PERFORMANCE IMPROVEMENT OF KEROSENE FUELLED SCRAMJET COMBUSTOR THROUGH MODIFIED FUEL INJECTION - A CFD STUDY

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Abstract

Full scale kerosene fuelled scramjet combustor of a hypersonic air-breathing vehicle is numerically explored for two different fuel injection systems. A commercial software CFX-TASCflow has been used for the reacting flow computation within the combustor. Three dimensional Navier-Stokes equations are solved along with k-ε turbulence model to analyse the flow field. Eddy Dissipation Model (EDM) with fast rate chemical kinetics is used for combustion modeling. Lagrangian Particle Tracking Method (LPTM) has been used to simulate the trajectory of the kerosene droplets. Kerosene is injected from the struts. Reacting flow simulations have been carried out for the fuel equivalence ratio of 1.0. The overall flow characteristics in the combustor are presented through the distribution of various thermo-chemical parameters at different cross sections. Kerosene which is injected in liquid phase completely vaporizes within the combustor. Considerable improvement in the performance in terms of thrust and combustion efficiency is observed with the modified fuel injection system.

Introduction

Development of a hypersonic air-breathing cruise vehicle is strongly dependent on the success of the supersonic combustion ramjet (Scramjet) engine. Injection of fuel in supersonic flow, their mixing and combustion are very complex and not fully understood. In a recent comprehensive review on scramjet technologies, Curran [1] has identified two emerging scramjet applications, namely, (1) hydrogen fueled engines to access space and (2) hydrocarbon fueled engines for air-launched missiles. Various kinds of fuel injection systems [2-4], namely, struts, cavity and pylon have been studied in scramjet combustor for better fuel penetration, mixing and reactions. The problem of slow lateral fuel transport in the supersonic air stream is circumvented by injecting fuel in core region by means of struts or pylon. Fuel injection from the struts has been experimented upon in subscale scramjet engine including airframe integrated scramjet module at Engine Test Facilities at National Aerospace Laboratories (NAL), Japan for Mach 4, 6 and 8 conditions [5-8]. A good number of experimental and numerical studies [9-13] were reported in the literature to focus on various aspects of flow phenomena including drag losses, mixing, combustion, intake combustor interaction etc., in strut based scramjet combustors with hydrogen fuel. The reported experimental and numerical studies on kerosene fueled supersonic combustion mostly address the issues of cavity based flame holder and injection system [14-19] in laboratory scaled combustor. The penetration of fuel in supersonic flow is critical in any practical scramjet combustor. The studies on strut-based scramjet combustor with kerosene fuel are highly limited. Vinogradov et al. [20] conducts experimental investigation to determine the ignition, piloting, and flame holding characteristics in a strut based scramjet combustor operating on kerosene. In order to improve the fuel distribution and mixing, kerosene was injected from the strut located in the middle of the combustor. Stable combustion of kerosene was achieved even after turning off pilot hydrogen. Bouchez, Dufour and Montazeal [21] carried out experimental investigation of hydrocarbon fueled scramjet combustor. Two identical metallic water-cooled and liquid kerosene cooled struts were used for the fuel injection in the combustor. To ensure ignition, pilot flames with gaseous hydrogen was used at the base of the struts. Kerosene equivalence ratio was varied from 0 to 1.0. Various flow parameters (wall pressure, wall heat flux, total temperature at combustor exit, thrust etc.) were measured. Optical methods including passive spectroscopy were also used to characterize the flow.

With the advent of powerful computer, robust numerical algorithm, CFD is complementing 'difficult to perform' experiment and thus playing a major role in

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developing a comprehensive understanding of the key phenomenon that dominate performances. Only very few numerical studies were reported on strut based liquid fueled scramjet combustor. Dufour and Bounchez [22] have numerically simulated the scramjet experiment [21] using a three dimensional Navier Stokes solver and single step chemical kinetics. A reasonably good match is obtained between the computational and experimentally measured wall static pressure. Recently, Manna et al. [23] presented a CFD based design and analysis for a flight scale scramjet combustor with kerosene fuel injected from struts placed in the combustor flow path and emphasized that higher combustor entry Mach number and distributed fuel injection system is required to avoid thermal chocking.

Panneerselvam et al. [24] presented a hypersonic-cruise airbreathing mission with an airframe integrated scramjet engine. Strut based injection system is considered as one of the option of injecting kerosene fuel in the combustor flow path. CFD techniques are used to predict and improve the performance of the scramjet engine before it is ground tested. In the present work, a full-scale scramjet combustor with a nine strut based configuration (as shown in Fig.1) with kerosene fuel is studied numerically using a commercial software CFX-TASCflow [25]. Performance of the combustor in terms of thrust and combustion efficiency is improved by redistribution of fuel injection pattern. A new fuel injection system is arrived from the thermo chemical analysis of various flow parameters. This paper presents the comparison of various flow parameters and combustor performance with two different fuel injection systems.

Combustor Geometry

Scramjet combustor with nine-strut configuration including the facility nozzle is shown in Fig.1. The combustor assembly consists of 5 sections. The first section of length 5.2h (h is height of facility nozzle throat). Facility nozzle is included in the computational domain to get a realistic boundary layer at the inlet of the combustor. The area ratio of the facility nozzle is 1.77 and expected to provide Mach 2 flow at combustor entry. The total length of the combustor without the facility nozzle is 43.26h. The second section is a constant area combustor of length 1.86h while third, fourth and fifth sections are of length 4.1h, 14.4h, 17.7h respectively are divergent area combustor with different divergence angles (1°, 4° and 7.5°) at top wall. The combustor is of constant width of 11.3h. The height of the combustor is 5.2h at the exit. Nine swept struts are placed along the width of the combustor in various cross sectional planes for the injection of liquid kerosene. First strut (one number) is placed at the middle (mid plane along the width) of the combustor. The second, third, fourth and fifth row struts are two numbers each and they are placed on either side from the mid-plane. Typical fuel injector strut geometry with fuel injection holes is shown in Fig.2. Hot vitiated air enters into the combustor through the facility nozzle and the kerosene fuel is injected transversely through 0.9 mm diameter holes provided in the struts.

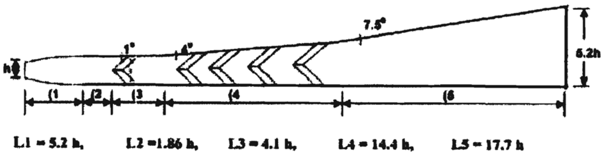


Fig.1 Schematic Diagram of Scramjet Combustor

The Solution Methodology

The software, used in the present study, is a three dimensional Navier Stokes code CFX-TASCflow [25] which is an integrated software system capable of solving diverse and complex multidimensional fluid flow problems. The code is fully implicit, finite-volume method with finite-element based discretisation of geometry. The method retains much of the geometric flexibility of finite-element methods as well as the important conservation properties of the finite-volume method. It utilizes numerical upwind schemes to ensure global convergence of mass,

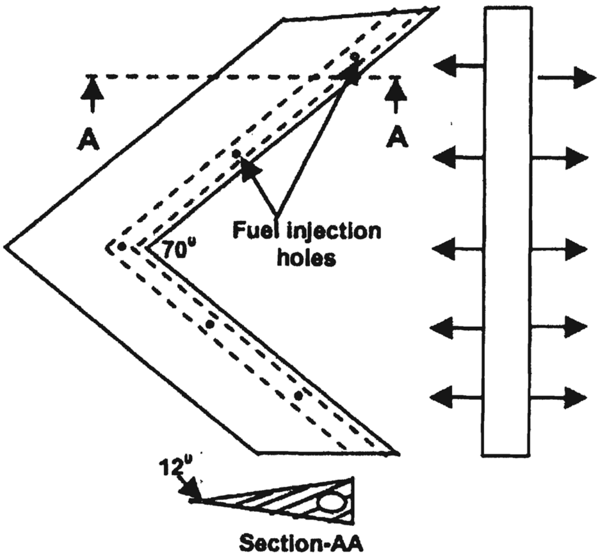


Fig.2 Typical Fuel Injector Strut

momentum, energy and species. It implements a general non-orthogonal, structured, boundary fitted grids. In the present study, to circumvent the initial numerical transient, the discretisation of the convective terms are done by first order upwind difference scheme till few time steps and subsequently, the convective terms are discretised through second order scheme to capture the flow features more accurately. The turbulence model used was k-ε model with wall functions.

The chemistry of kerosene air combustion reaction is represented by a single step infinitely fast kinetics: $C_{12}H_{23} + 17.75\,O_2 = 12\,CO_2 + 11.5\,H_2O$. The turbulence-chemistry interaction is modeled by Eddy Dissipation Model (EDM) and the rate of reaction is given as

$$R_{k,\,edm} = -A_{ebu}\,\rho\,\frac{\varepsilon}{k}\min\left\{Y_f, \frac{Y_o}{r_k}, B_{ebu}\frac{Y_p}{1+r_k}\right\}$$

where ρ, Y_f, Y_o and Y_p are the density and mass fractions of fuel, oxidizer and products respectively, A_{ebu} and B_{ebu} are the model constants and r_k is the stoichiometric ratio. Experimental studies [12, 21] have shown that the combustion process in the scramjet combustor for both hydrogen and kerosene fuel is mostly mixing controlled and infinitely fast kinetic can adequately describe the combustion process in the scramjet combustor.

To find out the accuracy and the range of applications, the software has been validated for various reacting flows pertaining to hydrogen and kerosene injection in the scramjet combustor including transverse H_2 injection in constant area duct [26], staged H_2 injection in from struts [27], pylon injectors [28], kerosene fuelled scramjet combustor with cavity injector [29] and ramp-cavity injector [30] All these simulations have revealed that although, there exists some differences near the injection zone, the computational and experimental value of the flow parameters in the diverging portion of the combustor (the major thrust providing element) match within 5%.

Computational Details

Taking the advantage of the geometrical symmetry, only one half of the combustor is considered for computational domain. The geometry of computational domain (half geometry) along with the boundaries is shown in Fig.3. The computational domain starts from the throat of the facility nozzle so that a realistic boundary layer can be obtained at the combustor entry. A total 288 x 36 x 29 structured grids are used in the simulation. The grids are fine near the leading edge and trailing region of the struts and near the wall region while coarser grids are provided in the remaining portion of the combustor. In the simulation, x-axis is taken along the length of the combustor, while; y-axis and z-axis are chosen along the width and height of the combustor respectively. The origin is placed at the inlet of the combustor at middle of the bottom surface. Since, the injection holes are very small in diameter; grids are made finer by doing the grid embedment (upto 3-8 times) adjacent to each injection point to capture the small diameter holes. At the nozzle entry, the stagnation temperature, pressure and Mach number of the vitiated air are 1940 K, 3.84 bar and 1.0 respectively, and the inlet mass flow rate is 8.4 kg/s. A total amount of 642 gm/s kerosene is injected with a rate of 7.64 gm/s per hole. Reynolds number at combustor entry is 0.5 million based on the height of the combustor at facility nozzle throat. No slip and adiabatic wall conditions are applied in the wall boundaries while symmetry conditions are prescribed in the symmetry plane. Supersoic outflow boundary is imposed in the outflow boundary. Solutions are marched in global time step and typical time step is 10^{-5} sec. Calculations are performed in a high-end work station with 4GB RAM and typical run time for reacting flow calculation is about 10 days. The log-normalized maximum residue of -04 is considered for the convergence criteria.

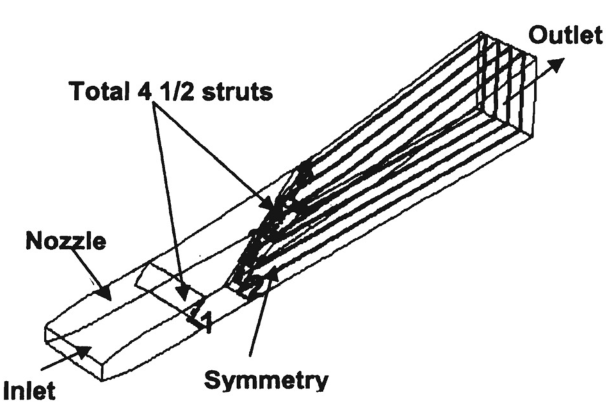


Fig.3 Computational Domain of Combustor (Half)

Results and Discussion

The simulations were first carried out with the fuel injection system as shown in Table-1. The cross sectional view of kerosene vapour and oxygen mass fraction at different axial locations (x/h = -5.15, 0, 2.06, 6.18, 10.31, 14.43, 18.56, 24.74, 30.93 and 37.11) is shown in Fig.4. Blown up view of kerosene vapour and oxygen at x/h = 10.31 and x/h = 24.74 is also presented in the figure to

Table-1 : Fuel Injection - Old Scheme

Strut No.	No. of Holes	Kerosene Injection (g/sec)	Fuel Equivalence Ratio
Strut-1	10	76.4	0.119
Strut-2	20	152.8	0.238
Strut-3	20	152.8	0.238
Strut-4	20	152.8	0.238
Strut-5	14	107.0	0.167

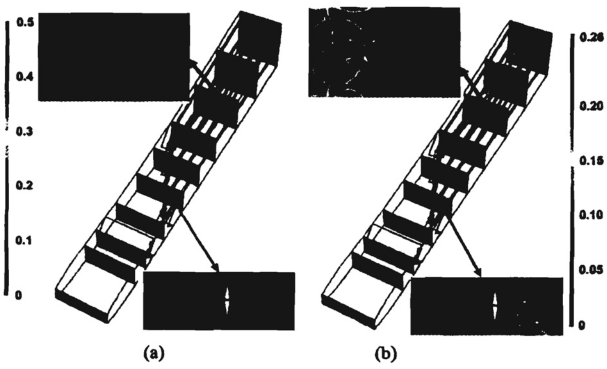


Fig.4 Mass Fraction Distribution at Different Axial Locations for old Scheme (a) Kerosene (b) Oxygen (x/h = -5.15, 0.0, 2.06, 6.18, 10.31, 14.43, 18.56, 24.74, 30.93 and 37.11)

depict the flow field more clearly. The detail examinations of these thermo-chemical parameters reveal that the reaction is mostly confined to the core region adjacent of the struts. It was also observed that although oxidizer is available near the sidewalls, the reaction did not take place because of the non-availability of the fuel in that region.

Based on these observations, the fuel injection scheme was modified by injecting more fuel towards the side wall and reducing the fuel injection in upstream location to avoid thermal choking. The revised (new) fuel injection scheme is presented in Table-2.

Table-2 : Fuel Injection - New Scheme

Strut No.	No. of Holes	Kerosene Injection (g/sec)	Fuel Equivalence Ratio
Strut-1	8	61.1	0.095
Strut-2	16	122.2	0.191
Strut-3	20	152.8	0.238
Strut-4	20	152.8	0.238
Strut-5	20	152.8	0.238

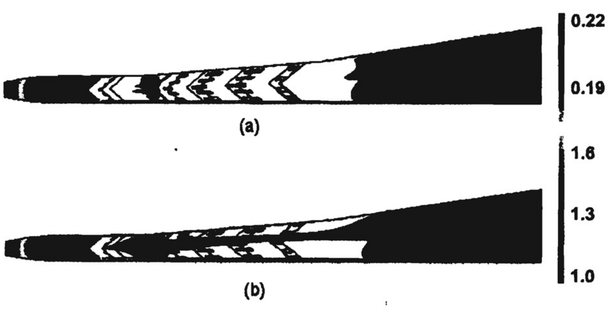


Fig.5 Mach Number distribution (Supersonic) on symmetry plane (a) Old Scheme (b) New Scheme

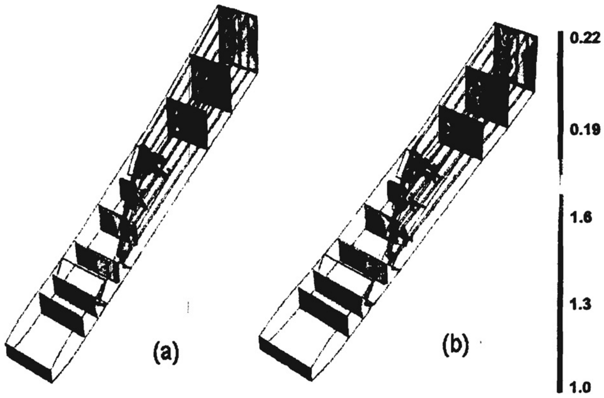


Fig.6 Mach Number distribution (Supersonic) at different axial locations (a) Old Scheme (b) New Scheme (x/h = -5.15, 0.0, 2.06, 6.18, 10.31, 14.43, 18.56, 24.74, 30.93 and 37.11)

The Mach number distribution (in supersonic scale) on symmetry plane for old and new schemes is compared in Fig.5. The Mach number at the combustor entry is about 2.0. Flow is seen to be subsonic behind the first strut and upto 5th strut for old scheme; while a continuous patch of supersonic region has been found to exist behind the first strut for new scheme. The Mach number distribution at different axial locations (x/h = -5.15, 0, 2.06, 6.18, 10.31, 14.43, 18.56, 24.74, 30.93 and 37.11) for supersonic region is shown in Fig.6. The subsonic region is seen behind the second strut and the area of subsonic region increases towards downstream till fifth strut due to heat release from the combustor. The axial distribution of area-averaged Mach number is compared for both the schemes in Fig.7, which indicates the existence of significant subsonic flow near the injection zone of the combustor. The axial length is non-dimensionalized with the height of the throat of facility nozzle. For the new fuel injection system, it is observed that there is no significant change in the subsonic portion of the flow field; but in the divergent portion Mach number has reduced due to more heat release. More heat release in the divergent portion is desirable for the performance improvement of the combustor.

The temperature rise due to reaction mostly occurred behind the struts. The temperature distribution for the new and old scheme at various cross sections are compared in Fig.8 and the axial distribution of area averaged static temperature is compared in Fig.9. Maximum temperature rise has been observed between the second and fifth struts where more than 90% of kerosene is injected. Higher temperature has been observed in new scheme because of more reaction of kerosene fuel with vitiated air.

The cross sectional distribution of kerosene vapour and oxygen mass fraction at different axial position for new injection scheme is shown in Fig.10. The cross sectional view at x/h = 10.31 and x/h = 24.74 is blown up so that the difference in the flow field for the old scheme and new scheme can be compared. From the figure, it is clear that unburnt kerosene vapour is decreased considerably compared to the earlier configuration (Fig.4a) with better utilization of the oxygen. Figs.11a and 11b compare the area averaged unburnt kerosene vapour and un-utilized oxygen mass fraction respectively for the two injection schemes. Unburnt kerosene vapours and excess oxygen at the exit of the combustor are found to be much less for new scheme, which indicates that more reaction has taken place in the combustor for the new scheme fuel injection system. Further optimization of the combustor has not been attempted as the combustion efficiency for the new scheme has become more than 80%.

The comparison of axial distribution of top wall surface pressure (at y = 0.0) between two fuel injection schemes is presented in Fig.12. Slightly higher pressures

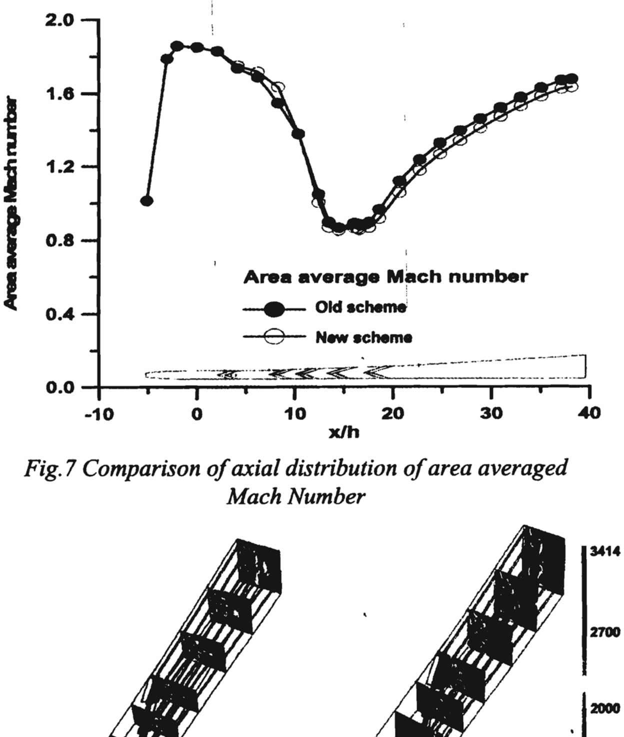


Fig.7 Comparison of axial distribution of area averaged Mach Number

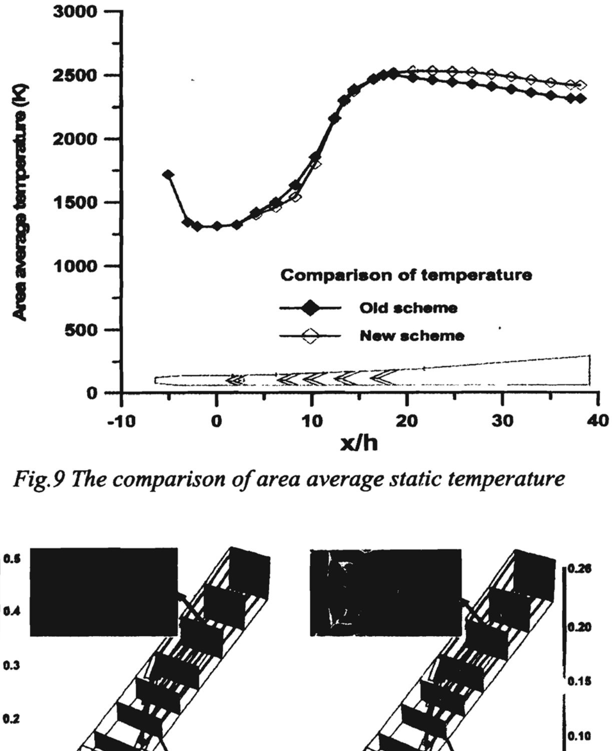


Fig.9 The comparison of area average static temperature

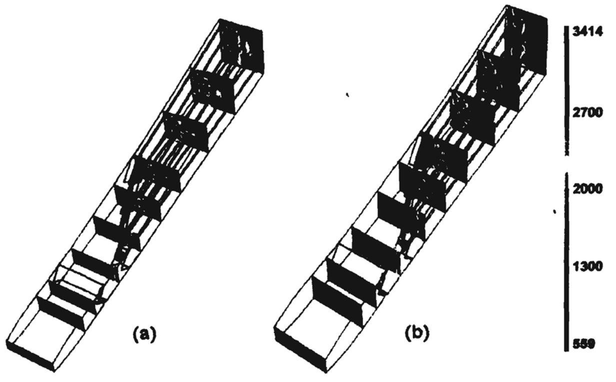


Fig.8 Temperature distribution at different axial locations (a) Old Scheme (b) New Scheme (x/h = -5.15, 0.0, 2.06, 6.18, 10.31, 14.43, 18.56, 24.74, 30.93 and 37.11)

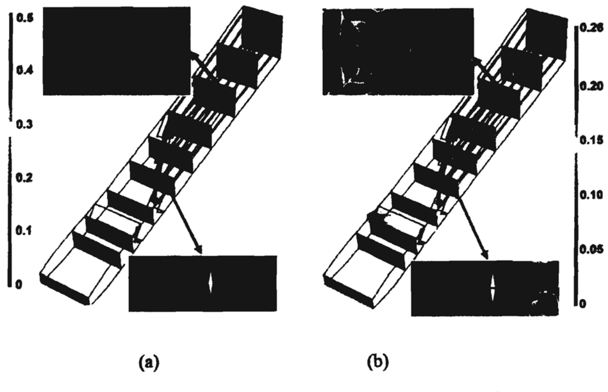
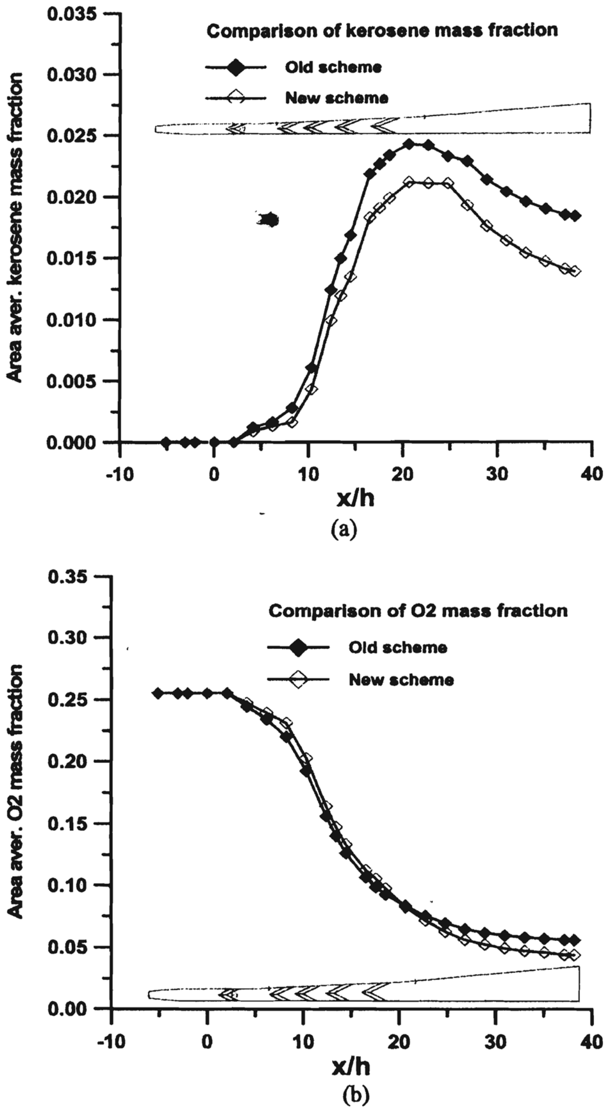


Fig.10 Mass fraction distribution at different axial locations for new scheme (a) Kerosene (b) Oxygen (x/h = -5.15, 0.0, 2.06, 6.18, 10.31, 14.43, 18.56, 24.74, 30.93 and 37.11)



(a)

(b)

Fig.11 Comparison of axial distribution of area average mass fraction of fuel and oxidizer of both schemes (a) Kerosene (b) Oxygen

observed at the divergent portion of the combustor for the new scheme compared to the old scheme is due to the fact that more fuel has been injected in the new scheme in the later part of the combustor which has reacted in the divergent portion.

The combustion efficiency achieved in the new scheme is 80.7% compared to 74.3% achieved for the old scheme fuel distribution system. The thrust obtained from the new scheme has increased to 470 kgf compared to 442 kgf from the old scheme fuel injection system.

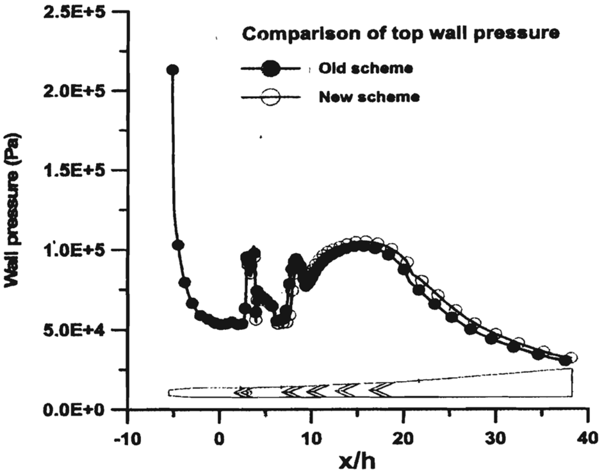


Fig.12 Comparison of axial distribution of top wall static pressure

Conclusion

A flight sized kerosene fueled scramjet combustor is simulated numerically. Three dimensional Navier Stokes equations along with k-ε turbulence model and infinity fast rate kinetics are solved. The vaporization of liquid kerosene is modeled through Lagrangian Particle Tracking Method (LPTM). Two different fuel injection schemes are studied. It was shown that by proper redistribution of fuel injection, the reaction zones and combustor performance could be increased significantly. The computed thrust and combustion efficiency has been increased to 470 kgf and 80.7 % for the new scheme injection systems from 442 kgf and 74.3 % for the old scheme injection system.

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