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SHORT PAPER

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Numerical visualization of vortical structures in a lean premixed swirl combustor using LES

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Abstract Large eddy simulation was performed to visualize the three-dimensional vortical structures interacting with a turbulent premixed in a lean premixed swirl combustor with varied equivalence ratio. It was found that the fluctuation of unsteady heat release due to the deformation of flame surface was significantly decreased as the equivalence ratio increased because of the change in interaction between inner vortical structures and flames. This phenomenon was another evidence of the amplification mechanism in the combustion instabilities due to the strong flame–vortex interactions under lean premixed conditions.

Keywords Combustion instability · Large eddy simulation · Swirl combustor

1 Introduction

Lean premixed flames governed by turbulent flame speed are naturally susceptible to the change in acoustic excitation that can cause the combustion instabilities. The combustion instabilities which are accompanied by large pressure amplitude oscillation can be driven through the interactions among acoustic pressure, heat release and equivalence ratio oscillations (Lieuwen et al. 1998). Considering that the oscillations of acoustic pressure and heat release are closely associated with the changes in the flow oscillations influenced by a recirculation flow and vortex shedding (Huang and Yang 2009), the visualization of three-dimensional vortical structures with the equivalence ratio varied is very important to better understand the physical processes associated with the combustion instabilities in a lean premixed swirl combustor. Recently, advanced laser diagnostics have been attempted to visualize the reacting flow field. However, there are many limitations to obtain the information on the complex vortical structure interacting with a turbulent flame. In the present study, thus, the large eddy simulation (LES) was performed to visualize the three-dimensional vortical structure interacting with a turbulent premixed flame in a lean premixed swirl combustor with the equivalence ratio varied.

2 Numerical setup

The unsteady three-dimensional compressible Navier–Stokes equations were used. Dynamic k^{sgs}-equation and G-equation flamelet models were employed as LES subgrid models for turbulence and combustion field,

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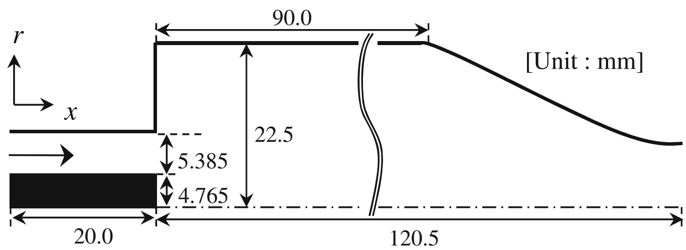

Fig. 1 Schematic of a premixed swirl combustor

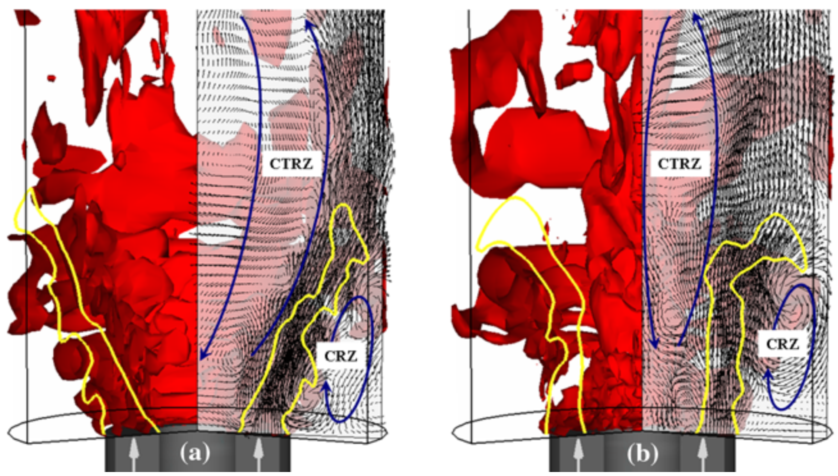

Fig. 2 Instantaneous vortical structures (at 40,000 s^{-1}) and flame surfaces (yellow lines) for $\phi = 0.54$ and 0.80

respectively. A dump combustor studied by Broda et al. (1998) was used as shown in Fig. 1. Natural gas was used as a fuel and Reynolds number based on the height of the inlet annulus was 29,700 with constant inlet velocity of 86.6 m/s. The inlet temperature and pressure were set to 298 K and 1 atm, respectively. The swirl number of 0.77 was considered for all cases. First, the vortical structures at constant equivalence ratios (ϕ) of 0.54 and 0.80 were compared. Second, the effects of temporal variation in ϕ on the vortical structure and flame dynamics were examined. Then the inlet temperature and pressure were changed to 670 K and 0.45 MPa in order to observe definitely the phenomena of the combustion instabilities.

3 Results and discussion

Figure 2 shows the instantaneous three-dimensional vortical structures using iso-vorticity surface at 40,000 s^{-1} for $\phi = 0.54$ and 0.80. The flame surfaces (yellow lines) are also plotted on specific x–r slices. The region corresponding to 100° in azimuthal direction was eliminated to identify the inner vortical structure. For $\phi = 0.54$, distinct twofold vortical structures are observed in the inner and outer regions. It was found that these two structures are located on the boundaries of a center toroidal recirculation zone (CTRZ) resulting from vortex breakdown phenomenon and a corner recirculation zone (CRZ) due to sudden enlargement of combustor inlet. The flame surfaces are established within the shear layer bounded between the CTRZ and CRZ, and significantly contorted due to the vortical motions. For $\phi = 0.80$, the inner vortical structure is concentrated near the center line and the flame is mainly affected by the outer vortical structure originating at the expansion plane due to the Kelvin–Helmholtz instability. This result strongly implies that the fluctuation of unsteady heat release due to the deformation of instantaneous flame surface is significantly decreased as ϕ increases because the inner vortical structure cannot play an important role in the deformation of flame surface. In addition, it can be thought that this phenomenon may be another evidence of the amplification mechanism in the combustion instabilities due to the strong flame–vortex interactions under lean premixed conditions.

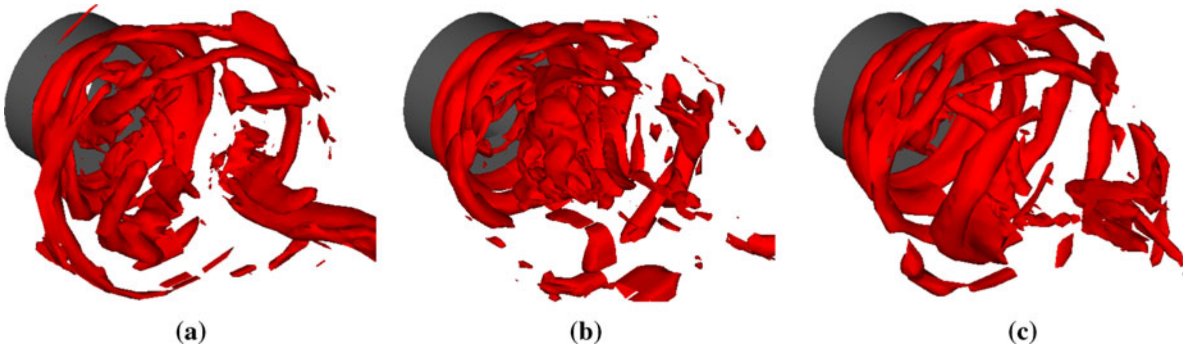

Fig. 3 Instantaneous vortical structures (at 64,000 s^{-1}) according to the temporal variation in ϕ **a** $\phi = 0.60$ **b** $\phi = 0.60 \rightarrow 0.54$, **c** $\phi = 0.60 \rightarrow 0.66$

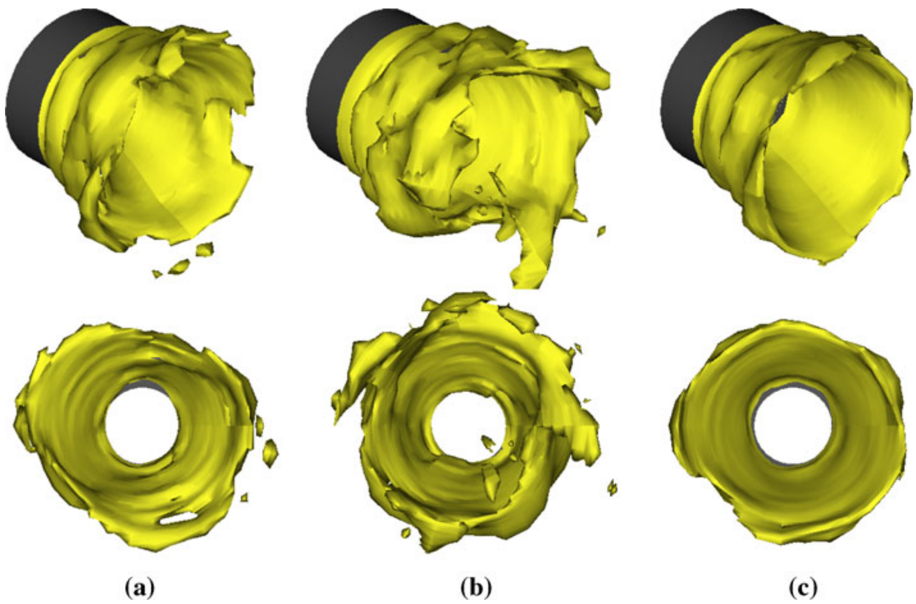

Fig. 4 Instantaneous flame surfaces according to the temporal variation in ϕ **a** $\phi = 0.60$, **b** $\phi = 0.60 \rightarrow 0.54$ **c** $\phi = 0.60 \rightarrow 0.66$

A small variation in ϕ under the lean premixed conditions results in large fluctuations of heat release and then significantly amplifies the acoustic pressure oscillation when the fluctuations of heat release are coupled with the acoustic pressure (Stone and Menon 2003). To examine the effects of temporal variation in ϕ on the vortical structure and flame dynamics, the inlet ϕ decreased (or increased) instantaneously from 0.60 to 0.54 (or 0.66) as the flame and flow were fully developed. Figures 3 and 4 show the instantaneous vortical structures and flamesurfaces for three cases: (a) constant $\phi = 0.60$, (b) $\phi = 0.60 \rightarrow 0.54$, and (c) $\phi = 0.60 \rightarrow 0.66$. The results in cases (b) and (c) were presented when evident changes in acoustic pressure amplitude were observed at 3 ms after the change in ϕ. On the basis of constant $\phi = 0.6$, there is no distinct difference in the outer vortical structures as the ϕ decreases or increases. For inner vortical structure, as the ϕ suddenly decreases to 0.54, the inner vortical structure of very irregular and complex shape is observed, but as the ϕ increases to 0.66, the inner vortical structure seems to consist of weaker vortex strengths compared to other cases. As shown in Fig. 4, the changes in vortical structure by temporal change in ϕ result in the significant differences in terms of instantaneous flame dynamics. That is, the considerable deformation of flame surface is found as the ϕ decreases to 0.54. However, the increase in ϕ leads to more uniform flame surface compared to that for constant ϕ. From these results, it can be concluded that the change in vortical structure according to the variation in ϕ is accompanied by the change in heat release oscillation and thus can be an important cause of the combustion instabilities in a lean premixed combustor.

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