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. There is a range of possible applications for scramjet engines like missile propulsion supersonic propulsion and part of stage space access applications. From the analysis it is evident that the extreme temperature of 2910K is produced in the recirculation areas.

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

1. Introduction

With the increasing of 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 mix the fuel with atmospheric air efficiently. The comparison of conventional ramps and cantilevered ramps for hypervelocity flow is we discussed by Heise and Pratt. (Heise and Pratt, 1994).

1.2. Mixing Enhancement Strategy

Mixing enhancement strategies are sought to improve the mixing quality 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.
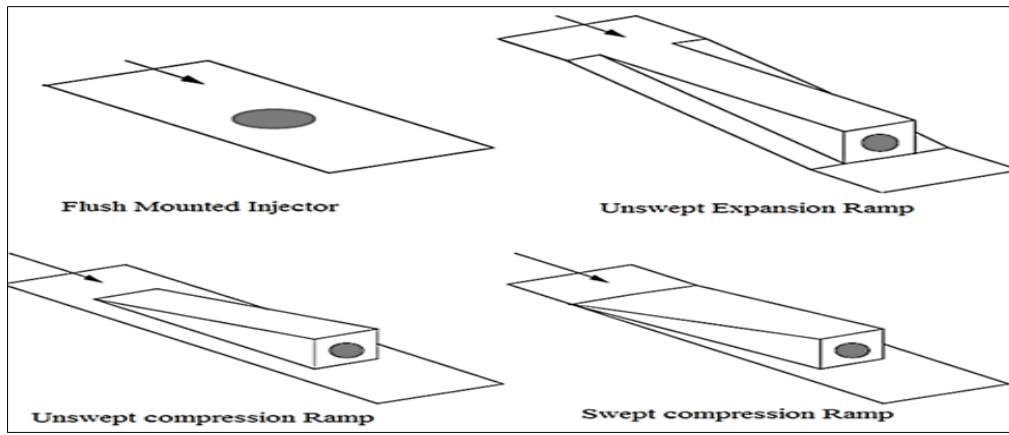
Fig. 1. Types of ramp injector

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 witnessed that the shock waves, viscous effects and incomplete mixing are the key factors leading to the thrust loss in supersonic combustors. When the flight Mach number goes above 6, the use of supersonic combustion allows greater specific impulse. These raised temperatures are sufficient enough to melt down most of the common 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

Outlet edge = 100 mm

Length of the ramp = 320 mm

Length of the combustion chamber = 600 mm

Angle of expansion (α_e) = 6°

Angle of compression (α_c) = 6°

3.2. Grid Independence Test

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

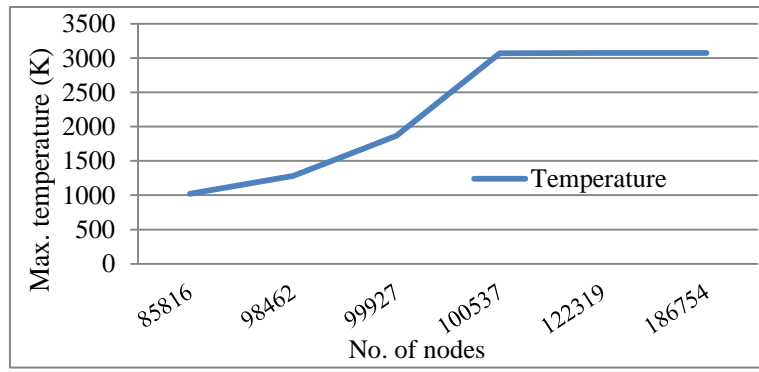| Refining levels	No. of nodes	Max. static temperature (K)
1	85816	1020
2	98462	1281
3	99927	1865
4	100537	3072
5	122319	3074
6	186754	3075

Fig. 2. Grid independence test for the ramp injector

The table 1 and figure 2 represent 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 present analysis carried out with a 186754 nodes.

4. Results and Discussion

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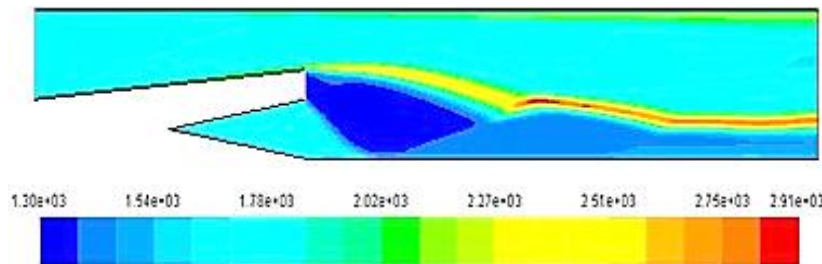
4.1. Temperature

Fig. 3. Static temperature contours

It is observed from the contour of static temperature that peak temperature of 2910K is produced in the recirculating areas which are produced due to shock wave interaction and fuel jet losses concentration which is shown in figure 3. Because of combustion, the recirculation area just behind the fuel injector temperature is drastically increasing towards the trailing edge of the ramp injector.
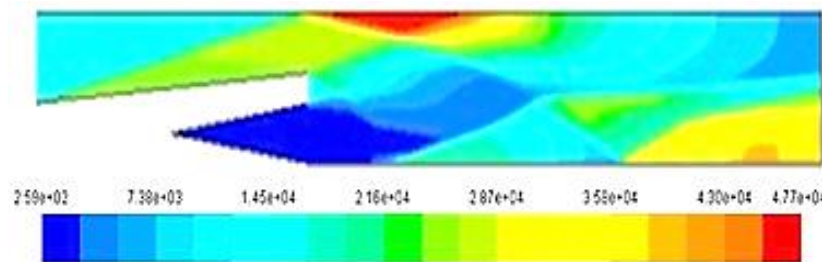
4.2. Pressure

Fig. 4. Static pressure contours

At the lower part of the ramp shear layers become more prominent due to the fact that continuous ignition follows within these shear layer. The leading edge shock wave is imitated from the upper and lower walls but the reflected shockwave from the upper wall is stronger compared to

that from the upper wall. From the pressure contour 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.
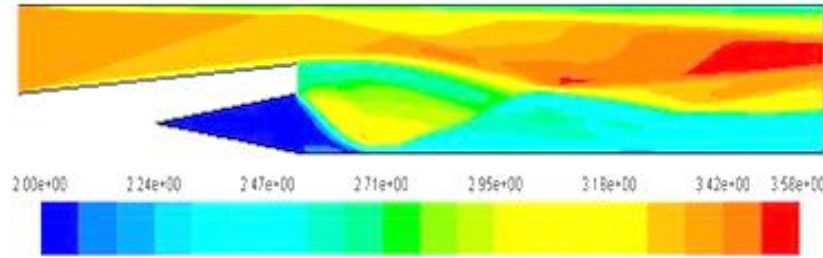
4.3. Mach Number

Fig. 5. Mach number contours

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.
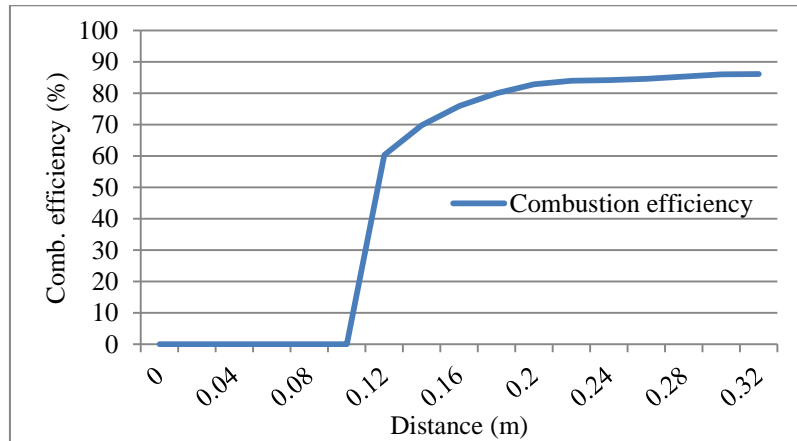
4.4. Combustion Efficiency

Fig. 6. Combustion efficiency

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

$$\eta_{Comb}(x) = 1 - \frac{\int A(x)\rho_{gas} \, u Y_{H2} \, dA}{\dot{m}H_{2,inj}} \qquad (1)$$

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 ($\varphi=1$) is almost 88% which is presented in figure 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

upper and lower 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.

References

1. W.H. Heiser, and D.T. Pratt, Hypersonic Airbreathing Propulsion, *AIAA Educational Series* (1994).

2. K.M. Pandey, and S. Roga, CFD Analysis of Scramjet Combustor with Non-Premixed Turbulence Model Using Ramp Injector, *Scientific.Net, Applied Mechanics and Materials,* 555, 18-25 (2014).

3. K.M. Pandey, S. Roga, and G. Choubey, Computational Analysis of Hypersonic Combustion Chamber Using Strut Injector at Flight Mach 7, *Combustion Science and Technology,* 187, 1392-1407 (2015).

4. D.W. Riggins, C.R. McClinton, and P.H. Vitt, Thrust Losses in Hypersonic Engines–Part 1: methodology, *Journal of Propulsion and Power,* 13(2), 281-287 (1997).

5. D.W. Riggins, C.R. McClinton, and P.H. Vitt, Thrust Losses in Hypersonic Engines–Part 2: Applications. *Journal of Propulsion and Power, Vol.13(2),* 288-295 (2007).

6. D. Andreadis, Scramjet Engines Enabling the Seamless Integration of Air and Space Operations, *Pratt and Whitney Space Propulsion*, Hypersonic, West Palm Beach, FL, 33410-9600 (2004).

7. P. Gerlinger, and D. Bruggemann, Numerical Investigation of Hydrogen Strut Injections into Supersonic Airflows, *Journal of Propulsion and Power*, 16(1), 22-28 (2000).

8. J.T. Guan, H. Yeoh, and C. Liu, Computational Fluid Dynamics, eBook ISBN: 9780080982779, *Elsevier Inc.* (2000).

9. M. Oevermann, Numerical Investigation of Turbulent Hydrogen Combustion in a Scramjet Using Flamelet Modeling, *Aerospace Science and Technology,* 4, 463-480 (2000).

10. K.M. Pandey, S. Roga, and G. Choubey, Numerical Investigation on Hydrogen-Fueled Scramjet Combustor with Parallel Strut Fuel Injector at a Flight Mach number of 6, *Journal of Applied Fluid Mechanics,* 9(3), 1215-1220 (2016).

11. K.M. Pandey, and S. Roga, CFD Analysis of Supersonic Combustion Using Diamond-Shaped Strut Injector with k-ω Non-Premixed Combustion Model, *Transaction on Control and Mechanical Systems,* 1(3) 114-124 (2012).

12. S. Roga, and K. M. Pandey, Computational Analysis of Hydrogen-Fueled Scramjet Combustor Using Cavities in Tandem Flame Holder, *Scientific.Net, Applied Mechanics and Material. Switzerland,* 772, 130-135 (2015).

13. K.M. Pandey, and S. Roga, CFD Analysis of Hypersonic Combustion of H_2-Fueled Scramjet Combustor with Cavity Based Fuel Injector at Flight Mach 6, *Scientific.Net, Applied Mechanics and Material,* 656, 53-63 (2014).