A CFD based Numerical Analysis of Scramjet Combustor

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***Abstract*— A CFD based modeling of flow phenomena in a modified DLR scramjet combustor has been performed. To enhance the air fuel mixing and to increase the combustion efficiency at the expense of low stagnation pressure drop, internal passages are provided in the wedge shaped strut fuel injector. Two-dimensional RANS equations are solved considering the flow to be steady, compressible, turbulent and reacting. A single step reaction is considered for hydrogen-oxygen reaction. A combination of eddy dissipation and finite rate chemistry models are used. The effects of divergence angle on the pressure drop and the combustion efficiency have been reported. A strut with internal passage shows higher combustion efficiency with less pressure drop than that without passages.**

Keywords—Hypersonic propulsion; Scramjet engine; Supersonic Combustion; Streamwise injection; Reacting flow; Combustion efficiency

I. INTRODUCTION

The desire for hypersonic flight necessitated the supersonic combustion ramjet (Scramjet) engine potentially expanding the speed envelope to the range of Mach 15. The term hypersonic refers to speeds exceeding Mach 5, that is, 1520 m/s at a typical operational altitude of 32.5 km. It is efficient to decelerate the air entering the engines of aircrafts cruising at flight Mach number equal to 4 or 5 to subsonic velocity before entering the combustion chamber. For hypersonic flights such deceleration becomes more difficult and costlier in terms of total pressure losses and it is necessary to make provision for the combustion chamber to burn its fuel in the supersonic airstream.

Design of combustors for scramjet engines is critical since the combustion must take place at supersonic speeds in such a way that enough heat is added to generate the required thrust. Too much heat addition will result in a normal shock standing at the combustor entrance. This is known as an inlet interaction. On the other hand, if too little heat is released the combustion cannot be sustained. The total residence time of the flow is of the order of 1-2 milliseconds. Within this short time the fuel should be mixed and burnt in the combustor and this requires highly efficient mixing strategies and effective flame stabilization methods.

In Scramjet combustor, the flow velocity of the main stream is high. Therefore the injected fuel (regardless of the direction of injection) tends to get blown downstream and does not travel any appreciable distance in the lateral or the vertical direction at all. In other words, it does not mix with the air. Mixing can be improved by cross-flow. However, any aggressive mixing strategy can lead to the formation of a normal shock at entry to the combustor, which is undesirable. For the same reason, mechanical flame stabilizer (such as V-gutters) cannot be used in the supersonic cross-flow .Therefore flame stabilization has to be achieved through aerodynamic feature in the combustor design. Realization of a working scramjet engine continues to be a challenge in the face of such conflicting and difficult requirements.

II. LITERATURE SURVEY

Reddy et al. carried out a two dimensional numerical investigation on DLR scramjet combustor with single strut for different divergent angles and its shock waves and the combustion efficiencies were reported. The scale effects and the effects of multi strut fuel injection on combustion characteristics were studied. Potturi, Edwards performed LES/RANS simulation of a supersonic combustion for reacting and non reacting flow in DLR scramjet combustor and reported that RANS model show better results for non reacting flow and LES/RANS for reacting flow. Aguilera et al. conducted an experiment in a Mach 2.1 wind tunnel simulating a scramjet internal flow path. A fin-guided fuel injection approach was used to optimize a trade-off between mixing enhancement and pressure loss. Numerical study of the effects of transverse jet injection into a supersonic turbulent flow in a scramjet combustor was done by Rana et al. they found that Kelvin-Helmholtz-type instabilities in the upper jet shear layer are primarily responsible for the mixing of the two fluids. Waidmann et al. reported the experimental results of scramjet combustion with hydrogen fuel in a simple geometry. It is one of the pioneering experimental results carried oud at the Institute for Chemical Propulsion of the German Aerospace Center, DLR.

Ganapathisubramani et al. studied the effects of upstream boundary layers on the unsteadiness of shock-induced separation. Experimental investigation of the phenomena of shock wave/turbulent boundary layer interactions and shock induced separation was done by Dussage et al. Large eddy simulation was performed on a supersonic flow in a DLR scramjet combustor and reported by Berglund and Fureby. They have performed simulations for non-reacting and reacting flow fields in scramjet combustors.

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In this paper, a CFD based investigation of the flow field in the modified DLR scramjet combustor with a strut fuel injector having internal passages for flow of air is carried out. The effect of divergence angle on the top wall of the combustor is reported. The effect of above said modifications on the combustion efficiency and stagnation pressure drop are presented.

III. DETAILS OF DLR SCRAMJET COMBUSTOR

The scramjet combustor used by Waidmann et al. at the institute for Chemical Propulsion of the German Aerospace Center, DLR is shown schematically in Fig. 1. The preheated air is expanded through a C-D nozzle. From the nozzle, air

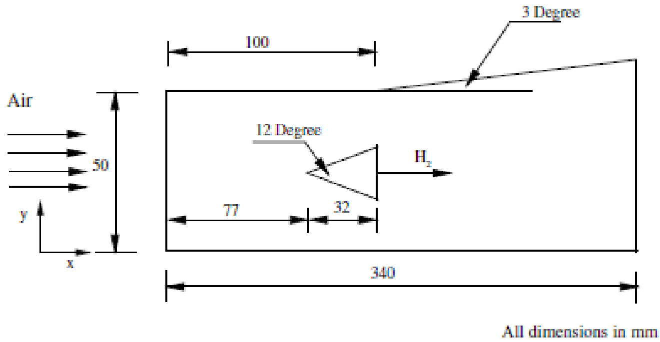

Fig. 1. Schematic diagram of DLR scramjet combustor

enters the combustor at M = 2. The width of the combustor is 40 mm. The height is 50 mm at the inlet and 62 mm at the exit. On the top wall of the combustor, a divergence angle of 3° is provided at a certain distance from the inlet. At the mid-plane of the combustor, at a distance of 77 mm from the inlet, a wedge shaped strut is placed. The half-wedge angle is 6° and the length is 32 mm. the strut has 15 circular injectors of each 1 mm diameter. Hydrogen is injected parallel to the air stream through these injectors. The inlet conditions of air stream and hydrogen are taken from Waidmann et al. and are shown in Table 1.

Table 1. Inlet conditions of Air stream and Hydrogen

Parameters	Air	Hydrogen
Mach number	2	1
Axial velocity (m/s)	730	1200
Static temperature (K)	340	250
Static Pressure (bar)	1	1
Density (kg/m^3)	1.002	0.097
O_2 mass fraction	0.232	0
H_2O mass fraction	0.032	0
N_2 mass fraction	0.736	0
H_2 mass fraction	0	1
Kinetic energy (m^2/s^2)	10	2400
Eddy dissipation (m^2/s^3)	650	1e8

IV. COMPUTATIONAL METHODOLOGY

The flow in the scramjet combustor is considered to be steady, compressible, turbulent reacting flow. Two dimensional Reynolds Averaged Navier Stokes equations are used. Turbulence is modeled with the standard k-ε model. Air is considered as an ideal gas with variable properties. Sutherland's law is used to calculate the viscosity. Convection-diffusion equation is used to calculate the mass fraction of each species. Piecewise polynomials are used to calculate the temperature dependent specific heat. The combination of finite rate chemistry and eddy dissipation models are used to model the combustion. A single step reaction is considered for hydrogen-oxygen reaction. $2H_2 + O_2$ $2H_2O$

Three different grids are generated. Coarse grid with 40000 elements, medium grid with 60000 elements and fine grid with

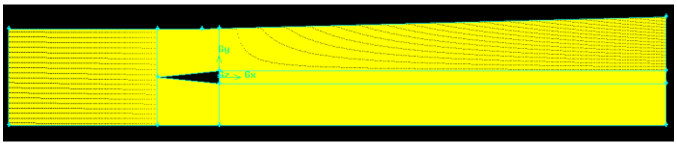

Fig. 2. Grid structure for the flow domain

80000 elements. Fine grids are used in the vicinity of fuel injector and also in the region close to the top and bottom walls of the combustor. The mass fraction of hydrogen is predicted along centre line of the combustor starting from the fuel injector for different grid sizes. The grid independency is achieved with medium grid.

Validation of computational results

The closeness of the computational results is tested with the experimental results of Waidmann et al. Static pressure along the centre line and bottom wall are shown in Fig. 3 and Fig. 4 respectively. The CFD results are in good agreement with the experimental results.

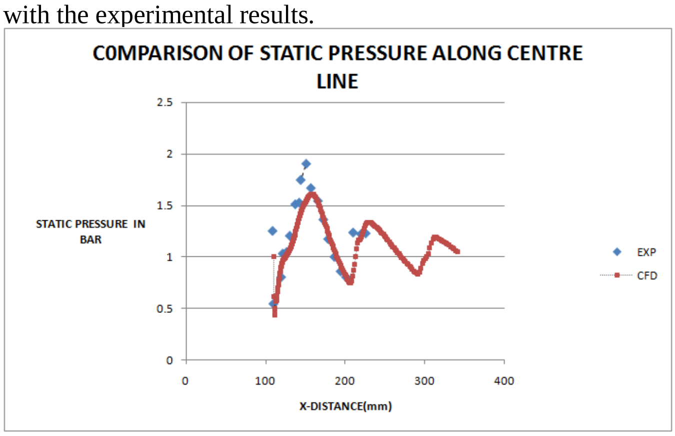

Fig. 3. Static pressure along the centre line

V. RESULTS AND DISCUSSION

Flow field in the scramjet combustor is reported for chemically reacting flow. Modifications are made for the strut injector. Internal passages are provided for the air flow with the projections at base of the strut to induce for circulation near injector for mixing enhancement.

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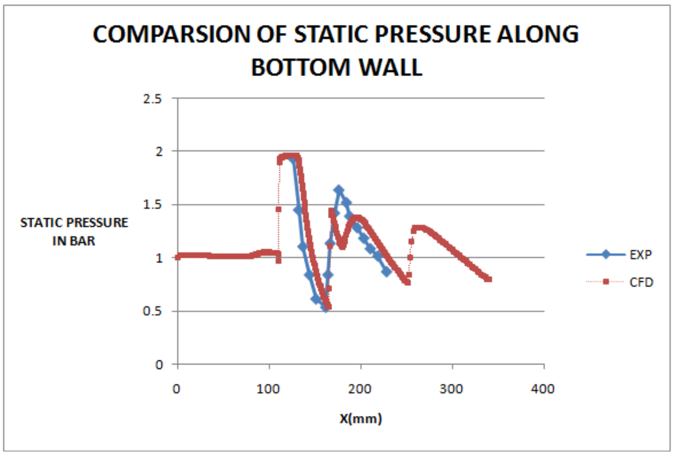

Fig. 4 Static pressure along the bottom wall

A. Modified strut fuel injector

The modified strut fuel injector with internal passages is shown in Fig. 5. Combustion efficiency is defined as the measurement of how well the fuel burnt is being utilized in the combustion process.

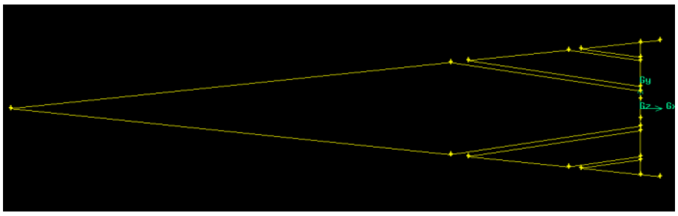

Fig. 5 Strut fuel injector with internal passages

The combustion efficiencies are calculated using the expression,

$$\eta_c = 1 - \frac{\int_A \rho u Y_{H_2} dA}{m_{H2inj}} = 1 - \frac{m_{H2(x)}}{m_{H2inj}}$$

where $m_{H2(x)}$ = mass flow rate of hydrogen at a given section and m_{H2inj} = mass flow rate of fuel injected. The combustion efficiency is plotted along the combustor as shown in Fig. 6.

The average stagnation pressure is calculated using the expression,

$$p_{0avg} = \frac{\int p_0 \rho u dA}{\rho u dA}$$

where p_0 = stagnation pressure, ρ = density, u = stream wise velocity. The average stagnation pressures along the combustor for different divergence angle are shown in Fig. 7. The stagnation pressure drop is large when divergence angle is zero degree. It is due to the fact that the oblique shock waves emanating from the leading edge of the strut and reflected waves joined together to form a shock wave system which are stronger to cause more pressure drop. Divergence angle on the top wall of the combustor allows for sufficient expansion of flow to take place. Therefore, the pressure drop between inlet and exit of the combustor is less with 3° divergence angle.

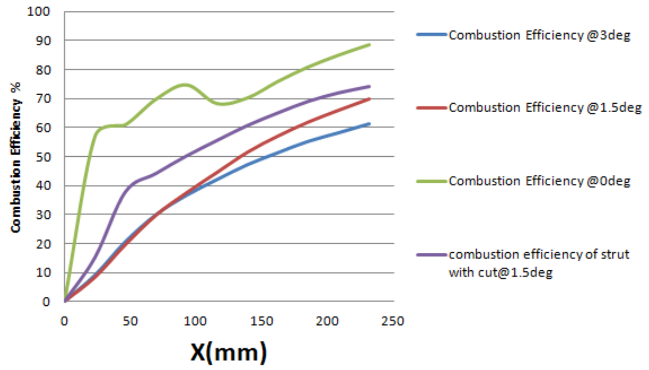

Fig. 6 Combustion efficiency along the combustor for different divergence angle and for the modified strut

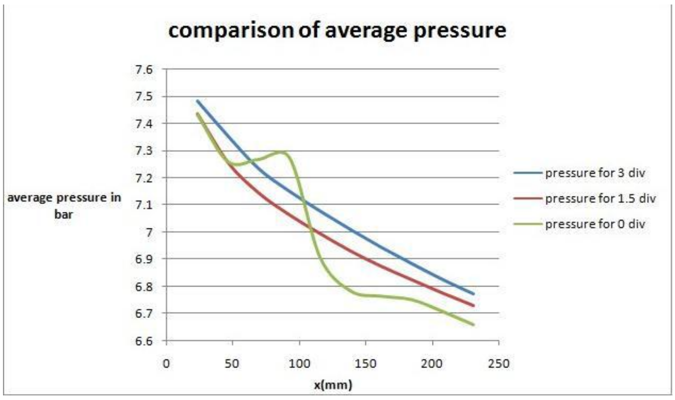

Fig. 7 Average stagnation pressure along the combustor for different divergence angle

At a section of combustor 150 mm downstream of the injector, the combustion efficiency is high for zero degree divergence. When comparing 1.5° and 3° divergence, the combustion efficiency for 3° exceeds that for 1.5°. With zero degree divergence formation of stronger shock wave system decelerates the flow, allowing more residence time for hydrogen air mixture, giving high combustion efficiency but at expense of more stagnation pressure drop. Therefore, combustor with 3° divergence gives optimum combustion efficiency with less stagnation pressure drop.

The modified strut with internal passages gives better combustion efficiency. The projections provided at the base of the strut create a recirculation region which helps to enhance the mixing of hydrogen and air. Multiple internal passages in the strut issue jet of air onto the recirculation region augmenting the mixing process.

VI. CONCLUSION

The flow field in the modified DLR scramjet combustor is investigated and reported in this paper. Present computational study predicted the shock wave pattern and flow circulations in the flow field. The divergence angle allows for expansion of flow, without which the flow incurs more loss in terms of stagnation pressure. Strut with internal passages enhances the hydrogen air mixing, increases the residence time and hence the combustion efficiency.

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