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ORIGINAL ARTICLE

Effect of ramp-cavity on hydrogen fueled scramjet combustor

J.V.S. Moorthy[a], **B. Rajinikanth**[a], **B.V.N. Charyulu**[a], **G. Amba Prasad Rao**[b,*]

[a]*Scientist, Defence Research and Development Laboratory, Hyderabad, Andhra Pradesh 500058, India*
[b]*Professor in Mechanical Engineering, National Institute of Technology, Warangal, Andhra Pradesh 506004, India*

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Abstract Sustained combustion and optimization of combustor are the two challenges being faced by combustion scientists working in the area of supersonic combustion. Thorough mixing, lower stagnation pressure losses, positive thrust and sustained combustion are the key issues in the field of supersonic combustion. Special fluid mechanism is required to achieve good mixing. To induce such mechanisms in supersonic inflows, the fuel injectors should be critically shaped incurring less flow losses. Present investigations are focused on the effect of fuel injection scheme on a model scramjet combustor performance. Ramps at supersonic flow generate axial vortices that help in macro-mixing of fuel with air. Interaction of shocks generated by ramps with the fuel stream generates boro-clinic torque at the air & liquid fuel interface, enhancing micro-mixing. Recirculation zones present in cavities increase the residence time of the combustible mixture. Making use of the advantageous features of both, a ramp-cavity combustor is designed. The combustor has two sections. First, constant height section consists of a backward facing step followed by ramps and cavities on both the top and bottom walls. The ramps are located alternately on top and bottom walls. The complete combustor width is utilized for the cavities. The second section of the combustor is diverging area section. This is provided to avoid thermal choking. In the present work gaseous hydrogen is considered as fuel. This study was mainly focused on the mixing characteristics of four

*Corresponding author: Tel.: +91 0870 2462342.

E-mail address: ambaprasadrao@gmail.com (G. Amba Prasad Rao).

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different fuel injection locations. It was found that injecting fuel upstream of the ramp was beneficial from fuel spread point of view.

1. Introduction

Supersonic combustion is the research area pursued by combustion scientists for optimization of the combustion process. Due to very high speed of air in the combustor and low residence time, it is difficult to achieve sustained and useful combustion in the combustor. Mixing, lower stagnation pressure losses, positive thrust and sustained combustion are the key issues in the field of supersonic combustion. Experimental and numerical research is being carried out by different researchers around the world.

Major focus towards improving the scramjet combustor performance is given to the effective mixing of fuel and air. Due to very high kinetic energy of the air stream, cross stream mixing between fuel and air is very difficult. Hence special fluid mechanism is required to achieve good mixing. In the design of supersonic combustion ramjet engine, fuel injections as well as flame holding are known to play a critical role. Fuel and air must be mixed at molecular level in the near field of fuel injection. To induce such mechanisms in supersonic inflows, the fuel injectors should be critically shaped incurring less flow losses. Then, fuel injection also should be done judiciously to utilize the flow field generated by fuel injectors to the fullest extent. Current investigations are focused on the effect of fuel injection scheme on a model scramjet combustor performance.

The strategy requires the placement of physical obstructions in the combustor to provide stream wise vortices that enhance the mixing of fuel and air. Such approaches are use of backward facing step and ramps [1]. Backward facing step generates recirculation zone that contains hot gases in it and serves as a continuous ignition source. However, the disadvantage of backward facing step is of relatively high stagnation pressure loss. Ramps at supersonic flow generate axial vortices which help in macro-mixing of fuel with air. Interaction of shocks generated by ramps with the fuel stream generates boro-clinic torque at the air & liquid fuel interface, enhancing micro-mixing. Cavities use an integrated approach as fuel injector and flame holder. This was first designed and used by CIAM (Central Institute of Aviation Motors) in Moscow in a joint Russian/French dual-mode scramjet flight-test [2]. Recirculation zones present in cavities increase the residence time of the combustible mixture and hence are better candidates for flame holding.

More over the large scale shear layer oscillations associated with cavities enhance the fuel-air mixing. Experimentally, the use of cavities after the ramp injector was found to significantly improve the hydrocarbon combustion efficiency in supersonic flow. Ben-Yaker et al. [3] used the cavities for flame stabilization in a solid fuel supersonic combustor and demonstrated self ignition as well as sustained combustion of polymethyl-methacrylate (PMMA) for supersonic flow conditions.

There are two types of cavities, open and close [4,5]. Numerical studies on supersonic combustion with cavity [6] and using innovative cavity [7] have dealt with supersonic studies using CFD (computational fluid dynamics) simulation with Fluent code. Due to the low pressure loss experienced by open cavities (Cavity $L/d < 10$), open cavities are useful in supersonic flow. Making use of the advantageous features of ramps and cavities, a ramp-cavity combustor is designed.

2. Combustor geometry

Rectangular scramjet engines are widely preferred from operational point of view. Hence, in our study a scaled two dimensional combustor of size 28 mm × 85 mm is considered for experimental/numerical investigations. The schematic of the combustor is shown in Figure 1.

The combustor has two sections. First, constant height section consists of a backward facing step followed by ramps and cavities on both the top and bottom walls. The ramps are located alternately on top and bottom walls as shown in Figure 2.

A constant area combustor of 28 mm × 40 mm size is designed to locate the rearward facing step. Three ramps are positioned in the base plate and two ramps are positioned alternately in the top plate of the combustor. Cavities of size 50 mm in length and 8 mm deep are located next to the ramps. A diverging combustor of semi-divergence angle of 1.8° joins the constant area combustor for sustained combustion. The complete combustor width is utilized for the cavities. The second section of the combustor is diverging area section. This is provided to avoid thermal choking.

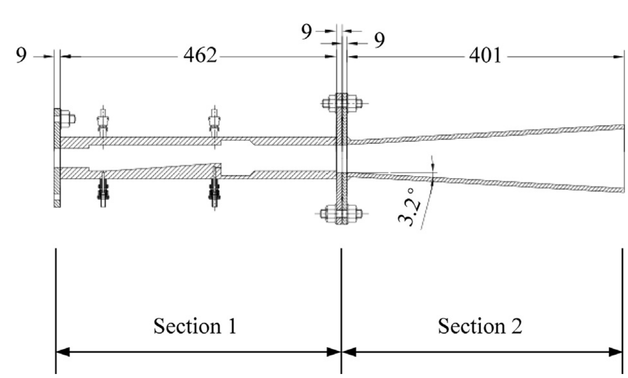

Figure 1 Schematic of the scramjet combustor.

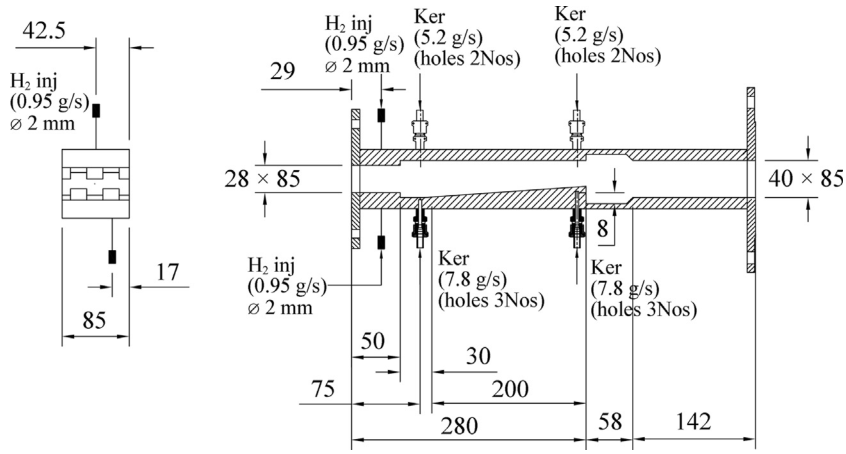

Figure 2 Arrangement of ramps in combustor.

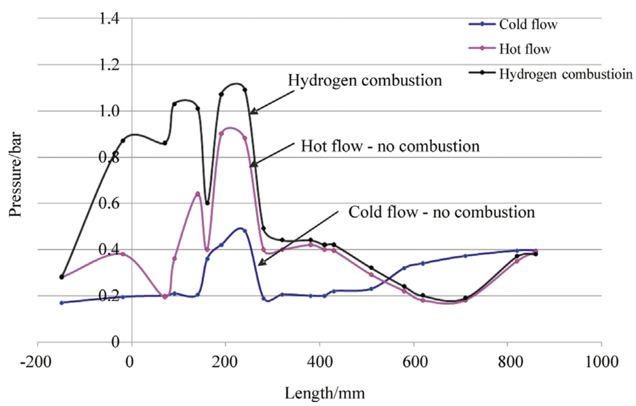

Figure 3 Wall static pressure distributions along combustor length.

In the present work, gaseous hydrogen is considered as fuel. Fuel injection is planned at different locations in the combustor, ahead of the ramps, at the base of the ramp, in the cavity etc. Effect of staged injection of fuel was explored. Entry Mach number of 2.5 was considered. As a preliminary step, a few experiments were conducted on the combustor.

Figure 3 shows the static pressure measured along the combustor with hydrogen injection during one of the experimental studies in DRDL on the hydrogen mixing with the air. Pressure rise could be observed during hydrogen combustion compared to no-combustion cases. The fuel is injected between the step and the ramp leading edge. Due to blockage created physically by ramps and by combustion, upstream influence is observed. Hence it is decided to carry out parametric study on various fuel injection schemes. It was decided to carry out the studies in two stages. In the first stage, the mixing performance of various fuel injection schemes was studied. Based on the results, suitable fuel injection schemes will be chosen and further simulations will be made to achieve better combustion efficiency without upstream influence.

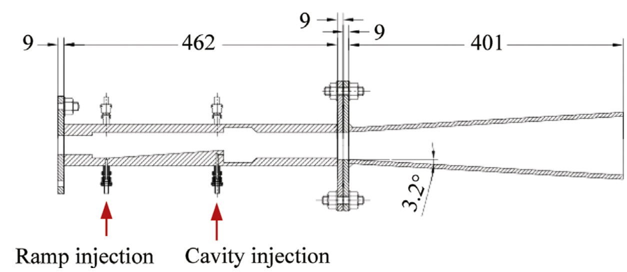

Figure 4 Fuel injection from ramp and cavity.

3. Fuel injection schemes

As discussed earlier the ramps are arranged alternately in the top and bottom and the cavities are running across combustor width on top and bottom. Fuel is injected upstream to ramp or from the front wall of the cavity as shown in Figure 4.

4. Numerical scheme

The simulations were carried out in Fluent. The governing equations for the simulation as applicable in Fluent are used in the present study. It is pertinent to mention that the application was carried out in Fluent by suitably using the schemes available for the simulation.

5. Solver details

Simulations were carried out using commercial CFD solver Fluent. The software has been validated for flows up to Mach no of 13. It has capabilities to simulate multi-phase flows and reacting flows. Following physical models have been used for our present simulations:

Solver: Density based solver
Discretization: Second order explicit
Species: O_2, H_2, N_2 and H_2O

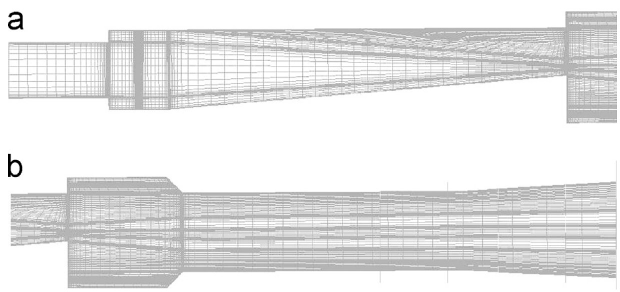

Figure 5 Grid at symmetry plane in (a) ramp region and (b) cavity region.

Turbulence model: Spalart Allmaras turbulence model without wall functions

Fuel injection: Gaseous hydrogen injection (2 gm/s from each injection hole)

The simulation domain has been constructed with all hexahedral cells. To capture the near wall gradients, grids were clustered near wall. Symmetry plane grid is shown in Figure 5.

"$Y+$" less than 15 has been achieved in all of our simulations. Simulations were done till mass deficit less than 0.2 g is achieved, that is 10% of the fuel injected from the one injection hole.

6. Results and discussion

Figure 6(a) shows the Mach number contour in the symmetry plane, where the ramp is located in the bottom wall.

Figure 6(b) shows the Mach number contour at a plane 15 mm away from the symmetry plane, where the ramp is located in the top wall.

Figure 7 shows the static pressure contours at these planes respectively. As expected the inlet flow undergoes an expansion at the step. But presence of the ramps, either on the top wall or bottom wall prevents it from expanding to complete height of the combustor. This is due to the interaction of the ramp leading edge shock with the recirculation zone after the step, causing large recirculation zone. Same can be observed in the pressure contour also. In the region after the step, expansion fan and ramp leading edge shocks are interacting, causing complex three dimensional gradients in pressure, temperature and velocities. These will enhance mixing of fuel with the air stream. Further, the flow is compressed by the ramp surface in the downstream. In the pressure contours, standing shock structure is clearly seen above the ramp regions. These high pressure and high temperature zones will help ignition of hydrogen fuel. At the end of ramps the flow undergoes second set of expansion, in the wall cavity region. In Figure 6(a), it can be seen that the shear layer from the front leading edge of the cavity re-attaches at the cavity rear wall. In the bottom the shear layer re-attaches far away from the cavity rear wall. Similar flow can be observed in Figure 6(b). This enhanced recirculation zone above the cavity will result in higher residence time for the flow. As the flow - Mach numbers are higher, any fuel injection towards end of the combustion will suffer from low residence time and incomplete combustion. This problem can be circumvented by providing mechanisms like cavities, which will improve the residence time for complete combustion. The recirculation zones at the cavities are high temperature and low velocity zones, which will act as flame holders. More over the instability of the cavity shear layer will improve the mixing efficiency coupled with the three dimensional flow field associated with the discrete ramps placed alternately on the top and bottom walls. The constant area section downstream of the cavities helps in sustaining the high pressure flow. This is followed by the diverging section, where the flow expands to avoid thermal choking. From these studies, it can be concluded that the fuel injection upstream of

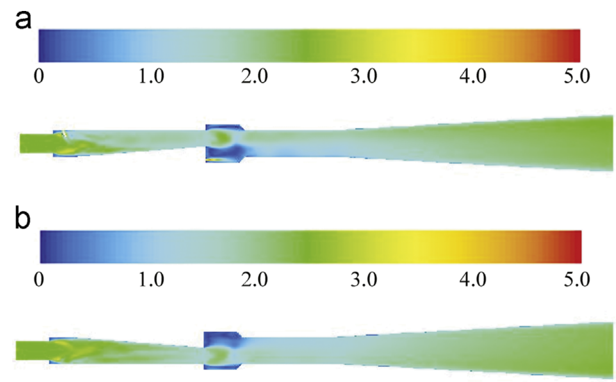

Figure 6 Mach number contour at (a) $Z=0$ mm and (b) $Z=15$ mm.

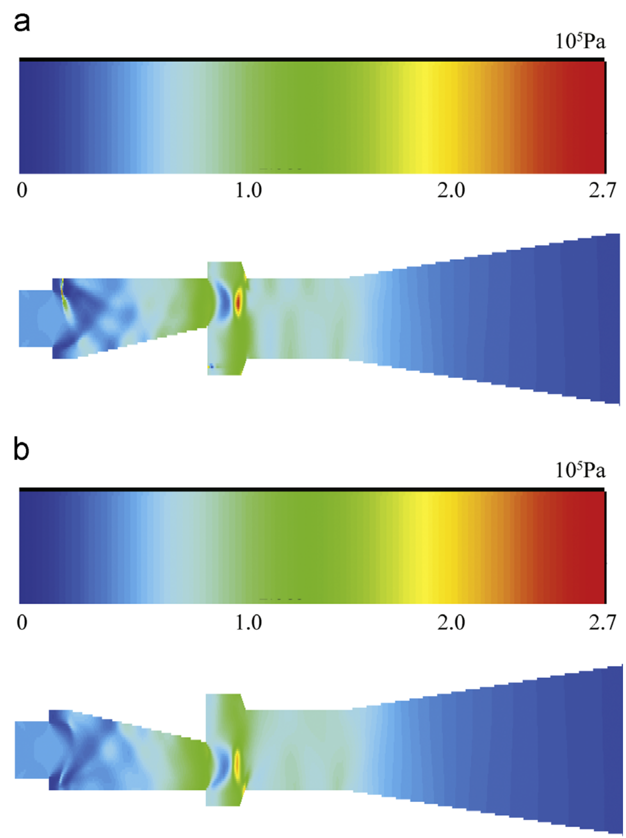

Figure 7 Static pressure contour at (a) $Z=0$ mm and (b) $Z=15$ mm.

the ramps and from ramp base (in-stream direction, which will help in recovering the fuel jet momentum in the axial direction) are favorable zones for better mixing, flame holding and complete combustion.

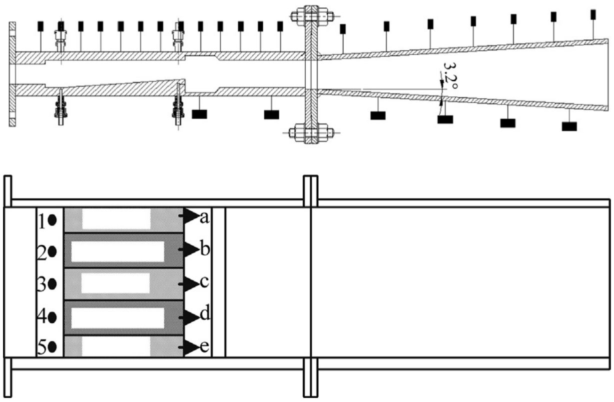

Figure 8 Fuel injection locations.

Based on above observations, two possible locations for fuel injections upstream of ramps are chosen, viz., middle of ramp width and in between ramps. Similarly from cavity, fuel is either injected in the middle of ramp width or between ramps. The fuel injection locations are depicted in Figure 8.

The injection location 2 on the top wall will be in between top ramps and on the bottom wall it will be middle of the bottom ramp. Similarly for all other injection locations can be identified. Four fuel injection schemes (listed below) have been identified, from combinations of these injection locations for the present study.

(a) Middle of ramp width for ramp and cavity injection (1, 3, 5 for top ramp and a, c, e for top cavity; 2, 4 for bottom ramp and b, d for bottom cavity) Case A.
(b) In between ramps for ramp and cavity injection (2, 4 for top ramp and b, d for top cavity; 1, 3, 5 for bottom ramp and a, c, e for bottom cavity) Case B.

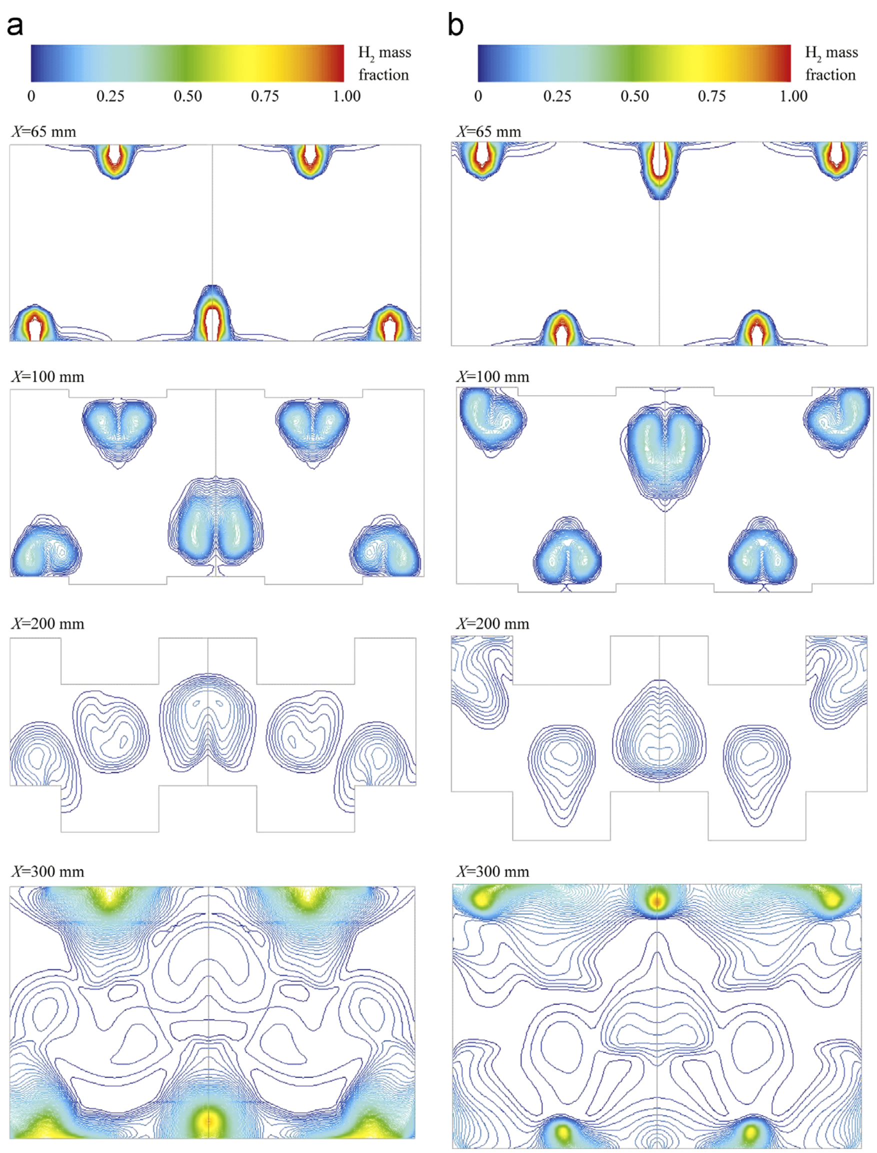

Figure 9 H_2 mass fraction contour. (a) Case A, (b) Case B, (c) Case C and (d) Case D.

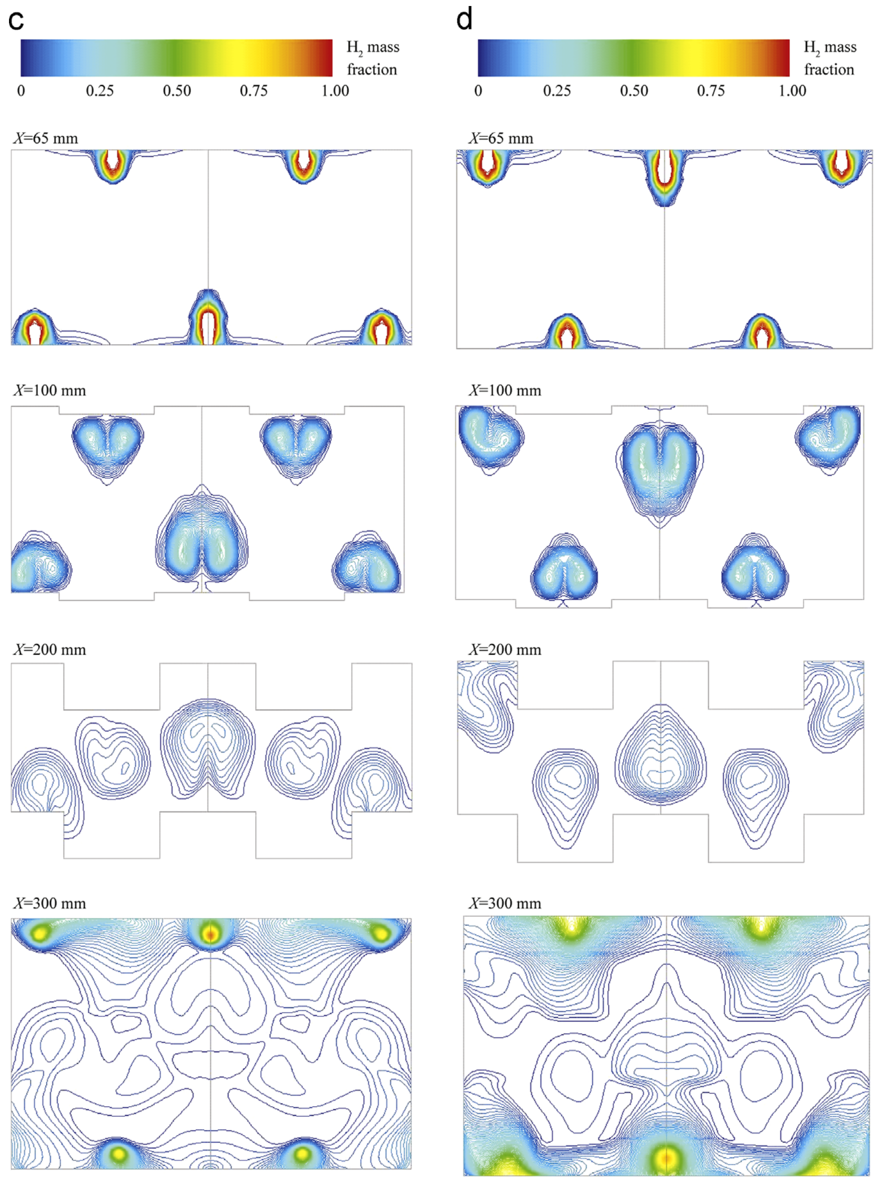

Figure 9 (*continued*)

(c) Middle of ramp width for ramp and in between ramp for cavity injection (1, 3, 5 for top ramp and b, d for top cavity; 2, 4 for bottom ramp and a, c, e for bottom cavity) Case C.
(d) In between ramp for ramp and middle of ramp for cavity injection (2, 4 for top ramp and a, c, e for top cavity; 1, 3, 5 for bottom ramp and b, d for bottom cavity) Case D.

Figure 9 show the “H_2 mass fraction” contours at various axial locations for injection for above mentioned cases. It can be observed that the H_2 penetration is higher in the middle plane for all four cases. This may be due to the three dimensional relief present in the combustor middle plane. In the ramp region, the fuel spread is similar between similar kind of fuel injection, either middle of the ramp or in between ramp. The fuel injected upstream of the ramp and in the middle of the ramp width (Case A and Case C) spread better than the other cases. This can be due to the flow spillage from high pressure generated on the ramp surface to the region between ramps. The fuel injected in the middle of the ramps seems to be constrained by the flow, the above stated reason will be present in this case also and hence the fuel is prevented from spreading by the flow spillage from ramps. More over the fuel injected in the middle of the ramp may be constrained by the ramp side walls. Considering all these the fuel injection upstream of the ramp at middle of the ramp provides better spread of the fuel and hence better mixing.

The next set of injection is into the cavities. In Case A and Case D, hydrogen is injected from the base of the ramp and in other two cases hydrogen is injected between ramps. The recirculation zone at the ramp base will be larger compared to that in between ramps. This causes the fuel

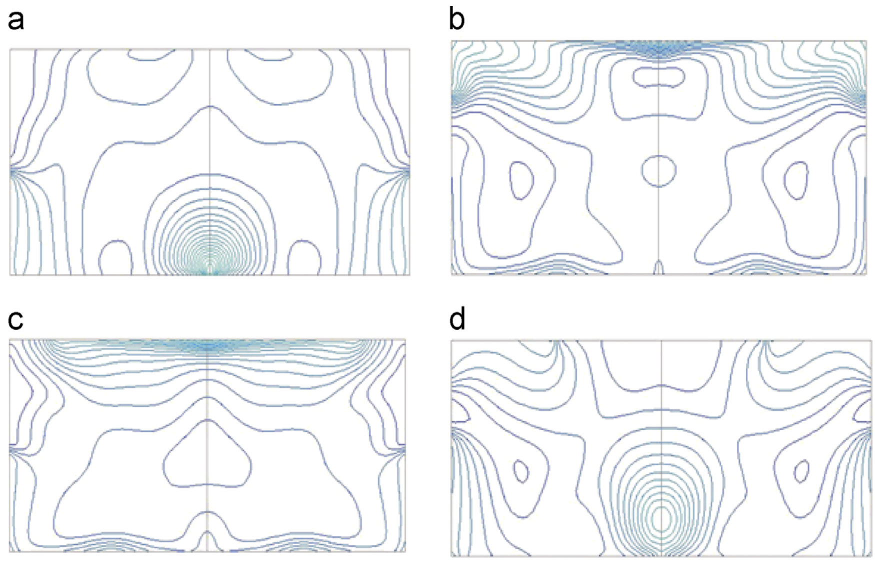

Figure 10 H_2 mass fraction contours at $X=400$ mm. (a) Case A, (b) Case B, (c) Case C and (d) Case D.

injected from the ramp base to spread faster compared to other cases. At first instant it may be seen that fuel injection from the ramp base to be better. But further fuel spread exhibits a different behavior. "H_2 mass fraction" contours at $X=400$ mm for all four cases are shown in Figure 10.

Interestingly Case C shows better uniformity in the hydrogen availability compared to all other cases. For Case A and Case D, large gradients of H_2 mass fraction are observed. This indicates that the fuel spread is still constrained because of the flow. Case B shows better mixing compared to Case A and Case D, but inferior to that of Case C. In Case B and Case D, the fuel is injected in the middle of the ramp. The vortex dominated flow caused by the ramps may be trapping the fuel injected in their core, constraining the fuel spread. In Case A, even though mixing of the fuel injected upstream of the ramps was better, fuel injected in the cavities were in the same line of action. This would have caused poor mixing in the cavity downstream. Hence it is preferable to inject fuel in the middle of the ramp width for ramp upstream injection and in between ramp for the cavity injection.

7. Conclusions

Present numerical studies are carried out on the effect of ramp-cavity arrangement on achieving better mixing in modal scramjet combustor. Based on the study, the following conclusions are arrived.

(1) The study was mainly focused on the mixing characteristics of four different fuel injection locations.
(2) Injection of fuel upstream of the ramp is beneficial from fuel spread point of view.
(3) The flows over the cavities were majorly influenced by the ramps. The ramp generated wakes and associated flow structures were containing fuel from spreading.
(4) The fuel injection in between ramps was found favorable, in which case the influence of ramp flow was aiding the fuel spread.

References

[1] H.A. Herman, J.D. Anderson Jr., J.P. Drummond, Supersonic flow over a rearward facing step with transverse nonreacting hydrogen injection, AIAA Journal 21 (12) (1983) 1707–1713.

[2] A.S. Roudakov, Y. Schikhmamn, V. Semenov, P.H. Novelli, G. Fourt, Flight testing an axisymmetric scramjet-Russian recent advances, in: 44th IFA Congress, Graz, Austria, October 16–22, 1993, IFA Paper 93-S.4.485.

[3] A. Ben-Yaker, B. Natan, A. Gany, Investigation of a solid fuel scramjet combustion, Journal of Propulsion and Power 14 (4) (1998) 447–455.

[4] A. Ben-Yaker, R.K. Hanson, Cavity flame holders for ignition and flame stabilization in scramjets: review and experimental study, AIAA-98-3122, 1998.

[5] X. Zhang, Compressible cavity flow of oscillation due to shear layer instabilities and pressure feedback, AIAA Journal 33 (8) (1995) 1404–1411.

[6] K.M. Kim, S.W. Back, C.Y. Han, Numerical study on supersonic combustion with cavity-based fuel injection, International Journal of Heat and Mass Transfer 47 (2) (2004) 271–286.

[7] D.W. Zhang, Q. Wang, Numerical simulation of supersonic combustor with innovative cavity, Procedia Engineering 31 (2012) 708–712.