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Numerical Studies on Flow Field Characteristics of Cavity Based Scramjet Combustors

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Abstract**—**The flow field within the combustor of scramjet engine is very complex and poses a considerable challenge in the design and development of a supersonic combustor with an optimized geometry. In this paper comprehensive numerical studies on flow field characteristics of different cavity based scramjet combustors with transverse injection of hydrogen have been carried out for both non-reacting and reacting flows. The numerical studies have been carried out using a validated 2D unsteady, density based 1st-order implicit k-omega turbulence model with multi-component finite rate reacting species. The results show a wide variety of flow features resulting from the interactions between the injector flows, shock waves, boundary layers, and cavity flows. We conjectured that an optimized cavity is a good choice to stabilize the flame in the hypersonic flow, and it generates a recirculation zone in the scramjet combustor. We comprehended that the cavity based scramjet combustors having a bearing on the source of disturbance for the transverse jet oscillation, fuel/air mixing enhancement, and flame-holding improvement. We concluded that cavity shape with backward facing step and 45^o forward ramp is a good choice to get higher temperatures at the exit compared to other four models of scramjet combustors considered in this study.

Keywords**—**Flame holding, Hypersonic flow, Scramjet combustor, Supersonic combustor.

I. INTRODUCTION

SUPERSONIC combustion ramjet (SCRAMJET) is a promising technology that can enable efficient and flexible aerospace transport system [1]-[15]. The development of the scramjet engines poses considerable challenges and it demands multidisciplinary design, analysis, modeling, simulation and system optimization. The hardware realization and testing becomes equally complex and multidisciplinary. Supersonic combustion, which plays a key role in the scramjet technology, was first demonstrated in the laboratory in the 1960s [1], [2]. Subsequently NASA developed considerable expertise in airframe integration and combustion testing facility in the 1970s and 1980s [3]. Literature review reveals that among the three critical components of the scramjet engine, the combustor presents the most formidable problems. The complex phenomenon of supersonic combustion involves turbulent mixing, shock interaction and heat release in supersonic flow. The flow field within the combustor of scramjet engine is very complex and poses a considerable challenge in design and development of a supersonic combustor with an optimized geometry. Such combustor shall promote sufficient mixing of the fuel and air so that the desired chemical reaction and thus heat release can occur within the residence time of the fuel-air mixture. In order to accomplish this task, it requires a clear understanding of fuel injection processes and thorough knowledge of the processes governing supersonic mixing and combustion as well as the factors, which affects the losses within the combustor. The designer shall keep in mind the following goals namely; (i) Good and rapid fuel air mixing, (ii) minimization of total pressure loss, (iii) high combustion efficiency.

The concept of injecting and mixing in the scramjet inlet rather than the combustion chamber, using localized shock structures in the combustor to achieve ignition even when the mean flow conditions are too mild, was demonstrated successfully in the experiments conducted in the T4 shock tunnel [4], [5]. It will lead to shorter and lighter scramjets with greater efficiency. An advanced scramjet configuration comprising three-dimensionally curved flow paths with rectangular-to-elliptical shape transition (REST) has been developed at the University of Queensland, Australia [6], designed by utilizing on the streamline-tracing techniques that have been contrived at NASA Langley Research Center [7]. Hypersonic inflow is compressed to a desired higher pressure (and consequently high temperature) at the exit of the inlet, which induces combustion in the downstream chamber. The reacted gas expands in the nozzle to produce thrust. The inlet and combustor, in particular, play a pivotal role in the scramjet mechanism; the combustion critically depends on the temperature of the airflow compressed by the inlet and must take place efficiently within limited time and combustor length, which has a direct impact on the structural weight as well as the overall drag due to immense skin friction on the surface of the combustor. Scramjet technology has thus advanced to a stage where sophisticated geometries must be explored for increased performance, in particular net positive thrust, which is essential for an access-to-space system. Scramjet engine design, however, represents a formidable challenge to conventional approaches due to the complexity of the associated flow fields involving various aerodynamic and aerothermal phenomena including shock wave / boundary layer interactions, flow separation and chemical reactions. Such a high degree of coupling necessitates the design of the scramjet components in an integrated manner rather than individual. Ogawa et al. [8] reported that the recent remarkable advancement of optimization techniques offers a

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powerful ability to assist the design process that involves a high degree of complexity.

Literature review further reveals that the overall performance of ramp and cavity injectors can be improved by combining them properly [9]. The combination of cavities and ramps generate a three dimensional flow field and turbulence for better mixing and combustion. Ramps will enhance the fuel penetration in to the core and cavities will enhance the flame holding characteristics. The ramp generated axial vortices can be utilized to scoop out the hot gases generated at cavities to improve the combustion efficiency. Thus Ramp and cavity combination shows promising characteristics for better scramjet combustor performance.

At a hypersonic flight speed, the flow entering the combustor should be maintained supersonic to avoid the excessive heating and dissociation of air. The residence time of the air in a hypersonic engine is on the order of 1 ms for typical flight conditions. The fuel must be injected, mixed with air, and burned completely within such a short time span. A number of studies have been carried out worldwide, and various concepts have been suggested for scramjet combustor configurations to overcome the limitations given by the short flow residence time. Among the various injection schemes, transverse fuel injection into a channel type of combustor appears to be the simplest and has been used in several engine programs, such as the Hyshot scramjet engine, an international program lead by the University of Queensland [6]. For the enhancement of fuel/air mixing and flame-holding, a cavity is often employed. For example, the CIAM of Russia introduced cavities into its engines [10] and US Air Force also employed cavities in the supersonic combustion experiments [11]. These are succinctly reviewed by Jeong-Yeol Choi et al. [12]. After considering the aforesaid geometrical aspects of the scramjet combustor this paper is focusing on the flow field characteristics of cavity based Scramjet Combustors aiming for its shape optimization.

II. Numerical Method of Solution

It is generally accepted that the ground tests and classical methods alone cannot give data with sufficient accuracy for design of hypersonic systems. Due to the closely integrated nature, component level testing will not be able to simulate accurately the complex flow field. It is difficult to simulate Reynolds number, boundary layer transition in ground test facilities. Also, the quality of air is difficult to simulate in the test facilities. Therefore there is a need to estimate the performance in the flight based on the results of ground tests. This can be accomplished only through the use of mathematical modeling of the flow, which is to be solved to first reproduce the result of the ground test and then used for predicting the flight conditions. The primary unknown on a physical plane consists of modeling turbulence and its interaction with chemistry. The issues on the numerical front consist of evolving algorithms to solve the N – S equations or their variants such that sharp gradient regions near the shocks are captured with numerical diffusion or overshoot. The prediction of wall heat transfer rate is another task to be handled both on the modeling plane and numerical experiments. One of the advantages of the mathematical model is that once it stands validated it can be used to conduct several numerical experiments on exotic ideas like with respect to enhanced mixing components with much less expense as compared to experiments. The experimental effort is not eliminated but reduced and better focused. This is in fact the current day approach to the solution to the problems of high-speed flight.

In this numerical study the flow field is assumed as two-dimensional for getting the computational efficiency and it is well described with the conservation equations for a multi-component chemically reactive system. The numerical studies have been carried out using a validated 2D unsteady, density based 1st-order implicit k-omega turbulence model with multi-component finite rate reacting species. In the parametric analytical studies no-slip boundary condition is imposed at the lower wall and slip boundary condition is imposed at the upper wall. The supersonic Mach number is achieved by introducing a CD nozzle ahead of the subsonic combustor with suitable boundary conditions. In all the cases the hydrogen is injected into the core flow with sonic velocity with an injection pressure of 0.5 MPa. An algebraic grid system is employed in all the cases and grids are clustered near the walls for capturing the flow physics.

III. Results and Discussion

Comprehensive numerical simulations have been carried out to understand the influence of the flow characteristics of scramjet combustors with different geometrical shapes of its cavity. As a first step scramjet combustor without cavity is considered for flow simulation including both non-reacting and reacting flows to establish the intrinsic flow physics in uniform duct with multi-component finite rate reaction. Fig. 1 shows the temperature contours at various time steps for the case of a scramjet combustor without cavity and with an injector pressure of 0.5 MPa. All the calculations were done for 5 ms from the initial condition, which is the typical time of the ground based experiment. Sequence of pictures from 1 ms to 5 ms show that reaction is advancing in the form of a thin sheet and not much mixing is seen in the duct during the 5 ms of operation.

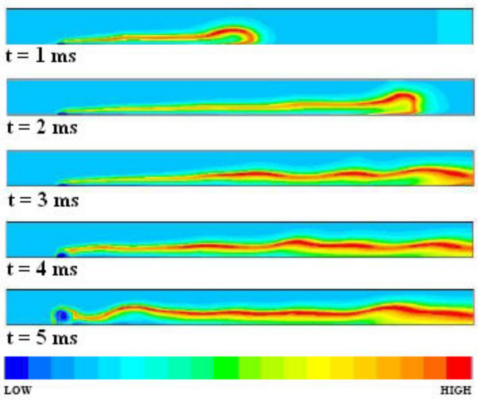
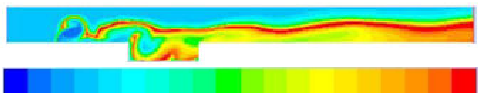
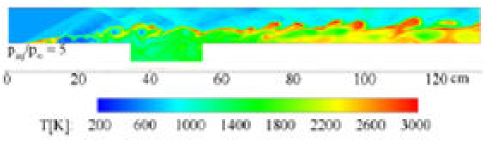


Fig. 1 Demonstrating the temperature contours at various time steps for the case of a scramjet combustor without cavity and with an injector pressure of 5 MPa



(a) Present Model



(b) Numerical results of Jeong-Yeol Choi et al. [12]

Fig. 2 (a)-(b) Temperature contour comparison using the present model and model used by Jeong-Yeol Choi et al. [12]

Fig. 2 (a) is generated using 2D unsteady, density based 1st-order implicit k-omega turbulence model with multi-component finite rate reacting species. Fig. 2 (b) is adopted from the published works of Jeong-Yeol Choi et al. [12] for validating our results qualitatively. The governing equations were treated numerically by Jeong-Yeol Choi et al. [12] using a finite volume approach. The convective fluxes were formulated using Roe's FDS method derived for multi-species reactive flows along with the MUSCL approach utilizing a differentiable limiter function [13]. We conjectured that the qualitative differences discerned in the temperature contours are attributed due to the model differences and marginal differences in the inflow conditions. Fig. 3 is highlighting the five different models and the corresponding grid systems in the computational domain used for parametric analytical studies for the geometrical optimization of the scramjet combustor. Fig. 4 is demonstrating the temperature contours at various time steps for a non-reacting case with cavity and without injection. Fig. 5 is demonstrating the temperature contours for an inviscid reacting case with cavity and with injection up to 5 ms. Figs. 6 (a), (b) are demonstrating the temperature and Mach number contours at various time steps for a reacting case with cavity and with high supersonic inflow with injection. The high-supersonic inflow condition is established using a CD nozzle. Using the selected model we have carried out several parametric analytical studies on scramjet combustors with different shapes of cavity. Figs. 7 (a), (b) show contours of static temperature, and turbulent intensity at various time steps up to 5 ms. While comparing the temperature contours of the scramjet combustor, qualitatively and quantitatively, with and without cavity one can easily comprehend that cavity is having significant influence on flow features for a better performance of the combustor.

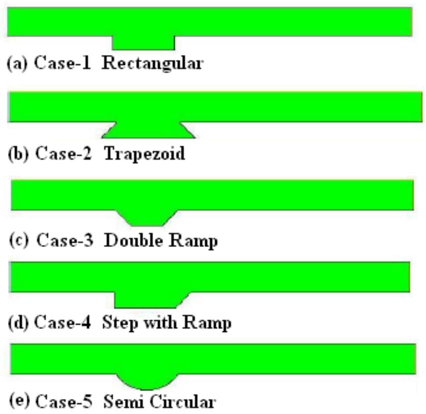


Fig. 3 Physical models and the corresponding grid systems

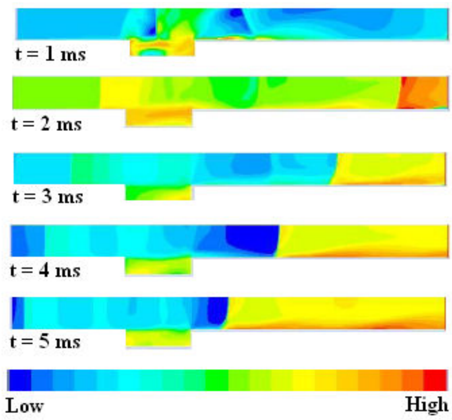


Fig. 4 Demonstrating the temperature contours at various time steps for a non-reacting case with cavity and without injection

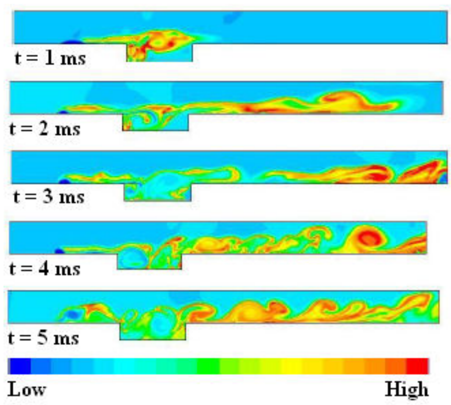


Fig. 5 Demonstrating the temperature contours for an inviscid reacting case with cavity and with injection up to 5 ms

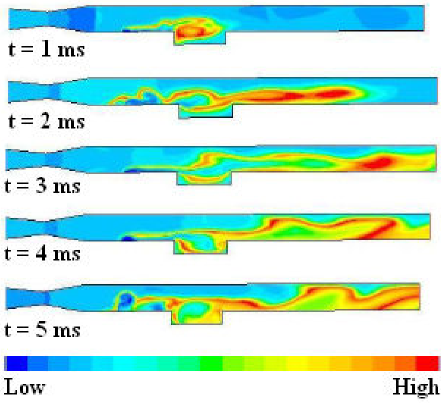


Fig. 6 (a) Demonstrating the temperature contours at various time steps for a reacting case with cavity and with high supersonic inflow with injection

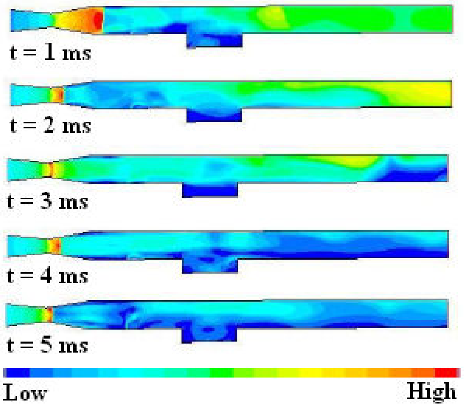
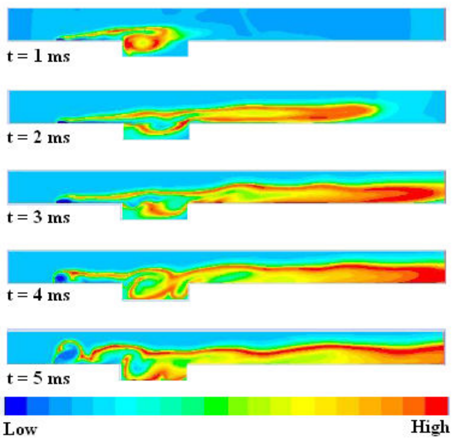
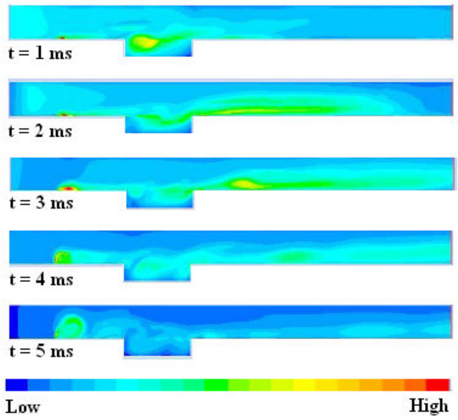


Fig. 6 (b) Demonstrating the Mach number contours at various time steps for a reacting case with cavity and with high supersonic inflow with injection



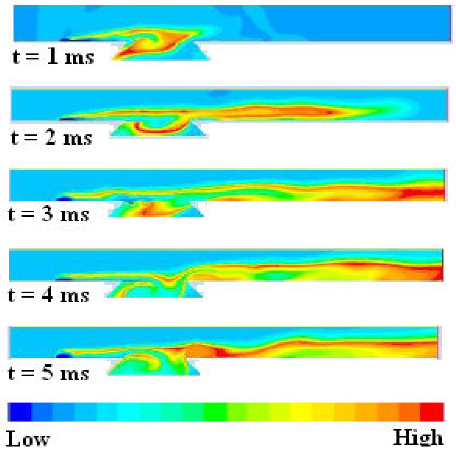
(a) Contours of Temperature



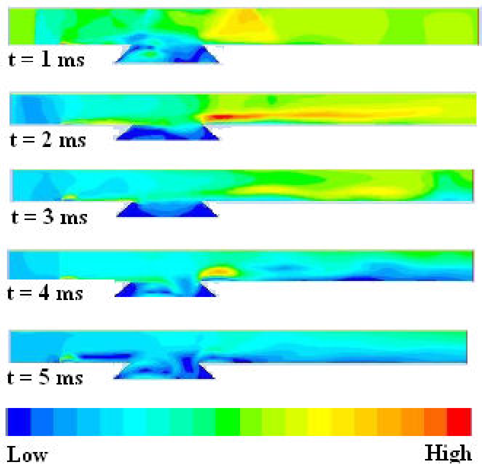
(b) Contours of Turbulent Intensity

Fig. 7 (a)-(b) Demonstrating the contours of static temperature, and turbulent intensity for a reacting case with cavity at various time steps up to 5 ms of Case-1

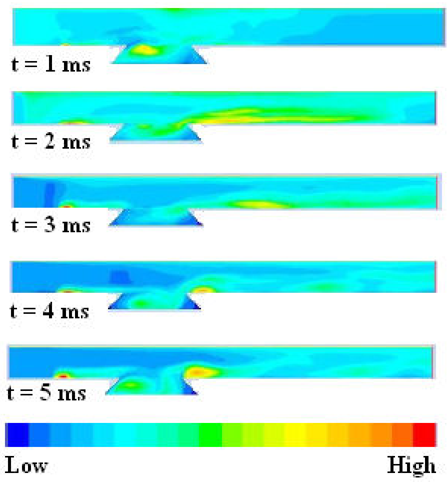
Figs. 8-11 show the various flow features of a scramjet combustor with different shapes of cavity, viz., cavity with trapezoid cross-section, double ramp, backward facing step with ramp, semi circular cavity. The numerical results show a wide variety of flow features resulting from the interactions between the injector flows, shock waves, boundary layers, and cavity flows. Fig. 12 shows the comparison of the radial exit temperature of five different cases. It is evident from Figs. 4-12 that the cavity based scramjet combustors having a bearing on the source of disturbance for the transverse jet oscillation, fuel/air mixing enhancement, and flame-holding improvement for a better exit conditions for improving the performance of the scramjet combustor. We observed that cavity shape with backward facing step and forward ramp (Case-4) is giving more exit temperature than the other four cases with the same initial and boundary conditions. Fig. 13 shows the comparison of the radial exit temperature profiles of Case-4 with four different ramp angles to the horizontal, viz., 15^o, 30^o, 45^o, & 60^o with same initial and boundary conditions. We have observed that a case with 45^o ramp angle is giving the highest average temperature at the exit. Therefore we have concluded that cavity shape with backward facing step and 45^0 forward ramp is a good choice compared to other four models of scramjet combustors considered in this study.



(a) Contours of Temperature



(b) Contours of Velocity



(c) Contours of Turbulent Intensity

Fig. 8 (a)-(c) shows contours of static temperature, velocity, and turbulent intensity up to 5 ms of Case-2

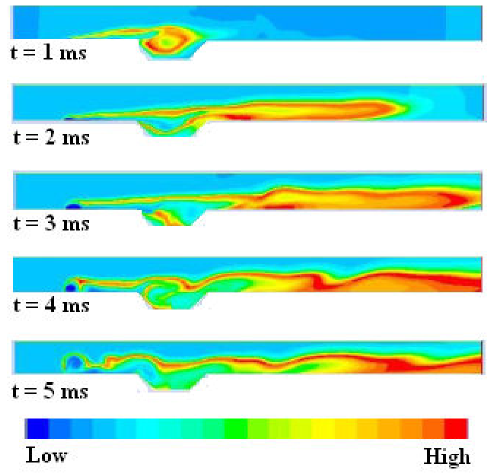
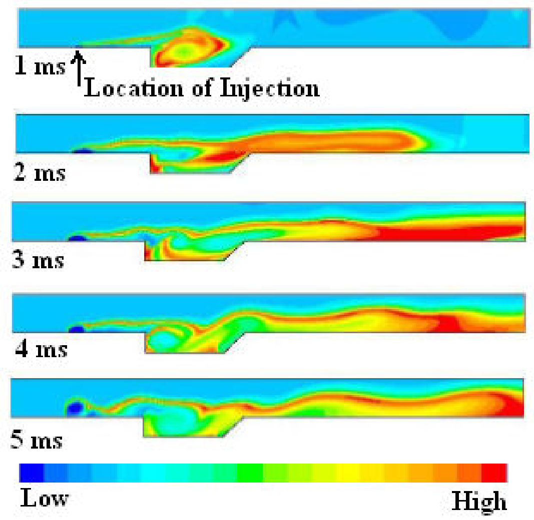
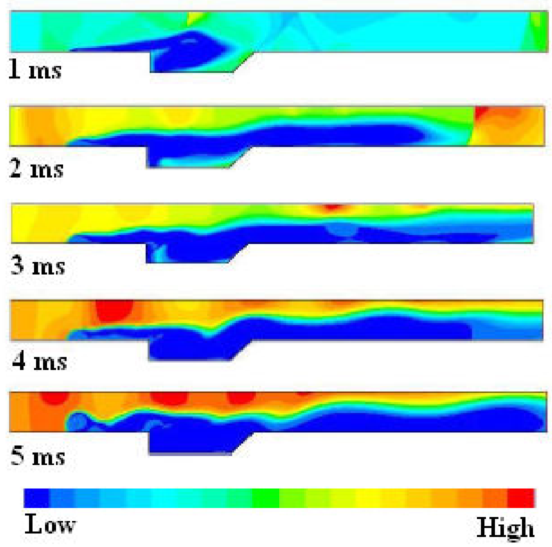


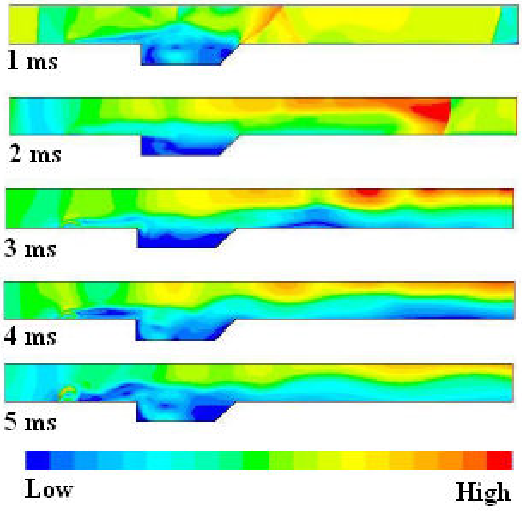
Fig. 9 Contours of temperature with double ramp (Case-3)



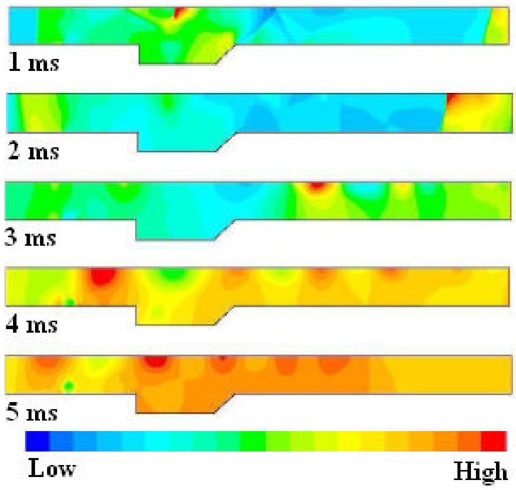
(a) Contours of Temperature



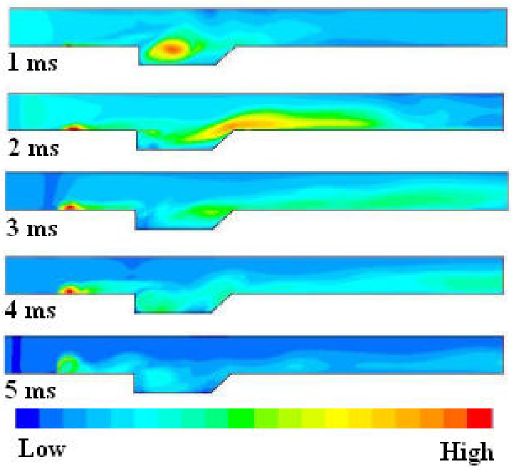
(b) Contours of Density



(c) Contours of Mach number



(d) Contours of Pressure



(e) Contours of Turbulent Intensity

Fig. 10 (a)-(e) Demonstrating various contours for a reacting case with cavity having step and 45° ramp at various time steps up to 5 ms of Case-4

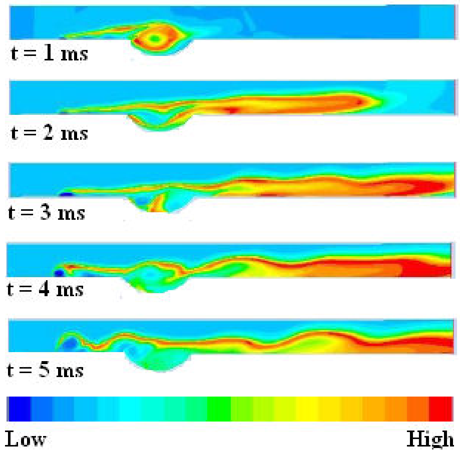


Fig. 11 Contours of Temperature with semi circular cavity (Case-5)

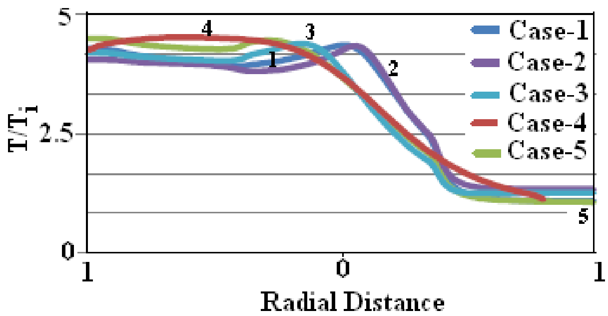


Fig. 12 Comparison of the radial exit temperature profile of five different geometrical shapes of the scramjet combustor cavity with same initial and boundary conditions

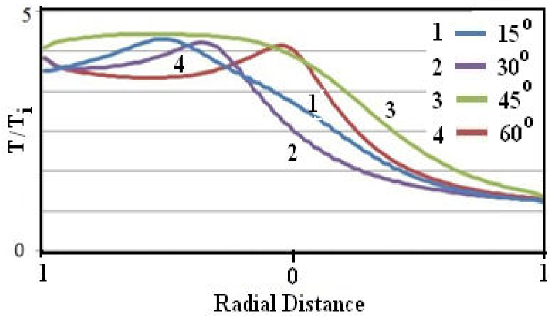


Fig. 13 Comparison of the radial exit temperature profiles of Case-4 with four different ramp angles to the horizontal with same initial and boundary conditions

IV. Concluding Remarks

The flow field within the combustor of any scramjet engine is very complex and poses a considerable challenge in design and development of a supersonic combustor with an optimized geometry. In this paper a successful attempt has been made numerically for the design optimization of a scramjet combustor. The numerical results show a wide variety of flow features resulting from the interactions between the injector flows and cavity flows. The characteristics of different cavity based combustors with transverse injection of hydrogen have been examined for both non-reacting and reacting flows. We conjectured that an optimized cavity is a good choice to stabilize the flame in the hypersonic flow, and it generates a recirculation zone in the scramjet combustor for meeting the residence time. We concluded that cavity shape with backward facing step and 45^0 forward ramp is a good choice to get higher temperatures at the exit compared to other four models.

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