Characteristics of Flame-holding in a Scramjet Combustor with a Cavity

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Abstract

Numerical simulations were conducted in a rectangular scramjet combustor with a cavity and/or a step in order to investigate their performances for flame-holding. Flow structures and OH radical profiles in the cavity and the step were calculated. The calculated results showed that the cavity generated a larger recirculation zone than the step that had the same depth. Additionally, the combustor with a cavity could make a large low-velocity area than the combustor with a step. The cavity performance was determined by its depth and length. The cavities with too large or too short length did not work effectively, and a certain aspect ratio showed high performance for flame-holding. There was a minimal depth under which the cavity did not work as flame-holder. The fuel injections upstream the cavity and inside the cavity were also tested to investigate the effects on the cavity performance. The result showed that the fuel injection inside the cavity reduced reaction areas and residence time. Therefore, the upstream injection was preferable to the inside injection.

Introduction

A scramjet engine is expected to be operated under a wide flight Mach number range, for example, 6-10[1]. Therefore, the entrance condition of the scramjet combustor varies in a wide range in temperature, pressure and Mach number according to the flight condition. Therefore, stable ignition and flame-holding in a supersonic flow is a great issue for the scramjet engine. Many researches[2-5] have been reported on improving of the flame holding with a strut and a step, and there appear many reports about the improvement of flame-holding performance using a cavity in recent years.

In our previous research[6], we investigated the ignition limit with kerosene fuel in a scramjet combustor with a cavity or a step. The result is shown in Fig. 1. The experiment was conducted by fixing the depth of cavity to 4.4mm, varying L/D as 3, 5, 7, and 9, where L and D denoted the cavity length and the depth. Despite our expectation, the result showed that there was no apparent difference of the performance for ignition limit between the step and the cavity. This result was different from the past reports. One of the reasons for the poor performance of the cavity was anticipated that the depth of the cavity was insufficient. Therefore, in this paper, we calculated the flow field behavior in the combustion with a cavity, with varying the depth and the length of the cavity.

Numerical Analysis

The governing equations of Numerical calculation were three-dimensional full Navier-Stokes equation. Nine species (H_2, O_2, OH, H_2O, H, O, HO_2, H_2O_2 and N_2) were considered. As a chemical reaction model, hydrogen-air reaction mechanism with 20 forward-backward elementary reactions was adopted. The SGS stress tensor is approximated with Smagorinsky model. The equations are given as follows;[7,8].

$$\partial_t(\overline{\rho}) + \mathrm{div}(\rho\tilde{\mathbf{u}}) = 0$$

$$\partial_t(\overline{\rho}\tilde{\mathbf{u}}) + \mathrm{div}(\rho\tilde{\mathbf{u}}\tilde{\mathbf{u}}) = -\mathrm{grad}\,\tilde{p} + \mathrm{div}(\tilde{\boldsymbol{\tau}} + \mathbf{B})$$

$$\partial_t(\overline{\rho}\tilde{e}) + \mathrm{div}((\rho\tilde{e} + \tilde{p})\tilde{\mathbf{u}}) = \mathrm{div}(\kappa\,\mathrm{grad}\,\tilde{T} + b) + \mathrm{div}((\tilde{\boldsymbol{\tau}} + \mathbf{B})\cdot\tilde{\mathbf{u}}) + \sum_{1}^{9}\mathrm{div}(\overline{\rho}h_i D_i\,\mathrm{grad}\,\tilde{Y}_i + \overline{\rho}h_i d)$$

$$\partial_t(\overline{\rho}\tilde{Y}_i) + \mathrm{div}(\rho\tilde{Y}_i\tilde{\mathbf{u}}) = \mathrm{div}(\overline{\rho}D_i\,\mathrm{grad}\,\tilde{Y}_i + d) + \dot{\omega}$$

where,

$$\tilde{\boldsymbol{\tau}} = 2\mu\tilde{\mathbf{S}}_{\mathbf{ij}} - 2/3(\mathrm{div}\,\tilde{\mathbf{u}})\mathbf{I},\ \tilde{\mathbf{S}}_{\mathbf{ij}} = 1/2(\mathrm{grad}\,\tilde{\mathbf{u}} + (\mathrm{grad}\,\tilde{\mathbf{u}})^t)$$

$$\mathbf{B} = 2\mu_k\tilde{\mathbf{S}}_{\mathbf{ij}} - 2/3\overline{\rho}\,k_k\mathbf{I}$$

$$\mu_k = \overline{\rho}(C_s\Delta)^2\sqrt{2\tilde{\mathbf{S}}_{\mathbf{ij}}\tilde{\mathbf{S}}_{\mathbf{ij}}},\ k_k = C_I\Delta^2 2\tilde{\mathbf{S}}_{\mathbf{ij}}\tilde{\mathbf{S}}_{\mathbf{ij}}$$

$$C_s = 0.173,\ C_I = 0.09$$

$$\Delta = \Delta_h(1 - \exp(-y^+/26)),\ \Delta_h = \min(\Delta_1, \Delta_2, \Delta_3)$$

$$b = \kappa_k\,\mathrm{grad}\,\tilde{T},\ d = D_{ki}\,\mathrm{grad}\,\tilde{Y}_i$$

$$\kappa_k = \frac{\tilde{C}p\mu_k}{Pr_t},\ D_{ki} = \frac{\mu_k}{\overline{\rho}\,Sc_t},\ Pr_t = 0.6,\ Sc_t = 0.6$$

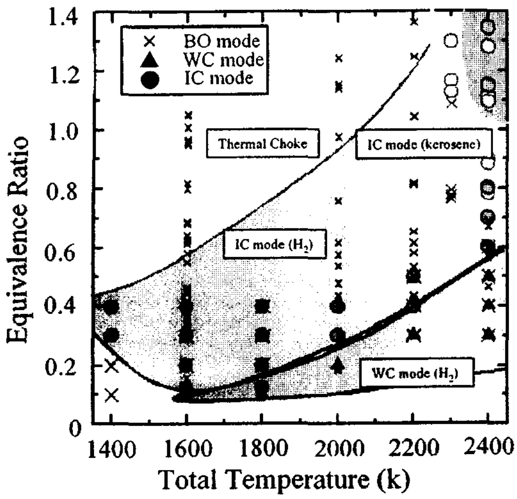

Fig.1 Ignition limit of liquid kerosene by experiment; blue: hydrogen, red: methane, green: kerosene with step, yellow: kerosene with cavity.

Figure 2 shows the calculation domain. The combustor length was 400 mm, the width was 30 mm, and the height was 36 mm. Three kinds of cavity depth (D) of 3.6, 6, and 12mm were adopted. The cavity length (L) was varied as 60 and 84mm. The number of grids was 301 x 61 x 61 (in x, y and z-direction, respectively). The thickness of the boundary layer at the entrance of the combustor was 3.0mm, which was determined by the experimental results. The top, bottom, and side walls were considered as non-slip isothermal walls. The wall temperature was set at constant 600K. The components, static pressure and the static temperature of the inflow (vitiated air) were calculated assuming that the reaction in the nozzle was frozen. At first, the steady supersonic flow field over the cavity or the step was calculated as a frozen flow. After that, the fuel injection and chemical reaction starts. The fuel was gaseous hydrogen. The injector was circular in 4.0mm diameter, and the fuel was injected perpendicularly at sonic speed. The effect of the location of the fuel injector was also investigated. The location of the fuel injector was at 42mm downstream of entrance when the fuel was injected from the upstream of the cavity. It was at 30mm downstream of the front edge of the cavity when the fuel was injected from the inside of cavity.

Results and Discussion

First, the effect of the cavity length on flow field was investigated by changing the length (L) of cavity to 60 and 84mm. The cavity depth (D) was fixed at 12mm. All calculations were performed with the same inflow conditions. The Mach number, total temperature, total pressure and the equivalence ratio were 2, 1800K, 0.38MPa, and 0.3, respectively. Figure3 shows the OH radical distribution near the cavity or the step on the center plane (y=15mm). The result shows that the large reacting region is observed in the combustor with a cavity whereas the reacting zone is small in that with a step. Large recirculation was generated in the cavity and it worked as a flame-holder. The size of the recirculation in case c was slightly larger than that in case b. However, the difference is small for the difference in the cavity length. Moreover, it is found that the reaction near the rear ramp of the cavities is intensive that is due to the recovery of the main flow. Therefore, the advantage of the cavity is not only generation large recirculation zone but also the generating recovery zone by the rear ramp.

Figure 4 shows the main flow streamlines that start from the combustor entrance in each case in Fig. 3. The combustors with cavity (cases b and c) have a large recirculation zone compared with a combustor with a step. In case c, the separated main flow reattached at the rear ramp whereas it flow over the cavity in case b. Namely the cavity can generate a larger recirculation zone than a step, but too large length does not make sense because it reduced to a step.

Figure5 shows the streamlines inside the cavity that start from 15mm downstream of the front edge, and height of 0.6mm. The color of the line indicates the residence time of fluid. When the color turns red, it means that the residence time reaches 1msec. In the combustor with the step (Fig. 5a), it is shown that small recirculation zones are just behind the step and another recirculation zone is observed near the reattachment point. The two recirculation zones

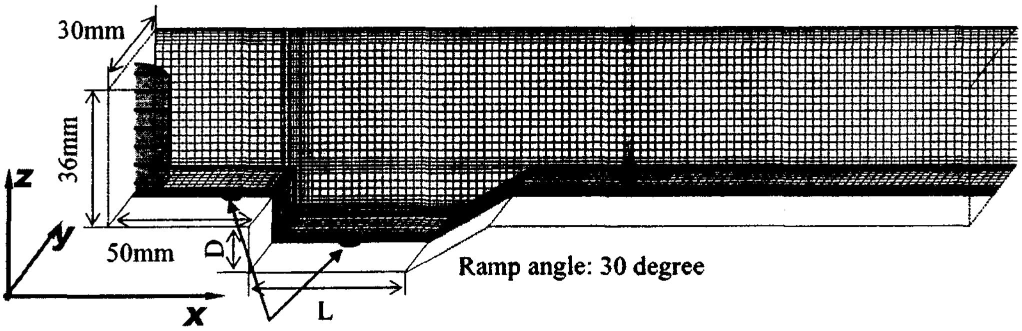

Fig.2 Schematic of the grid for numerical simulation

transfer the fuel in the spanwise direction and it is expected the enhanced mixing. In the case of b, it can be seen that the recirculation zone is crossing all over the inside of cavity. There has also two small recirculation zones in the spanwise direction like case a. Although a large recirculation zone is seen inside the cavity as the other conditions, the residence time in the cavity is shorter in case c. Moreover, as shown in c-2, the flow structure in the cavity is seems to be simple as contrasted with cases a and b. From the above results, in the case of L=60mm, the residence time in the cavity was largest in these tree condition because the recirculation zone developed greatly, and the sufficient time for fuel to react would be obtained. On the other hand, although the size of the reaction domain in case of L=84mm are similar to that in case of L=60mm, the residence time of the flow within the cavity is shorter, and it is thought that the flame-

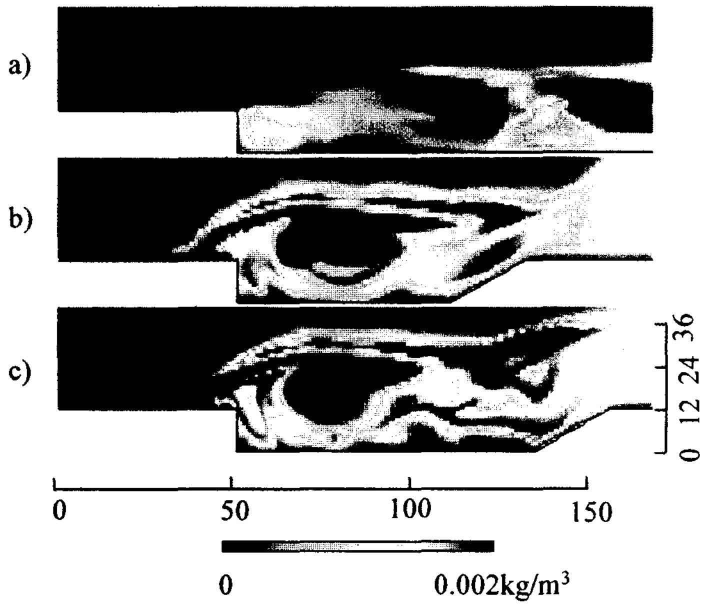

Fig.3 OH radical profiles in combustor at y=15mm with the a) step (D=12mm), b) cavity (D=12mm, L=60mm) and, c) cavity (D=12mm, L=84mm).

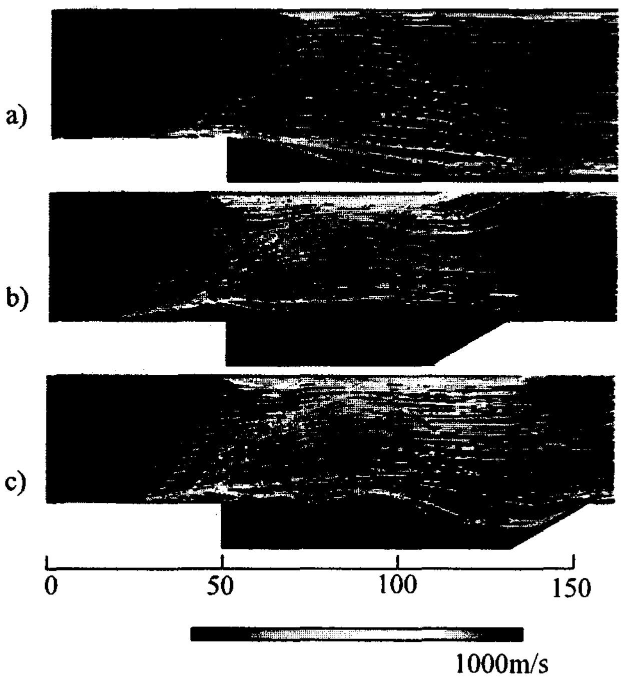

Fig.4 Flow lines of main flow in combustor with the a) step (D=12mm), b) cavity (D=12mm, L=60mm) and, c) cavity (D=12mm, L=84mm). The starting points are located on the entrance surface of the combustor.

holding effect caused by the low-speed domain would be weak in case c. In particular, when the liquid fuel like kerosene is used for the fuel, whose reaction rate is smaller than that of hydrogen, it becomes important how long the residence time takes.

Then, we investigated the effect of the cavity depth on the flame-holding. The cavity length (L) was fixed at 60mm, and the calculation was done with changing the cavity depth (D) as 3.6mm, 6mm and 12mm. Figures 6, 7 and 8 show the OH distribution, main flow streamlines and streamlines in the cavity, respectively. In Fig.6, it is seen that the reaction area becomes larger and the more intensive chemical reaction occurred as the cavity depth increases. Figure 7 shows that size of the recirculation zone is large in case a. However, the size in case b is small, and the recirculation zone disappears in case c.

Figure 8 shows that the recirculation zone is limited in the vicinity of the front edge in cases b and c, and the size is very small compared with that in case a. Additionally, the velocity in the cavity is larger due to strong shear force from the main airflow, which cases short residence time in the cavity. In case a, complex recirculation bubbles structure is observed. However, in case b, the structure becomes weak, and it collapses in case c. From this result, if the depth of cavity is smaller than a certain depth, reaction zone will not obtain sufficient residence time in the recirculation zone for flame-holding. Probably, the depth of about 10mm would be required for stable flame-holding.

Figures 9 and 10 show the OH distribution and the streamlines in the cavity when fuel injected from the inside of cavity, respectively. In case a, it is observed that the reaction region is widely distributed and the complex structure is developed as discussed earlier. On the other hand, in case b, the recirculation zone is divided by the fuel injection, into the front part and the rear part in the cavity. Moreover, in Fig. 10b-2, the complex structure behind the front edge disappears, and it is found that the flow velocity is larger than that in case a. According to the residence time of streamlines, in case a, the residence time in the cavity is more than 1.0msec. However, in case b,

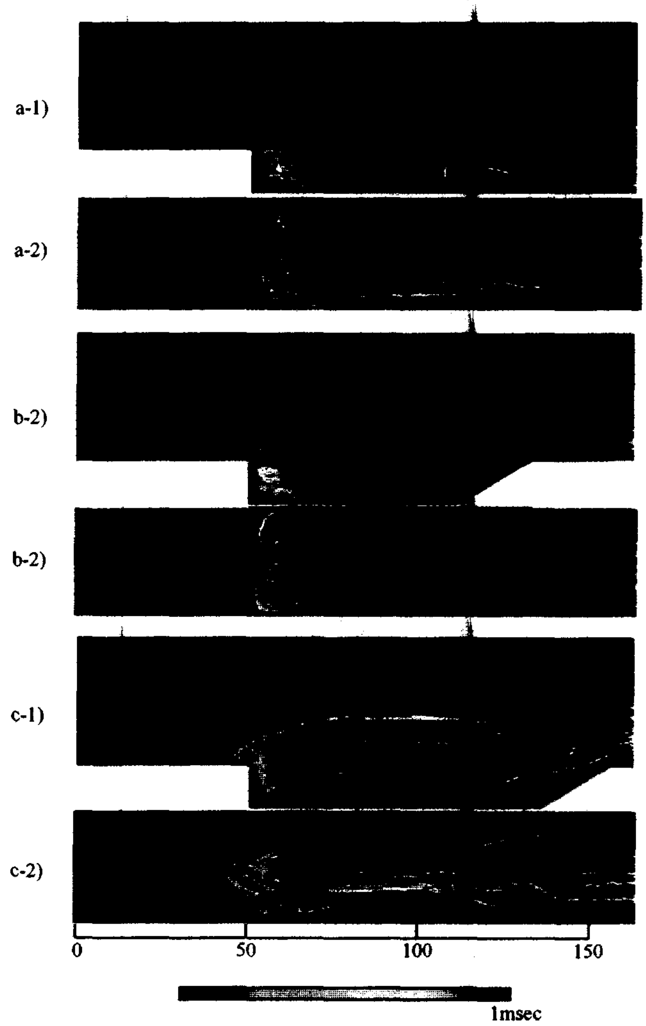

Fig.5 Streamlines in the step and cavity; a) step (D=12mm), b) cavity (D=12mm, L=60mm) and, c) cavity (D=12mm, L=84mm). The starting points are located on the line of x=60mm, and z=0.6mm.

the residence time is very short compared with that in case a. This result is due to large momentum of the fuel injection. Additional, the inside injection provides excess fuel in the cavity and it is not prefer for flame-holding. Therefore, it is thought that the fuel injecting from upstream of the cavity is effective in order to obtain long residence time within cavity.

Conclusion

Numerical simulation was conducted in a rectangular scramjet combustors with a cavity, where the fuel was injected from the upstream or inside of cavity. The results were as follows;

1. The cavity enlarged the recirculation zone and enhanced the reaction. The intensive reaction was observed just behind the front edge and on the rear

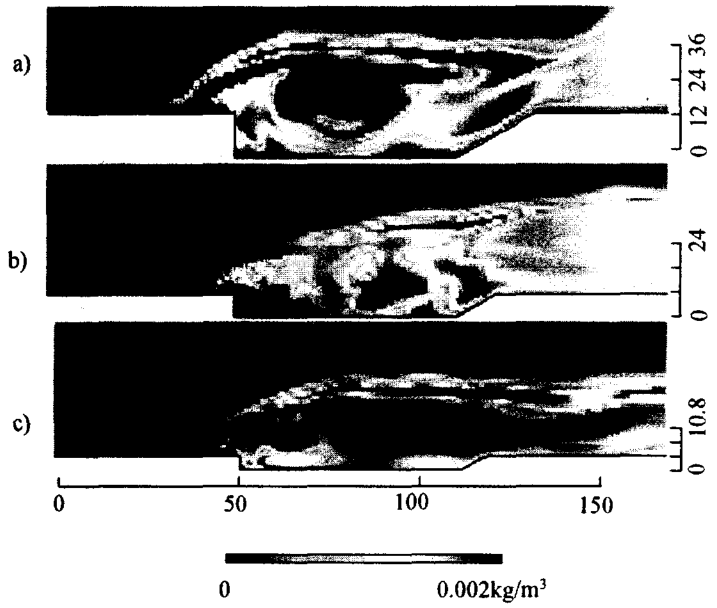

Fig.6 OH radical profiles in combustor at y=15 with the a) cavity (D=12mm, L=60mm), b) cavity (D=6mm, L=60mm), and c) cavity (D=3.6mm, L=60mm).

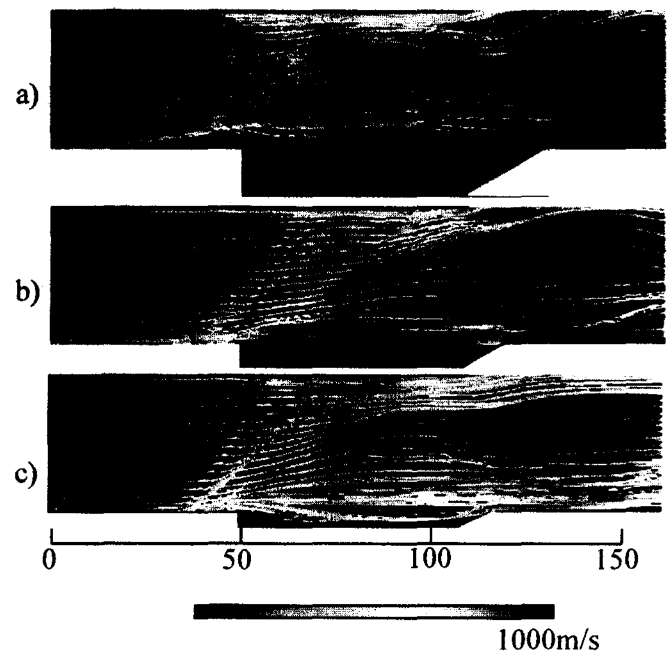

Fig.7 Flow lines of main flow in combustor with the a) cavity (D=12mm, L=60mm), b) cavity (D=6mm, L=60mm), and c) cavity (D=3.6mm, L=60mm). The starting points are located on the entrance surface of the combustor.

ramp. Additionally, it increased the residence time compared with the simple step.

2. The performance of the cavity for flame-holding was characterized by the depth and the length. If the depth was not enough deep or the length is too long, the main flow entered inside the cavity. It means that recirculation zone decreases and residence time in cavity becomes short. In such cases, the recirculation zone didn't developed to the spanwise direction, and the complex structure was not observed. This result implies that the cavity performance shows the maximum at some aspect ratio (D/L). Additionally, there was a minimal depth under which the cavity did not work effectively.
3. The case where the fuel was injected inside the cavity, the recirculation in cavity was divided by the fuel injection, and both the reaction zone and the residence time became small compared with those in the case of upstream injection. This is due to the large momentum of fuel injection and the excess fuel in the cavity. Therefore, the upstream injection is preferred for the stable flame-holding in the cavity.

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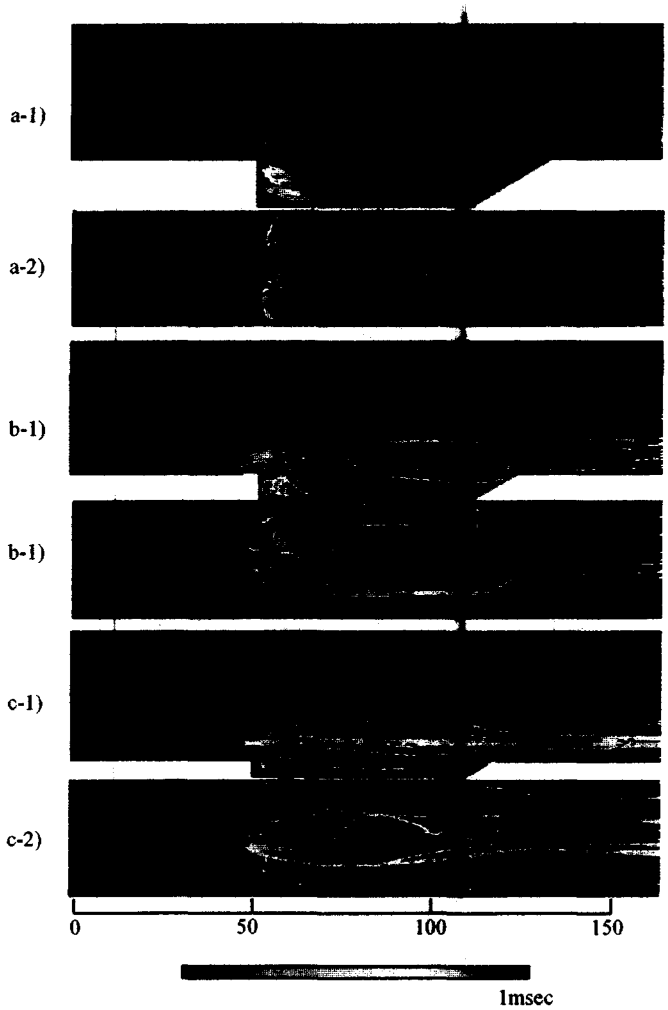

Fig.8 Streamlines in the step and cavity; a) cavity (D=12mm, L=60mm), b) cavity (D=6mm, L=60mm), and c) cavity (D=3.6mm, L=60mm). The starting points are located on the line of x=60mm, and z=0.6mm.

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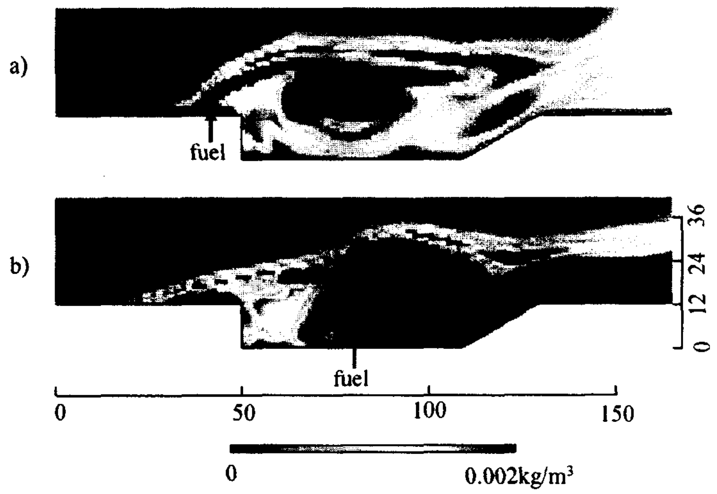

Fig.9 OH radical profiles in combustor at y=15 with the cavity. a)injection from upstream cavity, b)injection from inside cavity.

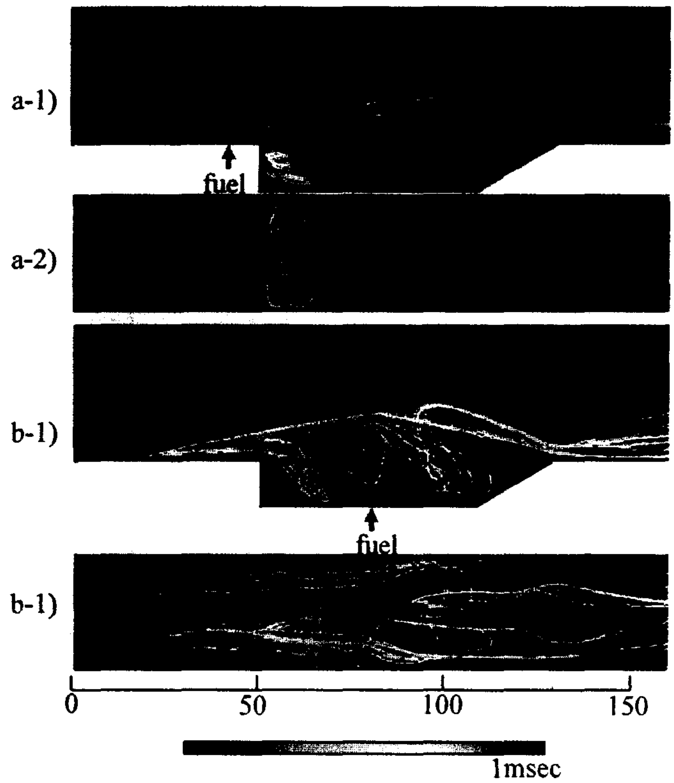

Fig.10 Streamlines in the cavity. a) injection from upstream cavity, b) injection from inside cavity. The starting points are located on the line of x=60mm, and z=0.6mm.