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DNS OF TURBULENT SWIRLING PREMIXED FLAME AND PRESSURE OSCILLATIONS IN A MICRO COMBUSTOR

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Summary Direct numerical simulation (DNS) of hydrogen-air swirling premixed flame is conducted to investigate hydrodynamic behaviors and characteristics of flame structures in a micro combustor under two swirl number conditions. Large-scale helical vortical structures are generated near the inlet of combustion chamber, and a lot of fine-scale vortices emerge downstream. Fine-scale eddies play an important role in flame wrinkling, whereas flame front tends to be entrained by large-scale coherent structures.

INTRODUCTION

In industrial gas turbine combustors, recirculation zone caused by swirling flow plays an important role in flame holding. To avoid flashback and oscillating combustion, which frequently occur for the premixed flames in a combustion chamber, characteristics of swirling flow and flame structures need to be clarified. In a lot of studies, turbulent swirling premixed and non-premixed flames and control of turbulent combustion have been investigated by experiments (e.g. [1, 2, 3, 4]) or by numerical simulations with large eddy simulation (e.g. [4, 5]). Studies related to precessing vortex core have been reviewed by Syred [6], and works on the lean-premixed swirl-stabilized combustion have been done by Huang and Yang [7]. Owing to the recent developments of computer technology, three-dimensional direct numerical simulation (DNS) of turbulent flames has been performed and turbulence-flame interactions have come to be discussed in more detail [8, 9]. Recently, DNS has been steadily applied to practical configurations, such as swirling flows [10, 11, 12]. In our previous study [11], hydrogen–air turbulent swirling premixed flame in a small cuboid combustor has been conducted by considering a detailed kinetic mechanism. In the present study, to clarify mechanism of combustion oscillation, DNS of swirling premixed flames in the small cuboid combustor with different swirl numbers is performed in long computational time.

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Details of the numerical method are found in the previous study [11]. The size of the cuboid combustor is assumed to be 15 mm in the flow direction (L) with 10 mm $\times$ 10 mm cross section. The shape of the inlet is a concentric annulus with 0.6 mm inner diameter and 2.5 mm outer diameter. Temperature of the wall is assumed to be 700 K. Equivalence ratio, pressure and temperature of unburnt mixture are 1.0, 0.1 MPa and 700 K, respectively. Velocity profile at the inlet is given analytically under assumptions of steady, axial symmetry and no-slip boundary conditions on the wall. The swirl number (S) is set to 0.6 or 1.2. Mean axial velocity at the inlet is 200 m/s and maximum perturbation intensity of the inlet velocity is 15% of the mean axial velocity. Number of grid points is $769 \times 513 \times 513$.

Figure 1 shows instantaneous contour surfaces of the second invariant of velocity gradient tensor which is normalized by the maximum value of velocity gradient ($Q^* = 0.2$) and distributions of heat release rate illustrated by volume rendering method for $S = 0.6$ and 1.2. As for $S = 0.6$, the large-scale helical vortical structures are formed in upstream region (region A in Fig. 1(a)). Fine-scale eddies develop in the downstream region and distribution of heat release rate is complex in the corresponding region. For $S = 1.2$, the large-scale helical and fine-scale vortical structures emerge in relatively upstream region, since strong shear layer is generated and turbulence develop rapidly compared to the low swirl number case. As a result, the combustion process is almost completed in the upstream region.

To investigate these characteristics in further detail, characteristics of flow field on a typical cross section are investigated for $S = 1.2$. Figure 2 (a) shows instantaneous two dimensional distributions of stream lines. Red means that the magnitude of velocity is 500 m/s. Large-scale recirculating flow are generated in the inner region (region A and B) and outer region (region C and D). Moreover, small scale recirculation can be observed in the inner region, for instance region E. Figure 2 (b) shows distribution of heat release rate, which is illustrated by gray scale and black represents high heat release rate. The lines shows isolines of second invariant of velocity gradient tensor. In the region with high second invariant, heat release rate tend to shows high value. In the previous study [11], the results for low swirl number case have been discussed in large part. In the low swirl number case, fine-scale eddies play an important role in flame wrinkling, whereas flame front of turbulent swirling premixed flame tends to be entrained by large-scale coherent structures. In the high swirl number case, fine-scale eddies are prone to develop in upstream region. Flame front is distorted by fine-scale eddies significantly in the upstream region.

To discuss combustion oscillation, pressure fluctuation on a wall are investigated. Figure 2 (c) shows time series of pressure fluctuations on a side wall of the combustor at two positions in the axial direction: $x/L = 0.25$ and 0.50 for $S = 1.2$. Large amplitude oscillation, of which period is about 60 μsec, and small amplitude oscillation, of which period is about 10 μsec can be observed. Here, sound velocity of burnt gas is about 1055 m/s, and the period of quarter wave mode of the combustor in the longitudinal direction is about 60 μsec, i.e. the large amplitude pressure oscillation occurs in the

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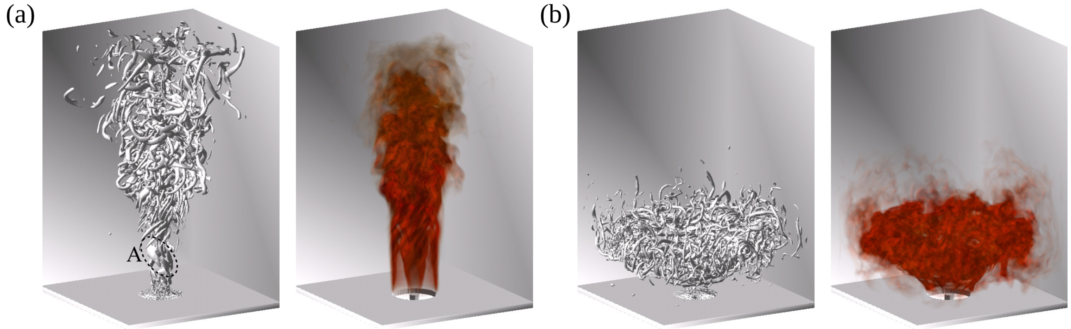

Figure 1. Instantaneous contour surfaces of the second invariant of velocity gradient tensor ($Q^* = 0.2$, left) and distribution of heat release rate illustrated by volume rendering method (right) for $S = 0.6$ (a) and 1.2 (b).

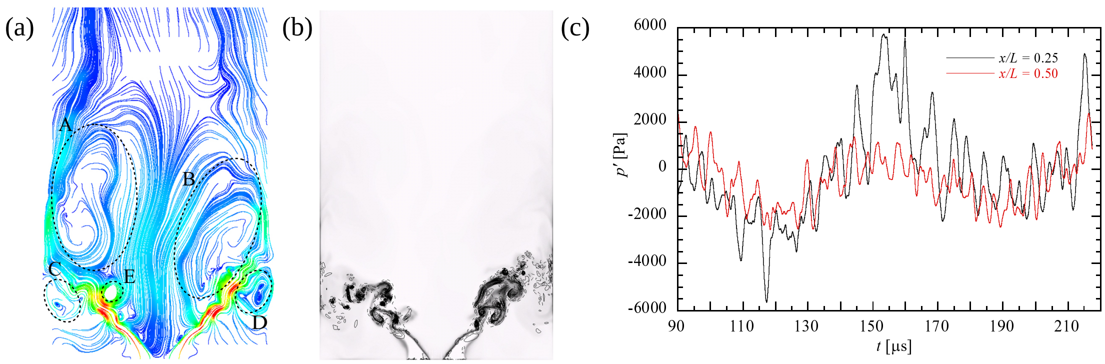

Figure 2. Instantaneous two dimensional distributions of stream lines (a), distribution of heat release rate (gray scale) and isolines of second invariant of velocity gradient tensor (b) and time series of pressure fluctuations on a side wall of combustor for $S = 1.2$.

resonance mode of the combustor. The position of $x/L = 0.25$ corresponds to the region in which outer recirculating flow is generated (shown in Fig. 2(a)). The distribution of heat release rate changes significantly with fluctuation of the recirculating flow and fine-scale eddies, which results in the larger amplitude of pressure fluctuation at $x/L = 0.25$ than that at $x/L = 0.50$. The amplitude of pressure fluctuation at $x/L = 0.25$ for $S = 1.2$ is about twice larger than that for $S = 0.6$ (the figure is not shown here). The relation between temporal development of pressure fluctuation in the combustor and those of flow and flame structures for different swirl number cases will be shown in the conference.

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