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Numerical Investigation to Enhance the Performance of Supersonic Combustor

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Abstract: **This paper shares about intense research work on design and development of hypersonic vehicle which flies at Mach 5 and above. The performances of such engines depend mainly on the supersonic combustor. In this study, the flow field within the combustor is numerically investigated by using the commercial software FLUENT. The results are obtained by using density based, Navier stokes equations, energy conservation equation and SST kω turbulence model. The combustor model analyzed in this study consist of rectangular chamber with both top and bottom walls diverged away by the small angle. The combustor has three stages of combustor and four H_2 injection slots on both the top and bottom walls.The influences of the fuel injection location and divergence angle on the flow field of the scramjet combustor with multiple cavity flame holders are investigated.**

1. INTRODUCTION

Ramjet and pulsejet engines were being used as auxiliary devices to provide good performance in high subsonic to low supersonic speed range. It is well known that efficient operation of ramjets is limited to about Mach 5, beyond which efficiency decreases drastically. The desire for hypersonic flight necessitated Scramjet engine potentially expanding the speed envelope to the Mach 15.For such flights, deceleration of air entering the engines 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.

It is necessary to understand the working principles of ramjet engine and scramjet engine in which the combustion chambers are used. This report expresses the detailed analysis of a transverse injection scheme integrated with cavity flame holder which is employed in scramjet engines. Numerical experiments were conducted to find more efficient methods to augment the mixing characteristics of transverse injection integrated with cavity flame holder to increase the performance of supersonic combustor. It is predominantly a numerical investigation executed utilizing the commercial CFD code FLUENT.

2. CAVITY FLAME HOLDERS – FUEL INJECTION

A cavity, exposed to a flow, experiences self-sustained oscillations, which can induce fluctuating pressures, densities, and velocities in and around the cavity, resulting in drag penalties. In general, cavity flow can be categorized into basic flow regimes depending primarily on the length-to-depth ratio, L/D.

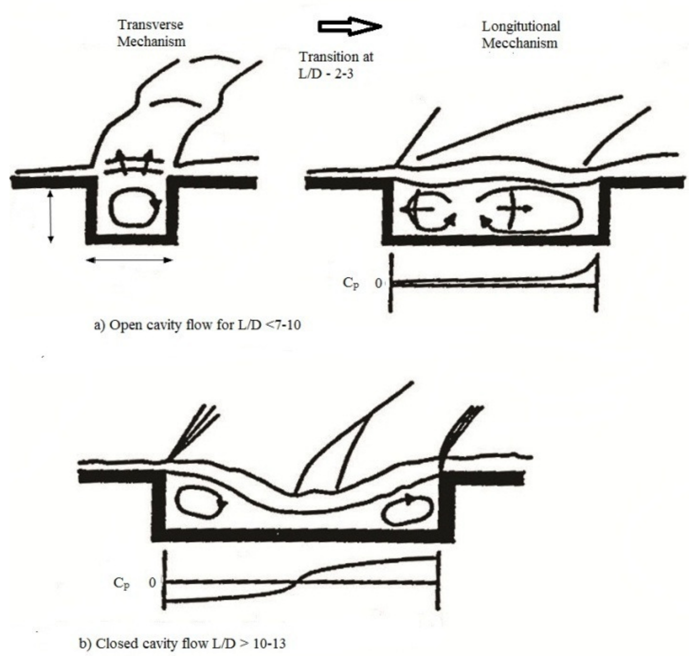

Figure 1. Flow field schematics of cavities with different L/D in a supersonic flow

In all cases, a shear layer separates from the upstream lip and reattaches downstream. For L/D < 7- 10, the cavity flow is termed as "open" because the upper shear layer reattaches to the back face. Small aspect ratio cavities (L/D <2-3) are controlled by transverse oscillation mechanism, whereas larger aspect ratio cavities, longitudinal oscillation becomes the dominant mechanism. For L/D > 10-13 the cavity flow is termed "closed" because the free shear layer reattaches to the lower wall. The pressure increase in the back wall vicinity and the pressure decrease in the front wall results in large drag losses. The critical length-to-depth ratio, at which a transition between different cavity flow regimes occurs, depends also on the boundary-layer thickness at the leading edge of the cavity, the flow Mach number, and the cavity width.

3. COMPUTATIONAL METHODOLOGY

The numerical analyses were carried out to obtain the solutions using the CFD code FLUENT which uses a control-surface based technique to convert the governing equations to algebraic equations.

3.1 Governing Equation

The governing equations comprise the mass conservation equations, the momentum conservation equations, the energy conservation equation and the equations of turbulence model used. These equations are non-linear and involve unknown correlations. In order to describe the equations a closed set, SST kω turbulence model is used.

3.1.1 Conservation Equation

The conservation equations: two dimensional continuity equations for air (a) and for hydrogen fuel (H_2), the three momentum equations and the energy equation are expressed in vector form.

$$\frac{\partial Q}{\partial t}+\frac{\partial E}{\partial x}+\frac{\partial F}{\partial y}=\frac{\partial E_v}{\partial x}+\frac{\partial F_v}{\partial y} \tag{3.1}$$

The solution vector (Q), the conservation vectors (E, F, Q) and the viscous vectors (E_v and F_v) are defined as

$$Q=[\rho_a,\quad \rho_{H_2},\quad \rho u,\quad]^T \tag{3.2}$$

$$E=\left[\rho_a u,\quad \rho_{H_2}u,\quad \rho u^2+p,\quad \rho uv,\quad \rho h_0\, u\right]^T \tag{3.3}$$

$$F=\left[\rho_a v,\quad \rho_{H_2}v,\quad \rho uv,\quad \rho v^2+p,\quad \rho h_0\, v\right]^T \tag{3.4}$$

$$E_v=\left[\rho_a\, u_a^d,\quad \rho_{H_2}\, u_{H_2}^d,\quad \tau_{xx},\quad \tau_{xy},\quad \tau_{xn}\, u_n-q_x\right]^T \tag{3.5}$$

$$F_v=\left[\rho_a\, v_a^d,\quad \rho_{H_2}\, v_{H_2}^d,\quad \tau_{yx},\quad \tau_{yy},\quad \tau_{yn}\, u_n-q_y\right]^T \tag{3.6}$$

3.2 Turbulence Modelling

The turbulence models can be categorized depending on the number of differential equations needed in addition to the conservation equations: zero-equation model, one equation model, two equation model, Reynolds stress models, algebraic stress models etc. The most commonly used turbulence models are the two equation models such as k-ε turbulence model, k-ω turbulence model, SST k-ω turbulence model etc. The quantities k, ε and ω are turbulent kinetic energy, rate of dissipation of turbulent kinetic energy and specific dissipation rate (ε/k) respectively.SST K-ω model is an accurate turbulence model for a wider class of flows and it uses blending function which activates K-ω turbulence model in the near wall regions and transforms k-ε turbulence model in the far field regions. The two additional equations used in the SST K-ω turbulence model are turbulent mixing energy equation and the specific dissipation rate equation.

3.2.1 Turbulence Mixing Energy

$$\frac{\partial(\rho k)}{\partial t}+\frac{\partial(\rho k u)}{\partial x}+\frac{\partial(\rho k v)}{\partial y}=\frac{\partial}{\partial x}\left(\Gamma_k\frac{\partial k}{\partial x}\right)+\frac{\partial}{\partial y}\left(\Gamma_k\frac{\partial k}{\partial y}\right)+G_k-Y_k \tag{3.7}$$

Where

$\boldsymbol{A}=\frac{\partial(\rho k)}{\partial t}$ $\quad$ $\mathbf{B}=\frac{\partial(\rho k u)}{\partial x}+\frac{\partial(\rho k v)}{\partial y}$;

$\mathbf{C}=\frac{\partial}{\partial x}\left(\Gamma_k\frac{\partial k}{\partial x}\right)+\frac{\partial}{\partial y}\left(\Gamma_k\frac{\partial k}{\partial y}\right)$; D = G_k and

E = Y_k

Specific Dissipation Rate

$$\mathbf{B}=\frac{\partial(\rho k u)}{\partial x}+\frac{\partial(\rho k v)}{\partial y}\frac{\partial(\rho\omega)}{\partial t}+\frac{\partial(\rho\omega u)}{\partial x}+\frac{\partial(\rho\omega v)}{\partial y}=\frac{\partial}{\partial x}\left(\Gamma_\omega\frac{\partial\omega}{\partial x}\right)+\frac{\partial}{\partial y}\left(\Gamma_\omega\frac{\partial\omega}{\partial y}\right)+G_\omega-Y_\omega+D_\omega \tag{3.8}$$

3.3 Numerical Scheme

The control-surface technique consists of integrating the governing equations about each control volume yielding discrete equations that conserve each quantity on a control-surface basis. The discretization of the governing equations can be illustrated by applying the steady-state conservation equation for the transport of a scalar quantity φ. The following equation is written in integral form for an arbitrary control volume V,

$$\oint \rho\,\phi\,\vec{v}\,.\,d\vec{A}=\oint \Gamma_\phi\nabla\phi.\,d\vec{A}+\int_V S_\phi\,dV \tag{3.9}$$

Where,

ρ = Density

$\vec{v}$ = Velocity Vector

$\vec{A}$ = Surface area vector

Γ_ϕ = Diffusion coefficient for φ

∇_φ = Gradient of ϕ

S_ϕ = Source ϕ per unit volume

The equation (3.9) is applied to each control volume or cell in the computational domain. Discretization of equation (3.9) on a given cell yields the following equation,

$$\sum_{f}^{N_{faces}} \rho_f \, \vec{v}_f \, \phi_f . \vec{A}_f = \sum_{f}^{N_{faces}} \Gamma_\phi \, (\nabla\phi)_n . \vec{A}_f + S_\phi V \quad \textbf{(3.10)}$$

Where,
N_{faces} = Number of faces enclosing cell
ϕ_f = Value of ϕ convicted through face f
$\rho_f \vec{v}_f . \vec{A}_f$ = Mass flux through the face
$\vec{A}_f$ = Area of face f
$(\nabla\phi)_n$ = Magnitude of $\nabla\phi$ normal to face f
V = Cell volume

4. PHYSICAL MODEL

In Scramjet design, Fuel injection and Flame Holder plays a vital role. In order to promote its performance, fuel and air must be mixed at the molecular level in the near field of the fuel injection. . One of the simplest approaches is to use the backward facing step (See figure 1). The presence of a cavity on an aerodynamic surface could have a large impact on the flow surrounding it. The flow field inside a cavity is characterized by recirculating flow that increases the residence time of the fluid entering the cavity. Because the drag associated with flow separation is much less over a cavity than for a bluff-body, a cavity inside a combustor makes a stable flame holder with relatively little pressure drop.

A rectangular cavity driven by a free shear layer provides a well-defined configuration to study the flow separation and reattachment. The engine investigated adopts the single-expanded combustor and fractional combustion mode, and it consists of an isolator and three staged combustors,(see figure 2).There are four cavity flame holders located on the upper and lower walls of the first and the second staged combustors, respectively. Hydrogen is injected from the slot, located at 5mm from the leading edge of the four cavity flame holders on both the upper and lower walls of the first and second staged combustor. The width of the slot is 1mm.

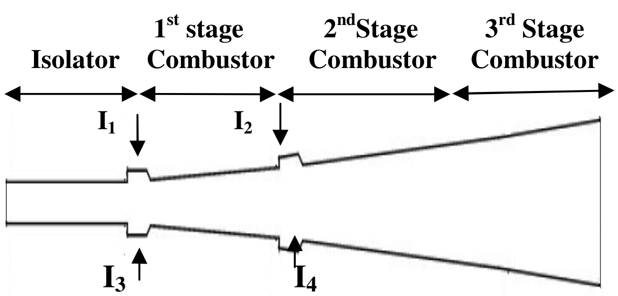

Figure 2. Combustor model with cavity flame holders

The primary geometry parameters of the cavity flame holder: the length of the cavity flame holder L=1.376, the height of the leading edge Du=0.275, the ratio of length-to-height L/Du=5.0, the swept angle θ=45° and the height of the trailing edge D_d=0.275. A schematic diagram of a typical cavity flame holder that has been investigated is shown in Figure 3.

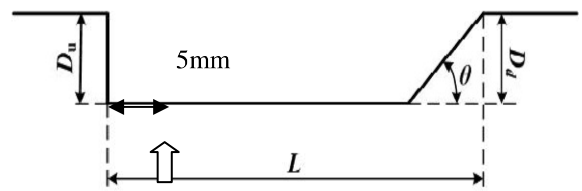

Figure 3. A schematic of a typical cavity flame holder that has been investigated.

5. COMPUTATIONAL GRIDS

To obtain the numerical solutions of all the combustor models, tetrahedral/hybrid cells are generated in the computational domain and in the regions where the gradients are high grid clustering is done. Fine grids are generated near the backward facing step of cavity flame holder and near the injectors to capture the recirculation zones, Mach disks and bow shocks. Grids fit all the solid boundaries smoothly and are compressed at the location of boundary layers.

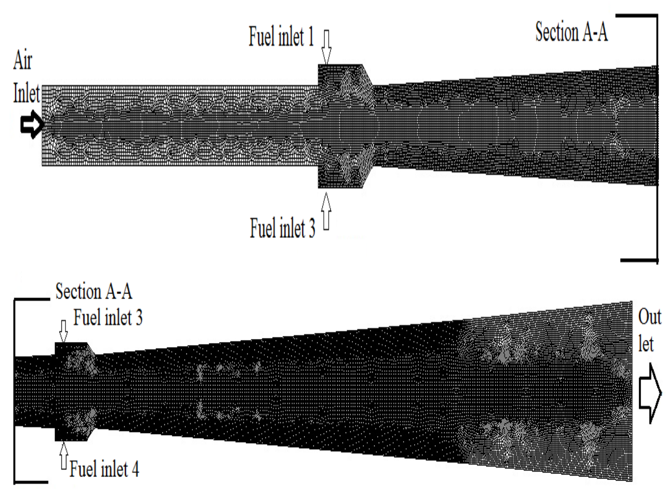

Figure 4. Grid structures of the model

6. RESULT

In order to discuss the effects on influence of the fuel injection location on the flow field of the scramjet combustor with multiple cavity flame holders, three sets of the fuel injection location are employed in this investigation, namely, I_2, I_4 and both I_2 & I_4. The other fuel injection locations are not considered here, i.e. I_1 or I_3, because placing the fuel injection location closer to the entrance of the combustor and more concentrated in a certain distance can be of much assistance in the optimization of the performance of the combustor, but the fuel injection location being excessively close to the entrance of the combustor can cause the interaction between the isolator and the combustor to occur more easily and push the shock wave forward. In supersonic combustion due to interaction shock wave stagnation pressure loss and also cause the inlet unstart. Due to effect of divergence angle on the both sides of the combustor weaker shock wave is generated. This shock wave does not affect the inlet conditions of the isolator. The performance of the supersonic combustor is mainly depending on the inlet condition. So the performance of the combustor will improve.

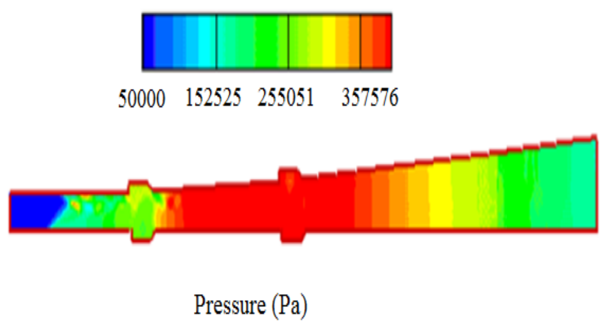

Figure 5.Static pressure in combustor model with Hydrogen injected from both I_2 and I_4

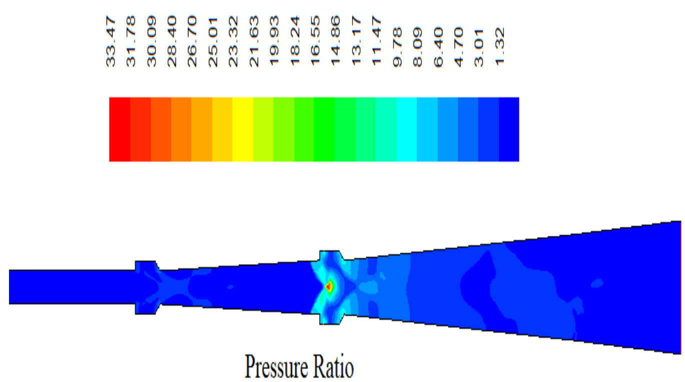

Figure 6.Contours of Static pressure in combustor model with Hydrogen injected I_2 and I_4

The effect of the divergence angles of the posterior stages on the performance of the Scramjet combustor is the most important, and the effect of the divergence angle on the first stage is the least important. When the location of the fuel injection moves forward, the effect of the divergence angle of the former stages becomes more important. When the hydrogen is injected from Both I_2 and I_4 the low static pressure region formed near the second upper and lower cavity flame holder.

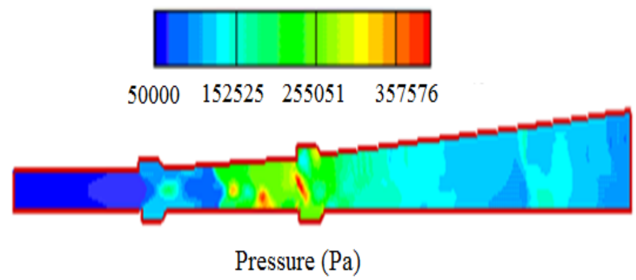

Figure 7. Static pressure in combustor model with Hydrogen injected from I_2

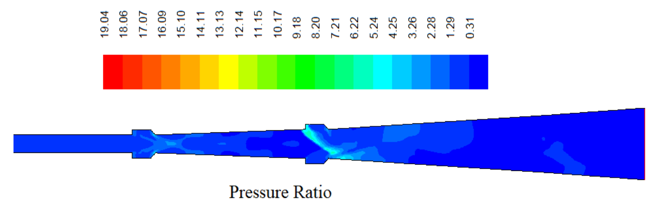

Figure 8. Pressure ratio in combustor model with Hydrogen injected from I_2

There exists a complex shockwave system in the combustor. When the hydrogen is injected from I_2, the shock waves generated from the leading edge of the first upper and lower cavity flame holders interact and form high pressure region.At the same time, observe that the high pressure region exists mainly in the vicinity of the combustion due to the fuel injection. There is a low Mach number region generated on the upper wall of the combustor due to the fuel injection. From figure 8, the shock wave generated from the leading edge of the second upper cavity flame holder. When the hydrogen is injected into the core flow from I_2, the shock wave generated from the leading edge of the first upper cavity flame holder is much weaker than that generated from the leading edge of the first lower cavity flame holder, and this makes the shock wave, after the interaction, deflect into the upper wall of the combustor. Same Aerodynamic Characters will occur when H_2 is injected from I_4, but only the difference is, high pressure region will be generated in the vicinity of the upper wall.

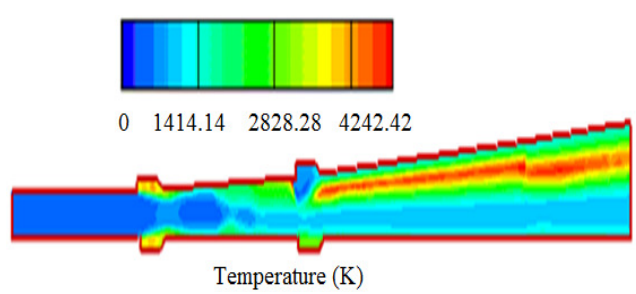

Figure 9. Temperature contours of the case with Hydrogen injected from I_2

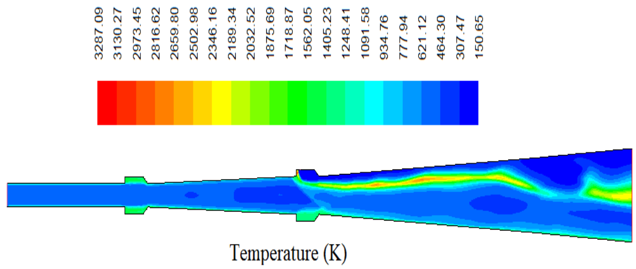

Figure 10. Temperature contours of the case with Hydrogen injected from I_2

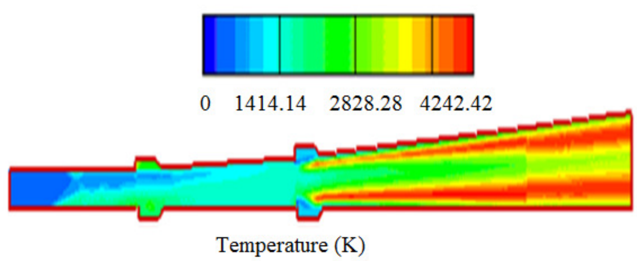

Figure 11. Contours of Temperature in combustor model with Hydrogen injected from I_2 and I_4

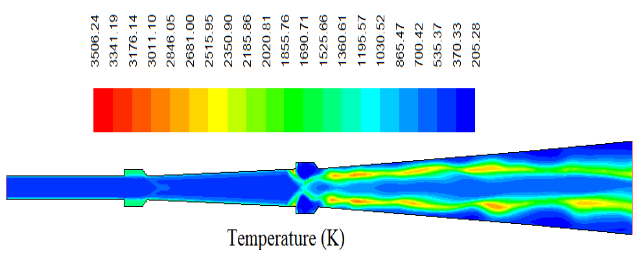

Figure 12. Contours of Temperature in combustor model with Hydrogen injected from I_2 and I_4

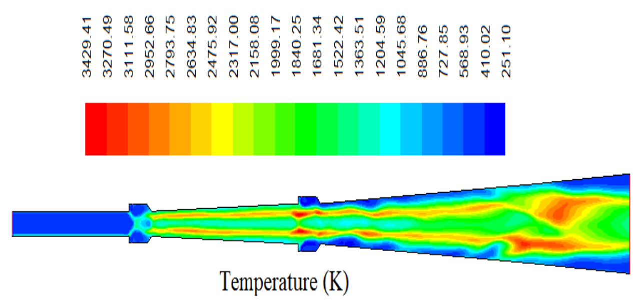

Figure 13. Contours of Temperature in combustor model with Hydrogen injected from I_1, I_2, I_3 and I_4

The static temperature in the cavity flame holders is slightly higher than that in the core flow. If we change the geometry of the combustor, to provide the divergence angle both sides, Temperature is increased in the leading edge of the second cavity flame holder while hydrogen is injected from I_2 or I_4 or both I_2 and I_4 . It can act as an igniter in the scramjet combustor. In this case, hydrogen is injected from I_1, I_2, I_3 and I_4 the static temperature in core flow is higher than that of near the wall. This helps to complete combustion of air fuel mixture.

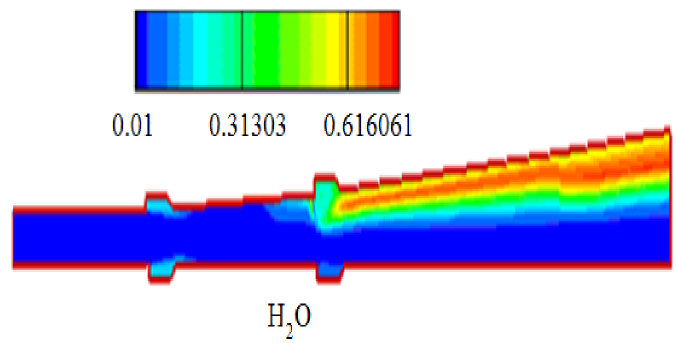

Figure 14. Contours of Mass fraction of H_2O in combustor with Hydrogen injected from I_2

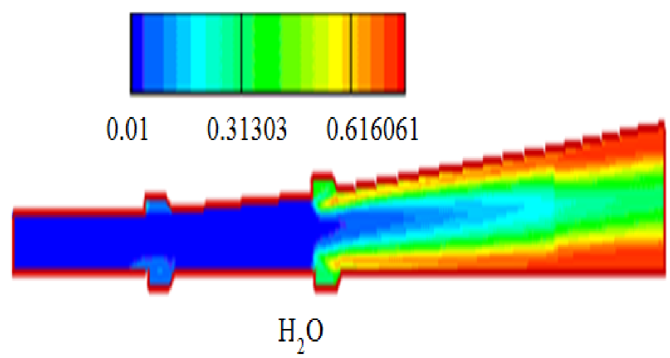

Figure 15. Contours of Mass fraction of H_2O in combustor with Hydrogen injected from I_2 and I_4

In the present study the combustion of the hydrogen takes place in the centre of the combustor. The combustion product H_2O distributes within the combustion chamber mainly depends on the hydrogen injection.

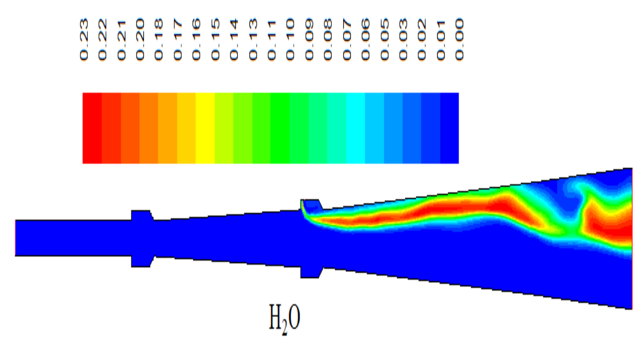

Figure 16. Contours of Mass fraction of H_2O in combustor with Hydrogen injected from I_2

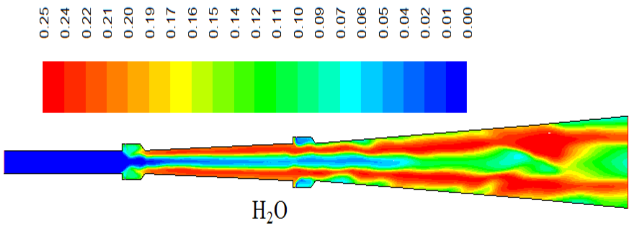

Figure 17. Contours of Mass fraction of H_2O in combustor with Hydrogen injected from I_1, I_2, I_3 and I_4

From the above figure, it illustrates that the injection pressure is high enough to make the fuel penetrate deeper. The recirculation zone is generated at this condition is much larger than that formed in the other cases and thus the flow can stay in the combustor much longer. . Because of the variation in the fuel injection location and the effect of the shock wave, small eddies are formed in both the upper and lower cavities of the first flame holders, and it lies on the rear edge of the cavity. The vortices can act as a recirculation zone for the mixture. At this condition, if the fuel is injected from the first staged combustor simultaneously, the performance of the combustor will be improved. While travelling over the cavity, the injected hydrogen interacts with the strong trailing edge shock wave, which plays an important role in the combustion. The trailing edge shock wave can improve the static pressure and the static temperature of the flow in the vicinity of the trailing edge of the cavity flame holder, and this can also benefit the combustion.

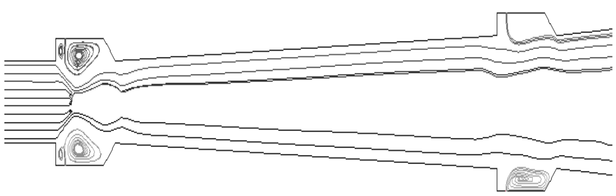

Figure 18. Stream line distributions in the combustor with Hydrogen injected from I_1, I_2, I_3 and I_4

7. CONCLUSION

(a) The numerical methods employed in this work can be used to accurately simulate the combustion flow field of the scramjet combustor, and predict the development status of the shock wave.

(b) The divergence angle makes a large difference to the combustion flow field of the scramjet combustor with multiple cavity flame holders.

(c) The cavity is a good choice to stabilize the flame in the hypersonic flow, and it generates a recirculation zone in the scramjet combustor. Further, if its geometry can be designed properly, it can act as an igniter for the fuel combustion, but the material of the cavity flame holder should be considered for operating at those high temperatures.

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