Numerical Simulation Study on Combustion Characteristics of Hypersonic Model SCRamjet Combustor

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Abstract

Air-fuel mixing and flame-holding are two important factors that have to be considered in the design of an injection system. Different injection strategies have been proposed with particular concern for rapid air-fuel mixing and flame-holding. Two representative injection techniques can be applied in a supersonic combustor. One of the simplest approaches is a transverse(normal) injection. The cavity flame holder, an integrated fuel injection/flame-holding approach, has been proposed as a new concept for flame holding and air-fuel mixing in a supersonic combustor.

This paper describes numerical efforts to characterize the flame-holding and air-fuel mixing process of a model scramjet engine combustor, where hydrogen is injected into a supersonic cross flow and a cavity. The combustion phenomena in a model scramjet engine, which has been experimentally studied at University of Queensland and Australian National University using a free-piston shock tunnel, were observed around the separation region of the transverse injector upstream and the inside cavity. The results show that this flow separation generates recirculation regions which increase air-fuel mixing. Self-ignition occurs in the separation-freestream and cavity-freestream interfaces.

Introduction

The success of high speed future vehicles which will be operated over Mach 6 is largely dependent on the development of hypersonic air-breathing propulsion systems. The scramjet engine is well known as a representative hypersonic propulsion system. Combustion process in the scramjet combustion chamber must be maintained at supersonic speeds to avoid excessive temperature and dissociation of the incoming air. In the combustion chamber, the residence time of a supersonic flow is of the order of 1ms at general scramjet operation conditions. Therefore, within 1ms effective fuel injection, air-fuel mixing and combustion process must be accomplished.

Substantial research about injector shape, injection method and mixing process have been carried out to overcome the problems originating from a short residence time within a combustor. One basic and simple injection technique is a transverse injection at a constant square area chamber. The UQ(University of Queensland, Australia) scramjet model which was used for the HyShot Program uses such an approach[1-4]. On the other hand, cavities can be used for air-fuel mixing and flame holding, such as adopted by the ANU(Australian National University, Australia) scramjet model.

From a scramjet reaction mechanism point of view ignition, flame holding and air-fuel mixing are three important factors that have to be considered in the design of an injection system. Once ignition is established, the efficiency of combustion depends directly on the efficiency of the molecular mixing. For self-ignition[6](and, therefore, combustion) to be accomplished in a flowing combustible mixture, it is necessary that four quantities have suitable values: static temperature, static pressure, air-fuel mixture, and residence time at these conditions. If there is self-ignition, the combustor length increases with ignition delay time and flow velocity, but the ratio of thrust and drag is in proportion to the ratio of combustor diameter and length. Therefore, a short combustor is needed. This can be obtained through a flame holder which decreases ignition delay time and supplies continuous radicals for chemical reactions within a short distance.

In general, flame holding is achieved by three techniques: 1) organization of a recirculation area where the fuel and air can be mixed partially at low velocities, 2) interaction of a shock wave with partially or fully mixed fuel and oxidizer, and 3) formation of coherent structures containing unmixed fuel and air, wherein a diffusion flame occurs as the gases are convected downstream[7].

This paper investigates and compares the ignition, flame holding and air-fuel mixing characteristics of two very different UQ transverse injection model and ANU cavity injection model.

Supersonic Combustor Models

Transverse Injection Model (UQ)

UQ's T4 free piston shock tunnel was used for the ground test under the conditions M=6.5, p=0.9-5.8kPa and T=285-291K. From the given conditions the total enthalpy is 3.0MJ/kg. The model scramjet consists of an intake, a combustor and a thrust plate. The intake consists of a 17° inclined wedge which compresses the incoming hypersonic flow. The flow is further compressed by the combustor cowl, after which hydrogen is injected. Combustion occurs in the combustor and hot gases from the combustion process

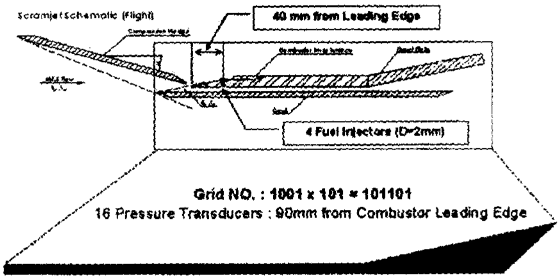


Fig. 1 UQ's Transverse Injection Model

are expanded through the thrust plate hence producing thrust. Fig. 1 describes the experimental model and computational grid of a combustor.

The combustor has a constant rectangular area and 16 pressure transducers which are mounted orderly 90mm downstream from the combustor inner surface leading edge. Each distance between pressure transducers is 13mm. The thrust plate has a 12° inclined plate and 11 pressure transducers which are mounted orderly 11mm downstream from the combustor exit. The distance between each pressure transducer is also of 13mm. Four injectors with a 2mm diameter are located 40mm downstream from the combustor inner surface leading edge with hydrogen injected transversally into the incoming supersonic flow. For the two-dimensional numerical analysis, the four fuel injectors were assumed to be one long slot of 75mm x 0.168mm with the same area. Free stream, combustor inlet and injector exit conditions are tabulated below. The size of each intake compression wedge, combustor and thrust plate is of 305mm x 100mm, 300mm x 75mm and 200mm x 75mm, respectively.

Table 1. Experimental Conditions of UQ

	Free Stream	Combustor Inlet	Fuel Injector
P [kPa]	2.216	83.48	307.14
T [K]	311	1256	250
Mach	6.750	2.74	1.0

(Phi = 0.426)

Combustor with Cavity (ANU)

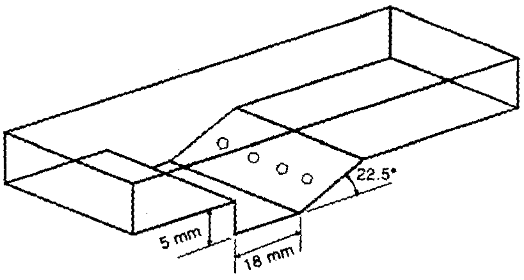


Fig. 2 ANU's Cavity Injection Model

ANU's T3 free piston shock tunnel was used to model the scramjet combustor with a cavity under the conditions Mach=3.8, p=110kPa and T=1100K. Such combustor flow conditions are representative of flight conditions at Mach 9. Hydrogen is injected transversally into the cavity at the slanted cavity back wall with a Mach number of 1. The equivalence ratio is controlled by the back pressure of the injector. Table 2 contains the detail experimental conditions.

Fig. 2 is the schematic of the ANU model scramjet with a cavity. Intake height and width are of 25mm and 50mm, respectively. The combustor has a cavity with 5mm-depth and 30mm-width at 152.5mm downstream from the combustor inlet. Four fuel injectors are located at the slanted cavity back wall. To measure wall pressure PCB 113M65 pressure transducers were mounted at the combustor bottom surface and windows were attached at the side wall for visualization.

Table 2. Experimental Conditions of ANU

	Combustor Inlet	Fuel Injector
P [kPa]	110	317
T [K]	1100	253
Mach	3.8	1.0

(Phi = 0.15)

Numerical Methods

Governing Equations

To analyze the chemically reacting supersonic viscous flow in a scramjet engine, the fully coupled form of the species conservation equations and Reynolds averaged Navier-Stokes equations is considered. The governing equations for a number of N species are summarized in conservative vector form as:

$$\frac{\partial \mathbf{Q}}{\partial t}+\frac{\partial \mathbf{F}}{\partial x}+\frac{\partial \mathbf{G}}{\partial y}=\frac{\partial \mathbf{F}_v}{\partial x}+\frac{\partial \mathbf{G}_v}{\partial y}+\mathbf{W}$$

where

$$\mathbf{Q}=\begin{bmatrix}\rho_1\\ \rho_2\\ \vdots\\ \rho_N\\ \rho u\\ \rho v\\ e\\ \rho k\\ \rho\omega\end{bmatrix}\quad \mathbf{F}=\begin{bmatrix}\rho_1 u\\ \rho_2 u\\ \vdots\\ \rho_N u\\ \rho u^2+p\\ \rho uv\\ (e+p)u\\ \rho uk\\ \rho u\omega\end{bmatrix}\quad \mathbf{G}=\begin{bmatrix}\rho_1 v\\ \rho_2 v\\ \vdots\\ \rho_N v\\ \rho uv\\ \rho v^2+p\\ (e+p)v\\ \rho vk\\ \rho v\omega\end{bmatrix}$$

$$\mathbf{F}_v=\begin{bmatrix}-\rho_1 u_1^d\\ -\rho_2 u_2^d\\ \vdots\\ -\rho_N u_N^d\\ \tau_{xx}\\ \tau_{xy}\\ \beta_x\\ \mu_k\partial k/\partial x\\ \mu_\omega\partial\omega/\partial x\end{bmatrix}\quad \mathbf{G}_v=\begin{bmatrix}-\rho_1 v_1^d\\ -\rho_2 v_2^d\\ \vdots\\ -\rho_N v_N^d\\ \tau_{xy}\\ \tau_{yy}\\ \beta_y\\ \mu_k\partial k/\partial y\\ \mu_\omega\partial\omega/\partial y\end{bmatrix}\quad \mathbf{W}=\begin{bmatrix}\omega_1\\ \omega_2\\ \vdots\\ \omega_N\\ 0\\ 0\\ 0\\ s_1\\ s_2\end{bmatrix}$$

As the Reynolds number in a scramjet is very high, a fully turbulent flow can be assumed. In the present study, turbulence eddy viscosity is calculated by the Menter's SST(Shear Stress Transport) model. The SST model combines several desirable elements of existing two-equation models. The two major features of this model are a zonal weighting of model coefficients and a limitation on the growth of the eddy viscosity in rapidly strained flows. The zonal modeling uses Wilcox's k-ω model near solid walls and the standard k-ε model(in a k-ω formulation) near boundary layer edges and in free-shear layers. This switching is achieved with a blending function of the model coefficients.

Numerical Methods

The finite volume cell-vertex scheme is used for the spatial discretization of the governing equations. The viscous terms are expressed by a central difference method and the convective terms are expressed as a difference of the numerical fluxes at the cell interface. The numerical fluxes containing artificial dissipation are formulated using Roe's flux difference splitting(FDS) method. The complete formulation of Roe's FDS method for multispecies chemically reacting flow is based on the method of Grossman and Cinnella extended to two-dimensional curvilinear coordinates.

The MUSCL scheme is used for the extrapolation of primitive variables at the cell interface. In addition, the minmod limiter function is used to overcome the severe dispersion error introduced by the higher-order extrapolation and to preserve the total variation diminishing property. By applying the LU-SSOR method, governing equations can be integrated fully implicitly by the diagonal lower and upper steps with an approximate Jacobian splitting method.

Results

Flame Holding in Transverse Injection

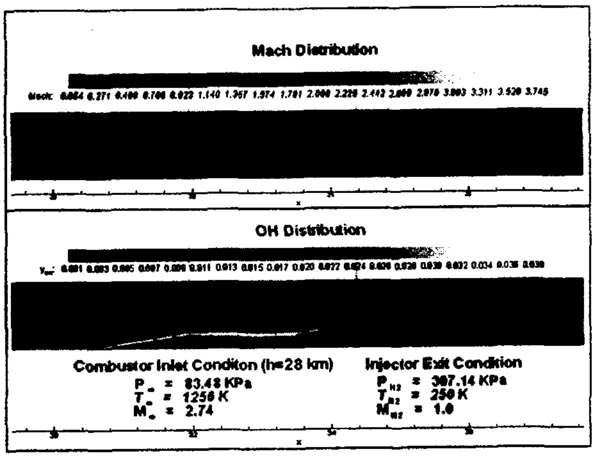


Fig. 3 Ignition and Combustion Regions of Jet-in-Cross-Flow

Computational studies about the chemically reacting flow of UQ's transverse injection model were carried out. The intake flow which is based on experimental conditions of Table 1 was calculated and the results were used as combustor inlet conditions. For detail results about the intake flow, the reader is referred to the previous paper[9].

In Fig. 3, the Mach number and OH radical distribution are shown around the fuel injector. It can be observed from the Mach number distribution that the velocities ahead of and behind the fuel injector are subsonic. OH radical distribution around flame sheets shows the ignition process and location. The hydrogen fuel which is injected into a supersonic cross-flow produces a strong bow shock in front of the injector and this shock causes flow separation. In the separation region, the boundary layer and jet fluids mix subsonically upstream of the jet exit and then self-ignition occurs in this region because of the high temperature and abundant radicals. In the OH radical distribution shown in Fig. 3, the flame sheet exists at the interfaces of supersonic out flow and separation region. The flame is continuous according to air-fuel mixture and forms wave-shape flame sheet. The recirculation region downstream of the injector promotes air-fuel mixing without flame. The detail procedure of these phenomena will be explained in the next section. Consequently, in the transverse injection into a supersonic cross-flow, the upstream separation region of an injector has self-ignition and flame holding effects.

Mixing and Combustion in Transverse Injection

In the transverse injection model, hydrogen fuel distributions of reacting and non-reacting flow were compared to analyze air-fuel mixing and wave-shape flame sheet. The differences between reacting and non-reacting flow arise from the complicated shock structures and the coupling between the recirculation region with the separation bubble in the combustor.

Fig. 4 and Fig. 5 show hydrogen fuel distributions of reacting and non-reacting flow as time progresses. The hydrogen distribution of non-reacting flow in Fig. 4 looks relatively stable without time dependence. Therefore, air-fuel mixing is not so active and most of the fuel is located at the combustor bottom. On the contrary, the hydrogen of reacting flow in Fig. 5 is changed into a repetitive wave-shape distribution from stable situation with the passage of time. This repetitive wave-shape distribution increases the contact surface of air-fuel and improves the mixing process. As a result of the wave-shape distribution, the flame sheet occurs according to the improved air-fuel mixing in the mixing layer.

Fig. 6 and Fig. 7 show the shock structures of Fig. 4 and Fig. 5 at the same time level. The shock structures of the first two stages are relatively similar but those of the other two stages are obviously different. At the first stage of Fig. 6 and Fig. 7, the strong shock caused by upstream separation of the injector exit impinges against combustor upper wall and forms a separation bubble.

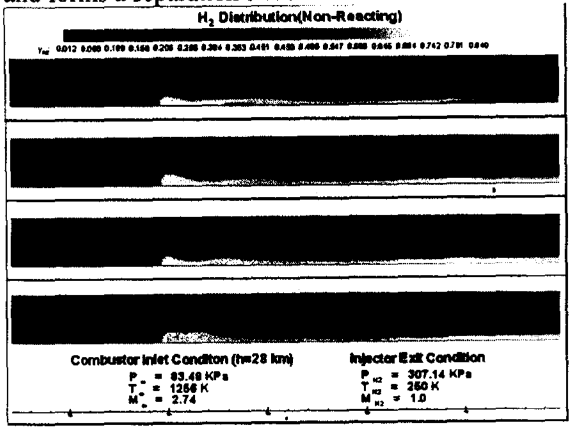


Fig. 4 H_2 Distribution around Injector in Non-Reacting Flow

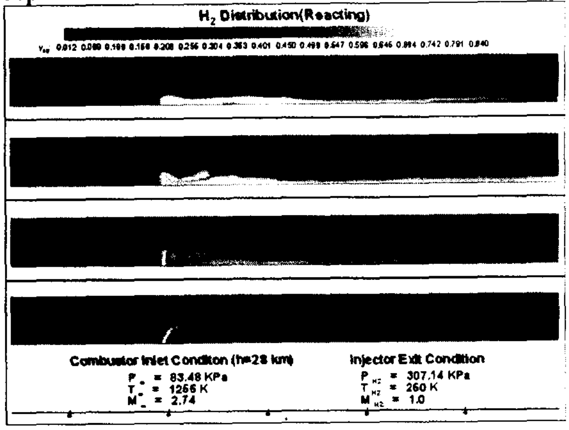


Fig. 5 H_2 Distribution around Injector in Reacting Flow

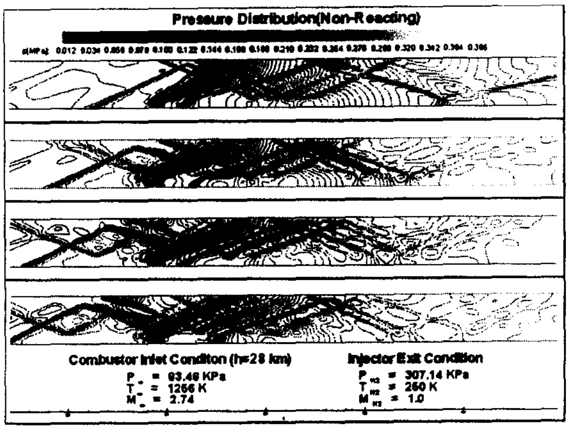


Fig. 6 Shock Structures around Injector in Non-Reacting Flow

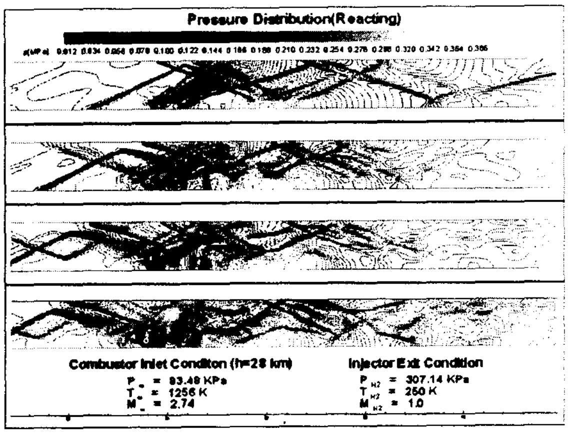


Fig. 7 Shock Structures around Injector in Reacting Flow

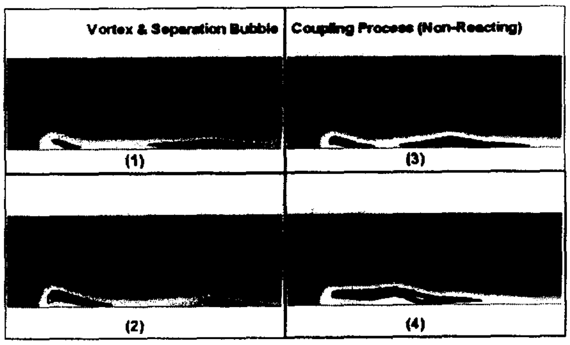


Fig. 8 Recirculation and Separation Bubble Coupling in Non-Reacting Flow

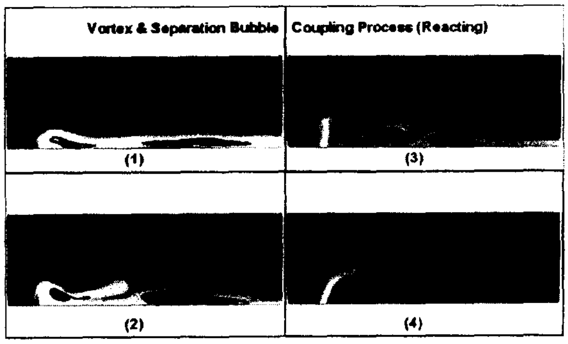
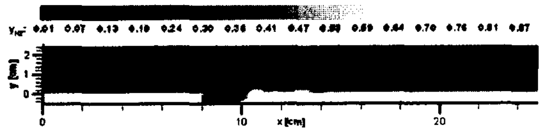
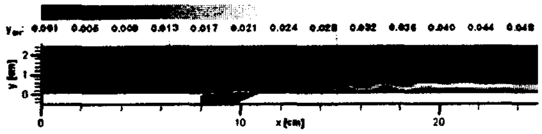


Fig. 9 Recirculation and Separation Bubble Coupling in Reacting Flow

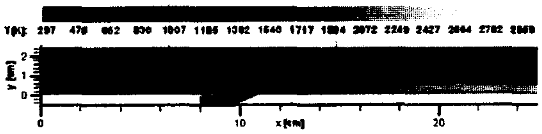
The separation bubble on the combustor upper wall causes a shock which impinges against the combustor bottom wall and forms another separation bubble. At the second stage of Fig. 6 and Fig. 7, as the bubble of combustor upper wall grows, a strong reattachment shock occurs at the grown bubble behind. This reattachment shock impinges against the combustor bottom wall and increases the separation bubble size on combustor bottom wall. This rather strong separation bubble on the combustor bottom wall is coupled with the recirculation region of injector downstream. The coupled bubble and recirculation cause a wave-shape flame sheet. In the case of reacting flow, combustion phenomena behind the fuel injector cause higher back pressure compared with non-reacting flow. This back pressure induces strong shock structures and the growth of the separation bubble. Although each stage of Fig. 6 and Fig. 7 has the same time level, the shock structures of the reacting flow field are moving forward further than those of the non-reacting flow field. In the other two stages of Fig. 6 and Fig. 7, the shock structures are much different due to the back pressure raised by changes in the shock structure induced by combustion in the reaction flow field.



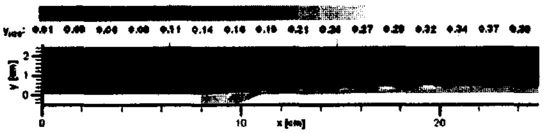
H2 Distribution



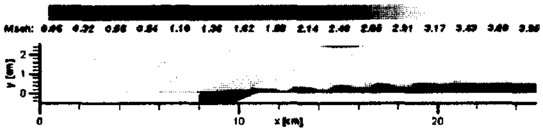
OH Distribution



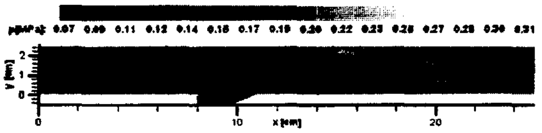
Temperature Distribution



H2O Distribution



Mach Distribution



Pressure Distribution

Fig. 10 Reacting Flow Property Distributions in Supersonic Combustor with cavity

Using streamlines, Fig. 8 and Fig. 9 show the coupling procedure of the recirculation region and the separation bubble behind the injector. Both the recirculation region caused by fuel injection and the separation bubble caused by shock impingement approach each other and eventually unify. The pressure between the recirculation and the separation bubble is rather low because of the expansion fan originating from the recirculation region. The pressure of the separation bubble downstream is rather high because of combustion and shocks. Therefore, the pressure difference makes the separation bubble move forward and combines the latter with the recirculation region. As a result of strong combustion and shock structures, there are stronger recirculation and separation bubble in the reacting flow field and the coupled recirculation region is much stronger than the one of the non-reacting flow field. This strong recirculation region described above adds perturbation to hydrogen fuel behind injector and gives a wave-shape form to the hydrogen fuel distribution. This repetitive wave-shape increases the contact surface of air-fuel and improves mixing and combustion.

As stated above, fuel injection and shock structures produce recirculation and the separation bubble and the coupled recirculation region activate mixing through an increase of the air-fuel contact surface. Therefore, stable combustion phenomena can be maintained in the combustor.

Flame Holding and Mixing in Cavity

A stable cavity can be used for flame-holding applications. Many efforts have been carried out to reduce combustor length for effective supersonic combustion. The cavity setup is one of these efforts. The main idea is to create a recirculation inside the cavity with a hot pool of radicals, to reduce the induction time, such that autoignition of the air-fuel mixture can be obtained. However, for a stable combustion process, the cavity recirculation region has to be stable to provide a continuous ignition source.

One of the goals of the ANU cavity model with fuel injected at a rear inclined cavity wall was to analyze air-fuel mixing and combustion phenomena. Fig. 10 shows the reacting flow field of the ANU combustor including the cavity. As can be seen from the hydrogen contours, the distribution of hydrogen in a cavity is relatively even. The presence of a recirculation region due to the rapid free stream and slow cavity flow, and the strong recirculation caused by fuel injection on the rear cavity inclined wall improves air-fuel mixing in the cavity. Therefore, autoignition and combustion can be obtained through the interaction between shear layer and enough radicals in the cavity. The OH radical distribution around the contact surface of the outside of the cavity and the free stream supports the above statement. It can be seen that combustion occurs evenly in the cavity from the temperature and H_2O contours and that the cavity acts as a flame holder. Mach number and OH radical contours show that there is supersonic combustion according to the air-fuel mixing layer. In the cavity with fuel injection at a slanted back wall, the perturbation effect which is caused by the interaction between the oblique shock and shear mixing layer is small and this leads to a decrease of oscillation within the cavity and physical characteristics of the cavity flow.

Conclusion

Various techniques for flame-holding and air-fuel mixing can be applied to supersonic combustion. One of the simplest techniques is transverse injection and another representative technique is the use of a combustor cavity. This study chose UQ's scramjet model for HyShot Program as transverse injection case and ANU's scramjet model as the combustor with cavity. Reacting and non-reacting calculations for each case have been carried out to analyze flame holding, mixing and combustion phenomena.

In the case of transverse injection air-fuel mixing and ignition occur at the separation region located upstream of the fuel injector. This region has a flame-holding capability. The combination of recirculation and separation bubble, which originate from fuel injection and shock impingement downstream of injector, activate air-fuel mixing and maintain wave-shape flame sheet.

In the case of cavity combustor with a slanted back wall there is a recirculation region which captures high temperature and abundant radicals in the cavity and autoignition occurs in the shear layer. Also, the cavity plays the role of flame-holder. However, in the cavity flow field further investigation is required to design an optimal cavity for supersonic flame holding due to the various complicated effects influencing fluidic characteristics, such as the shape of the cavity and the aspect ratio, for instance.

Acknowledgements

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