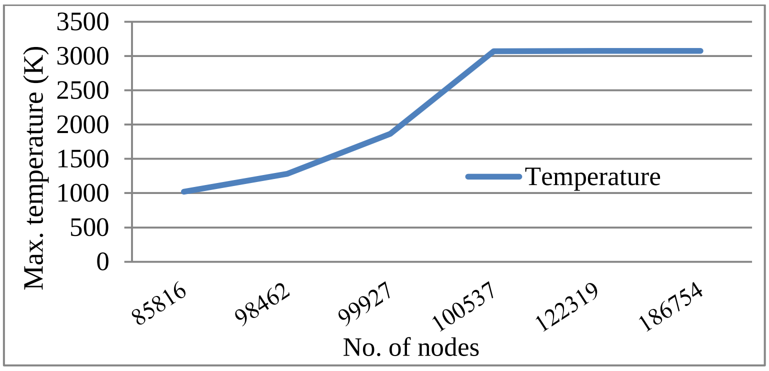

Fig. 2. Grid independence test for the ramp injector

The table 1 and figure 2 represents the specifications of the grid and grid independence test for the ramp injector and from the table and figure it is evident that better agreement is observed between 100537, 122319 and 186754 nodes. Therefore the current analysis is carried out using a grid size of 186754 nodes.

4. Results and Discussion

The CFD analysis for supersonic combustion using ramp injector with k-ε turbulence model is discussed below:

4.1. Static Temperature

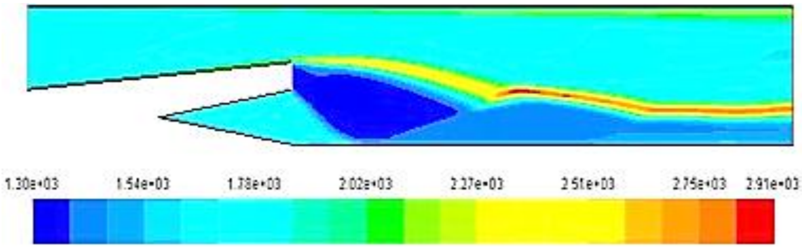

Fig. 3. Contours of static temperature

It is observed from the contour of static temperature that the maximum temperature of 2910K is produced in the recirculation areas which are produced due to shock wave interaction and fuel jet losses concentration which is shown in figure 3. Due to combustion, the recirculation region behind the injector becomes larger as compared to mixing case which acts as a flame holder for the hydrogen diffusion flame. The leading edge shock reflected off the upper and lower combustor walls makes the setting of combustion when it hits the wake in a region where large portions of the injected fuel have been mixed up with the air.

4.2. Static Pressure

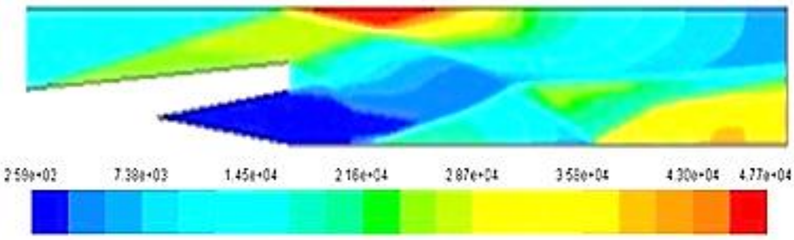

Fig. 4. Contours of static pressure

At the base of the ramp the shear layers become more pronounced due to the fact that continuous ignition follows within these shear layer. The leading edge shock wave is imitated from the top and bottom walls but the reflected shockwave from the bottom wall is stronger compared to that from the top wall. From the analysis it is witnessed that after the combustion the maximum static pressure of 47.71kPa is produced and it's represented in figure 4. There is also a subsonic recirculation zone at the base of the ramp.

4.3. Mach Number

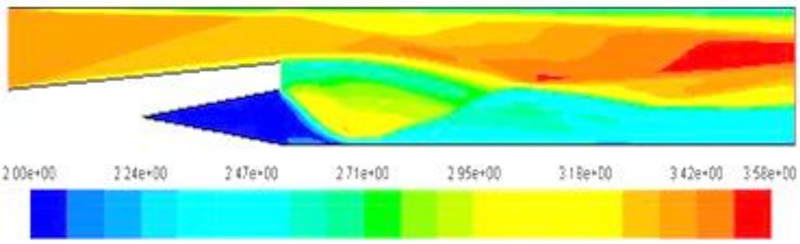

Fig. 5. Contours of Mach number

The figure 5 shows Mach number distribution. In a supersonic stream, large non-uniformities of Mach numbers are possible owing to the presence of waves crossing the stream. Then at supersonic speed, the flow field at any given section of the duct can have a wide variation of local Mach number. In the Mach number plots, the inlet-compression shock is visible. After hydrogen injection, the Mach number decreases in the area where combustion takes place and the maximum Mach no of 3.58 is generated which is investigated from the figure 5.

4.4. Combustion Efficiency

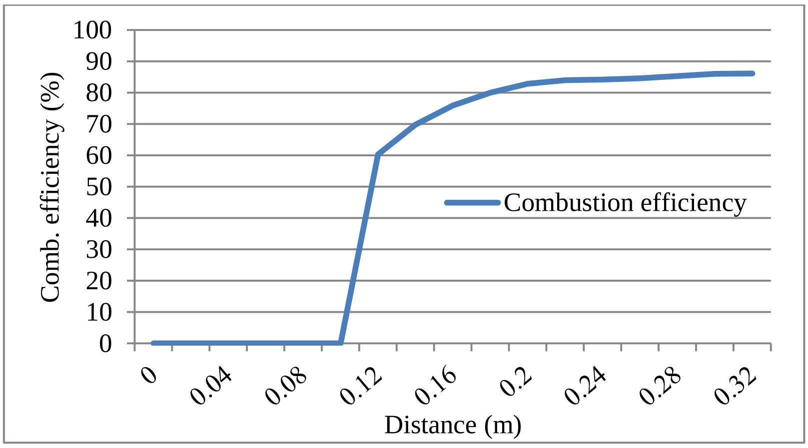

Fig. 6. Combustion efficiency

Combustion efficiency, η_{Comb} represents how much of the hydrogen has been burned in a given cross section. (A_x) with respect to the total injected hydrogen. The combustion efficiency is defined by Gerlinger (2008) as:

$$\eta_{Comb}(x) = 1 - \frac{\int A(x)\rho gas\, uY_{H2}\, dA}{\dot{m}H_{2,inj}} \quad (1)$$

Here ρ, Y_{H2} , $\dot{m}H_{2,inj}$ and u are the gas density, mass fraction of hydrogen, injected hydrogen mass flux and velocity component normal to the cross section respectively. The ignition of the fuel/air mixture takes place downstream of the trailing edge of the injector. In the present case, the highest combustion efficiency for a stoichiometric condition (φ= 1) is almost 88% which is presented in Fig. 6.

5. Conclusion

The CFD analysis is intended to study the flow structure and combustion efficiency for the present ramp injector base scramjet combustor. There is increase in temperature and pressure on the top and bottom walls of the scramjet combustor with strut injectors because of the impingement of the reflected shock wave on the expansion wave on the walls. As there is a proper mixing between air and fuel, there is almost complete combustion and the combustion efficiency is found to be almost 88%. During combustion the conventional emissions (NOx, CO, HC) are reduced, therefore this combustion system is almost eco-friendly.

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