Effect of Ramp-Cavity Injector in Supersonic Combustion

R. Mohamed Arif, S. Sangeetha
Assistant Professor[1, 2], Department of Aerospace Engineering, SRM University, Chennai.

Abstract - A computational analysis has been carried out in a Scramjet engine combustor with the multiple ramp-cavity injectors which will enhance the fuel air mixing in a short flow residence time for both cold flow and reacting flows. Inclined injection of hydrogen is used for the combustion analysis. The analysis includes: 1. Study and analysis of multi cavity effect in flame holding enhancement at supersonic flows by cold flow. 2. Reacting flow analysis of multi ramp-cavity injectors with different fuel injection angels in the scramjet combustor. It is observed that the ramp-cavity injector in supersonic combustor helps to lift the fuel away from wall and enhances the mixing and flame holding capabilities in supersonic combustion which was identified by the increment in combustor exit temperature and combustion efficiency. The roles of the cavity, ramp, injection angle, and heat release in determining the flow dynamics are examined systematically. The contour of Temperature and pressure explains the extent of combustion taking place in this case.

Index Terms - Scramjet and Supersonic combustion, Flame holder, Shock waves, Vorticity, Ramp & Cavity, Compressibility, Wall injector.

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1. INTRODUCTION

The success of future high-speed air transportation will be strongly dependent on the development of hypersonic air-breathing propulsion engines. Although there are many fundamental issues, combustor represents one of the core technologies that dictate the development of hypersonic propulsion systems. At hypersonic flight speed, the flow entering the combustor should be maintained at supersonic level to avoid the excessive heating and dissociation of air. The residence time of the air in a hypersonic engine is on the order of 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.

1.1 Scramjet engine Combustion Chambers

The combustion chamber could be designed, theoretically, to operate at a constant Mach number to capitalize on the maximum heat release; alternatively, it could be designed with constant area or for operation at constant pressure. Here it maintains the constant pressure by divergent duct.

Generally, the designs suggested so far included the following components: a constant area for rapid heat release followed by an expansion that allows additional heat addition after thermal choking has taken place at the end of the constant cross-section area and a further diverging section that may be considered the internal nozzle leading to the external nozzle. An isolating section is needed between the inlet and the combustion chamber to accommodate the pressure differences between these two components (Ortwerth[33], 2000). Often a step expansion is included at the combustion chamber entrance to offer additional separation while, at the same time, acting as a flame holding device and a thrust surface (Abbitt [1] 1993). In the divergent part of the combustion chamber, additional fuel can be injected, provided that the constant cross-section area has not reached thermal choking and the flow continues to remain supersonic (Heiser & Pratt [19], 1994).

1.2 Scramjet engine - Technological challenges

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.

1.3 Few Remedies

1.3.1 Cavity Based Injection

Generation of pressure oscillations is also considered to be a better candidate to achieve better mixing. Unsteady shear layers generate acoustic oscillations. Wall mounted cavities generates these oscillations to aid the mixing enhancement. Cavities are characterized by their L/D ratio

(Heller [20], 1975).

1.3.2 Ramp injectors

One of the strategies to solve the aforesaid problems of mixing is generation of axial vortices. Axial vortices possess a better far field mixing characteristics. Also they are being propagated to a considerable distance, even with the suppressing characteristics of the supersonic core flow. There are several ways to generate the additional vortices needed to enhance the mixing of fuel in a supersonic combustor. One of the practical method is to introduce a physical ramp (Weidong & Zhang [57] 2010).

1.3.3 Combination of Ramp and cavity injectors

The overall performance of ramp and cavity injectors can be improved by combining them properly. The combination of cavities and ramps generate a three dimensional flow field and turbulence for better mixing and combustion (Gardner [16], 2001). 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.

1.4 Combustor Solution Procedure

The combustion process takes place at constant pressure. The most relevant simplifications are made in the modeling of this component; it is assumed that the products are in chemical equilibrium. The following equations are used:

1.4.1 Conservation of mass

The expression for mass conservation is given by: $\dot{m}_1 + \dot{m}_{fuel} = \dot{m}_2$ Where the subscripts 1 and 2 denote the upstream and downstream faces of the combustor respectively and where $\dot{m}_{fuel}$ is the mass inflow rate due to in-mixing from the fuel stream.

1.4.2 Conservation of energy

The adiabatic constraint is given by conservation of energy as in the following equation:

$$\dot{m}_1 h_1 + \dot{m}_{fuel} h_f = \dot{m}_2 h_2 + q$$

1.4.3 Conservation of linear momentum

Assuming constant pressure for the steady-flow mixing (P1 = P2) and reaction process and neglecting shear stresses at control volume boundaries, conservation of linear momentum gives:

$$\dot{m}_1 v_1 + \dot{m}_{fuel} v_f = \dot{m}_2 v_2$$

1.5 Flow properties:

To above equations, the thermodynamic parameters depend on area ratio, temperature ratio, pressure effect and total energy as:

$$\frac{dA}{A} = (M^2 - 1)\frac{dV}{V}$$

$$\frac{T_0}{T} = \left(1 + \frac{M^2}{2}(\gamma - 1)\right)$$

$$\frac{P_0}{P} = \left(1 + \frac{M^2}{2}(\gamma - 1)\right)^{\frac{(\gamma-1)}{\gamma}}$$

$$P_2 = P_3$$

$$P_2\left(1 + \frac{M_2^2}{2}(\gamma - 1)\right)^{\frac{(\gamma-1)}{\gamma}} = P_3\left(1 + \frac{M_3^2}{2}(\gamma - 1)\right)^{\frac{(\gamma-1)}{\gamma}}$$

$$\frac{T_3}{T_2} = \left[\frac{1 + \frac{M_2^2}{2}(\gamma - 1)}{1 + \frac{M_3^2}{2}(\gamma - 1)}\right]$$

$$\frac{P_3}{P_2} = \left[\frac{1 + \frac{M_2^2}{2}(\gamma - 1)}{1 + \frac{M_3^2}{2}(\gamma - 1)}\right]^{\frac{(\gamma-1)}{\gamma}}$$

$$Q = C_p(T_3 - T_2)$$

3. METHEDOLOGY

The models have been developed for a complete simulation of supersonic combustion process. Here, the preprocessor tool GAMBIT has been used for the purpose, and it has the flexibility of creating geometrical configurations, meshing the models and defining the boundary entities. The models have been meshed into 40,000 to 60,000 numbers of quadrilateral cells. The selections of grids and cells numbers are depend on computational limitations.

The computational solution has been achieved by performing the following steps. First, the model has been generated and imported to FLUENT from GAMBIT by using mesh file option. The checking of the grid, material properties, operating conditions and boundary conditions has been assigned respectively. Initially, steady state calculations are carried out to remove the transient till the residuals of all governing equations are of the order of 10-5. Then convergence criteria have been applied for the residual. After the required convergence of the solution, solution has been stopped and results of the solution are analyzed.

3.1 Physical Model and Boundary Conditions:

The supersonic combustor considered in this study indicated in the above figure with appropriate dimensions. The cavities taken into the analysis has a L/D ratio of 4 & 5 with the back wall angle of 45° because Zhang et al [60] experimentally found that these configurations have minimal drag penalties.

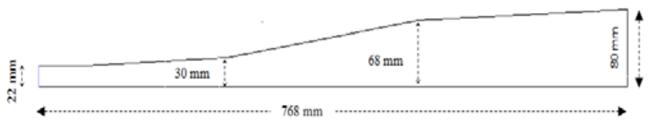

Figure 1: scramjet combustor model

The ramp taken into this study has wedge angle of 10° and blockage ratio of 20% which has been found suitable for this study by analytical and numerical analysis as follows:

For 30% BR, reduction in mass flow rate and thrust is 35% and for 15° wedge angle, reduction in Mach number is 20%.

The effect of multiple cavities and ramps in flame holding and mixing enhancements in supersonic combustion are analyzed with the cold flow in the subsequent sections and finally the effect of combined multi ramp-cavity injectors in supersonic combustion are analyzed by the reacting flow analysis.

The boundary entities for the solver have been set as below:

COLD FLOW			
Parameters	Units	Inlet	Outlet
Total pressure	MPa	6	6
Static pressure	MPa	0.3	0.1
Total temperature	K	2800	2799
Static temperature	K	1190	880.7
Velocity	m/s	1798	2308
Mach No	-	2.6	3.3

REACTING FLOW			
Parameters	Units	Air Inlet	Fuel Inlet
Total pressure	MPa	4	2
Static pressure	MPa	0.15	0.7
Total temperature	K	2800	400
Static temperature	K	1123	302
Velocity	m/s	1880	1584
Mach no	-	2.8	1.2

The details of analysis carried out on the development of multiple Cavity and Ramp injectors in combustor chamber with cold flow are highlighted in the subsequent sections.

4. RESULTS & DISCUSSION

4.1 Cold flow analysis:

The effect of multiple cavities in the mixing and flame holding has been analyzed in the combustor model mentioned above. Due to the short fuel residence time, the fuel should be injected in front half of the combustor so that it will maintain enough residence time for the proper mixing and combustion. So the cavities have been placed in the front half of the combustor because the fuel injectors are normally placed in and around the cavity.

Main purpose of the cavity is flame stabilization because the very high temperature inside the cavity may act as the flame holder and igniter in the combustion process. Hence temperature profile has been taken for this analysis.

Case: 1

The below figures describe the temperature profile of combustor model. For the inlet temp 1190 k, the wall temperature increased to around 2400 k due to viscous heating shown by red lines. And temperature at the interior is keeps on decreased towards exit to around 800 k due to the flow acceleration in divergent duct shown by a black line.

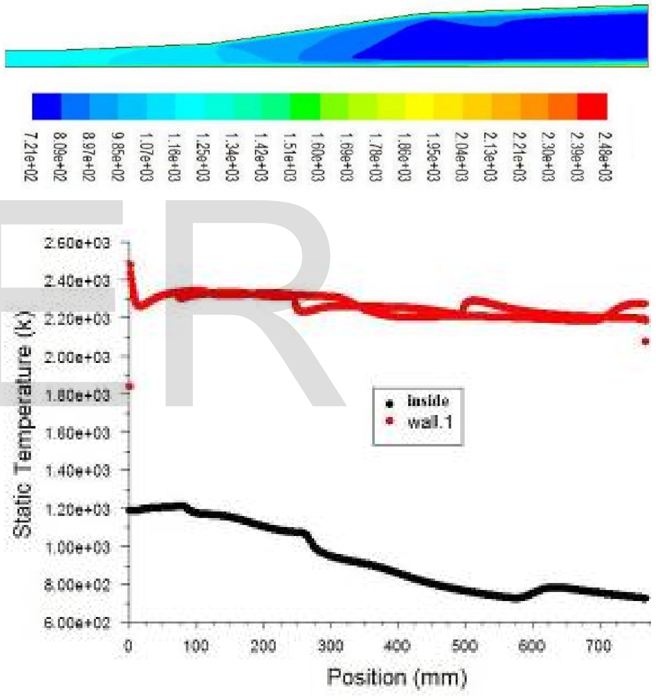

Figure 2: static temperature contour and profile of combustor model

Case: 2

The cavity with L/D ratio of 4 and back wall angle of 45° has been placed at the exit of the isolator. The below temperature contour indicates that the inlet temperature increased to 2710k inside the cavity due to the flow stagnation.

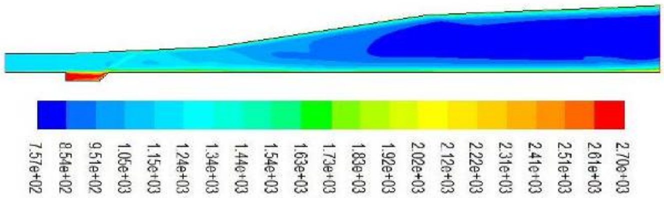

Figure 3: static temperature contour of combustor model with single cavity

Case: 3

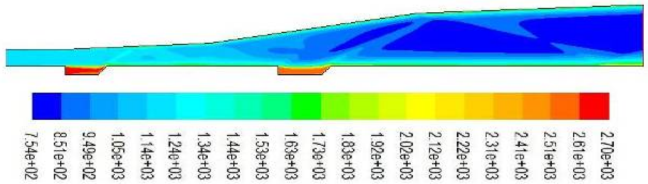

Figure 4: static temperature contour of combustor model with two cavities

The second cavity with L/D ratio 5 and back wall angle of 45° has been placed at mid of the combustor. From the above temperature contour it is found that the temperature inside the second cavity is only 2500k which is less than the first cavity so the effect of second cavity in flame holding capability is less compared to the first cavity and the temperature rise in second cavity is near equal to combustor wall temperature, which itself producing 2400 k.

Case: 4&5

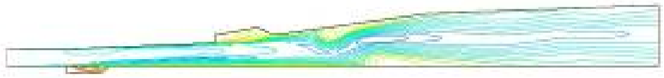

Figure 5: static temperature contour of combustor model with two cavities

Figure 6: static temperature contour of combustor model with three cavities

For the combustor model with a cavity placed at the upper wall, the solution is not converged and results showing some disturbed flow. So it is highly recommended to modify the upper wall cavity.

Case: 6

From the results obtained by the above cases, the second cavity on same wall has been eliminated and the upper wall cavity has been replaced by a backward step, which giving proper contour to the combustor profile. The modified combustor model is shown in below figure. The temperature profile shows the temperature inside the cavity and rearward step are same around 2710k.

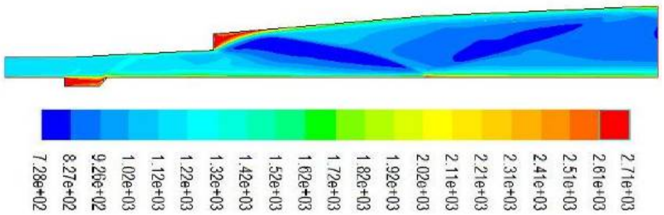

Figure 7: static temperature contour of combustor model with cavity and backward step

The above pressure contour indicates that due to the sudden expansion in cross sectional area, the backward step produces expansion wave at the leading edge corner which will cause very low pressure behind the wave. So this pressure difference at the front wall will creates axial vortices to lift and mix the fuel injected inside the cavity

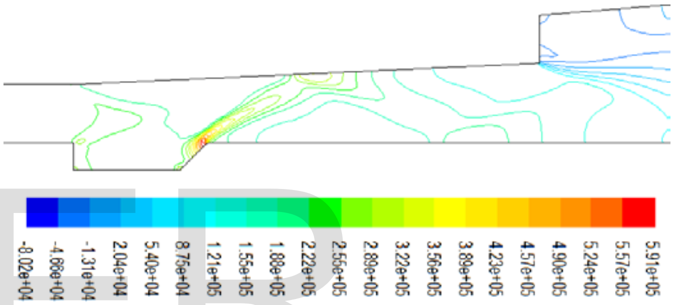

Figure 8: static pressure contour of combustor model with cavity and backward step

But in the first cavity, the expansion wave is replaced by the compressive nature of separation wave by angled back wall to reduce the drag penalties. So there won't be such a pressure difference to lift the fuel from base.

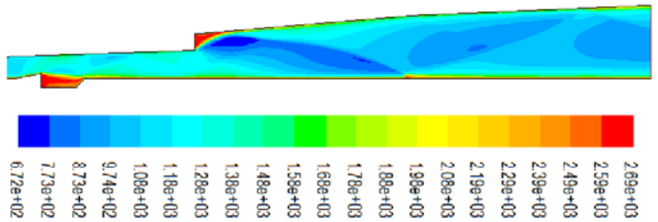

Figure 9: static temperature contour of combustor model with cavity and backward step

To overcome this problem, cavity needs some additional devices such as ramp or pylon, which are the promising devices to produce the axial vortices. But the temperature distribution is same for this configuration as indicated in the above figure.

Comparison:

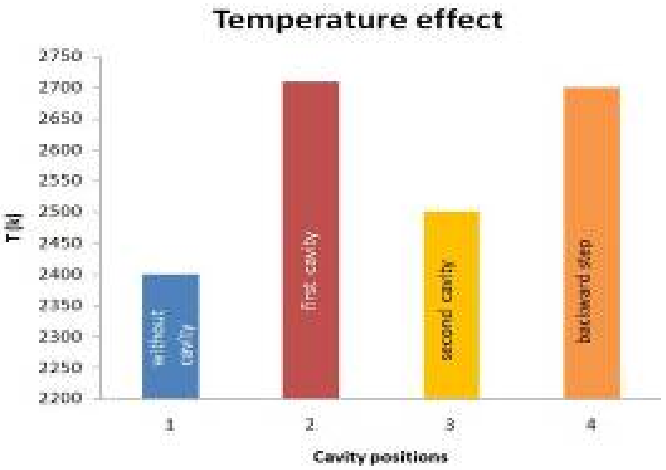

Figure 10: comparison of combustor exit temperature

The above bar chart indicates the followings: the first cavity and backward step having better flame holding characteristics in supersonic flow. And the second cavity has less effect than first cavity. So it is possible to operate the combustor without this second cavity because the flame holding effect of the second cavity is less compared to its drag penalties.

4.2 Reaction flow analysis

Finally, the details of analysis carried out on the development of Ramp-Cavity combustor with injection of hydrogen fuel for different injection angles 15° & 30° is highlighted in the subsequent sections.

The overall performance improvement of multi Ramp-Cavity injectors in combustion efficiency has been taken for the analysis.

The combustion efficiency depends on the high combustion chamber exit temperature hence it can expand the gas more to produce high thrust. So temperature and pressure profiles are considered for the analysis.

Case: 1

Hydrogen fuel is injected in the combustor model by 3 wall injectors at 30° injection angle.

The figure shows the temperature distribution shows that, for the inlet temperature of 1100k, temperature is increased to above 3000k near the 1st injector and reduced to 2600k at the combustor exit due to improper mixing and combustion at 2nd & 3rd injectors.

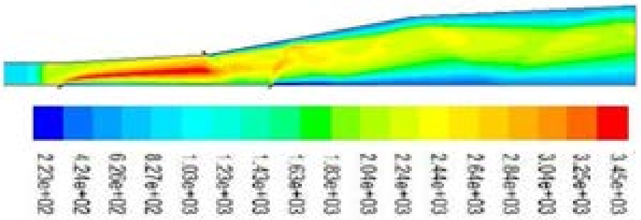

Figure 11: combustor with 3 wall injectors inclined at 30°.

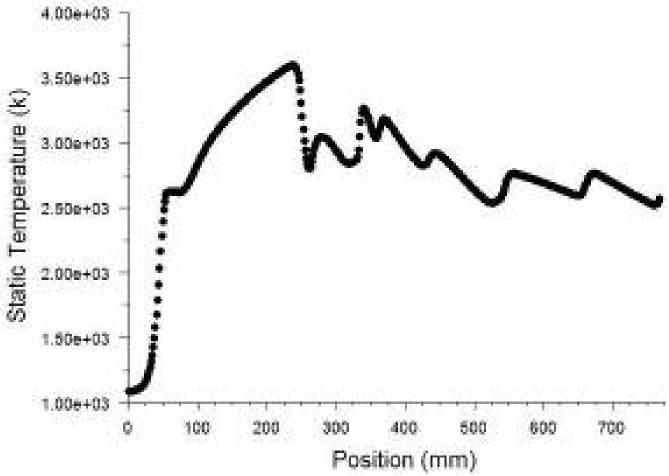

Figure 12: static temperature distribution at centre

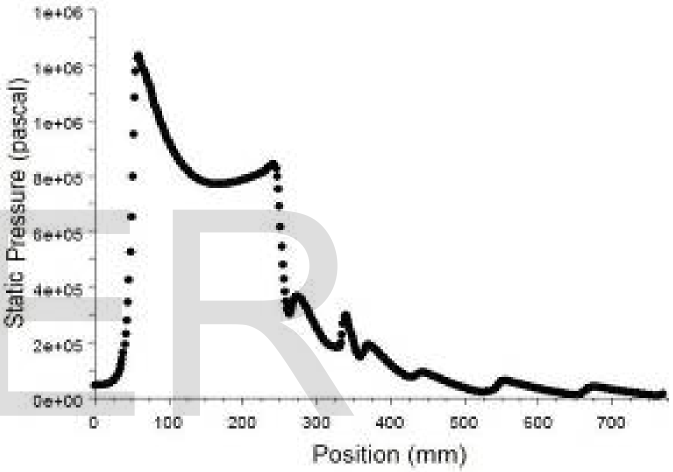

Figure 13: static pressure distribution at centre

The profile shown above, which has nearly equal pressure distribution at inlet and exit of the combustor proves the combustion process at constant pressure.

Case: 2

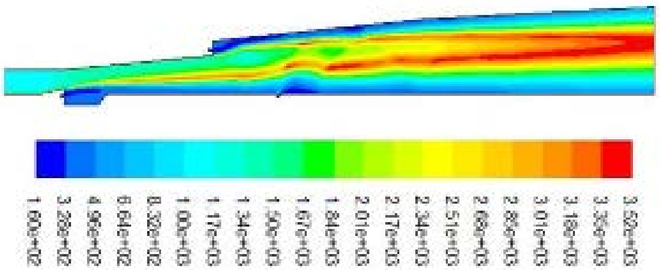

Figure 14: static temperature contour

Hydrogen fuel is injected in the combustor with 15° injection angle at ramp-cavity and backward step and 30° injection angle at simple wall injector as shown in figure.

The inlet temperature of 1100k increased to above 3000k at all injectors due to the combustion and maintained 3500k at downstream, which is shown by the following figures.

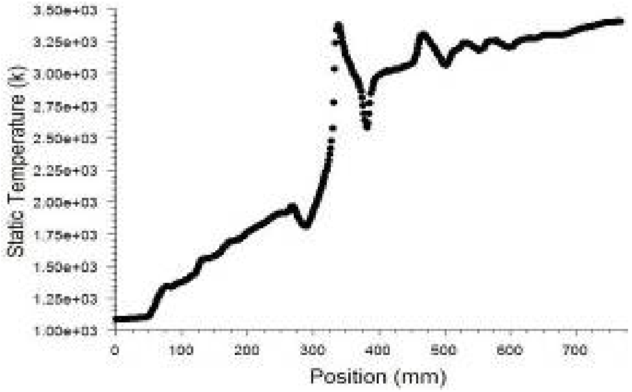

Figure 15: static temperature distribution at centre

Case: 3 & 4

Hydrogen is injected with 15° injection angle in the combustor with ramp injector instead of simple wall injector placed along with ramp-cavity injector and backward step as in figure below.

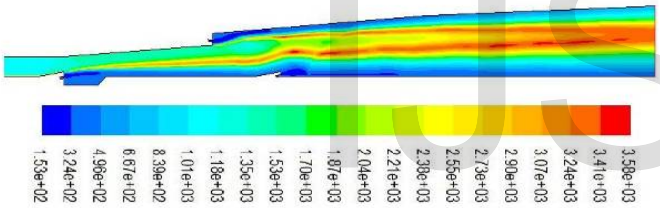

Figure 16: static temperature contour

For the same model, the second ramp injector is replaced by second backward step instead of wall injector as in the figure below.

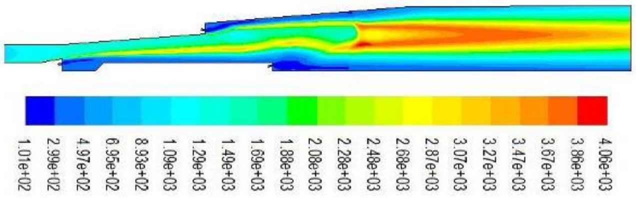

Figure 17: static temperature contour

From the temperature distribution of above two models, it is found that, the combustor exit temperatures of both models are less than that of combustor with simple wall injector. So it is possible to operate the combustor without the second ramp or cavity which is already proven by cold flow analysis.

5. CONCLUSION

Detailed numerical simulations of the scramjet combustor with the ramp-cavity injectors have been performed for the mixing enhancement and flame holding capabilities in supersonic combustion using non-reacting and reacting flows.

The results show a wide variety of phenomena resulting from the interactions between the injector flows, shock waves, boundary layers, and cavity flows. Major findings are summarized as follows:

1. With the fixed depth and the fixed length-to-depth ratio, the temperature inside the rectangular cavity found to be very high, which may act as a flame holder in combustion process and we must consider its material in the design process when employing it as the flame holder.
2. Placing a two mixing enhancement devices like cavity or ramp on the same side of combustor, it has been found that the effect of second device has not considerable in enhancement. So it is possible to operate the combustor without the second cavity or ramp which may increase the drag penalties solely rather than helps to combustion.
3. In the backward step, the axial vortices have been produced due to the expansion wave at the leading edge corner which helps to scooped out the fuel mixture from the bottom wall. But it has been observed that the cavities need some additional devices like ramp to lift the fuel.
4. The fuel mixture has been lifted from the cavity and maintained away from the wall to the core flow axially due to the ramp placed over it. Hence, the fuel axial momentum will increase the portion of the thrust. It also eliminates the hot spots at the walls and special structural requirements.
5. Also it is found that the ramp-cavity injector configuration shows better mixing and flame holding capabilities in supersonic combustion than the simple wall injectors.

It was expected that this project will serve its purpose as an overview of mixing and flame holding enhancement on the performance characteristics of supersonic combustion.

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