Principal Strain Rates at Flame Front of Three-Dimensional Turbulent Premixed Flames

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1 Introduction

The model of turbulent premixed flames has significant effects on accuracy of numerical prediction of combustors. Recently, many approaches [1],[2] have been attempted to develop high accuracy turbulent combustion model. In these approaches, developed models are validated by using results of numerical simulation or experiments. Direct numerical simulation (DNS) with detailed kinetic mechanism is the most precise computational method [3],[4]. However, DNS requires large amount of computational resources. As the result, most of them are limited to two dimensions. However, in three-dimensional turbulence, it has been clarified that principal strain rate of the velocity gradient tensor have two positive and one negative eigen values on the average. This inherent nature of the strain field of turbulence is never represented by two-dimensional DNS.

As for the modeling of turbulent flames, strain rates at the flame fronts have been treated as an important property to describe the local characteristics of the flame dynamics. Nevertheless, the response of the flame elements to the strain rate has been discussed based on two-dimensional DNS except for three-dimensional DNS with quite simple chemical reactions or low Reynolds number. As for experiments, simultaneous measurements of PIV and several PLIF [5] give detailed experimental information on the local flame structure. In general, however, experimental results obtained in two-dimensional cross section have been used to investigate the characteristic of local flame elements and confirm the various turbulent combustion models [6],[7]. Recently, even for experimental researches, few three-dimensional measurements have been proposed and conducted for turbulent premixed flame [8] and for non-premixed flame [9], whereas these experimental techniques are required to be more sophisticated and to be applied for lots of combustion conditions.

In general, local flame structure has been discussed based on the assumption that mean flow (or mean shear flow) scarcely affects the flame structure and local flame elements can be approximated as so-called flamelet. The recent simultaneous measurement [10],[11] suggested that magnitude of the mean flow may change flame structure and its dynamics. These observations cause queries relating to conventional approaches for the investigation and modeling of turbulent combustion.

In this study, three-dimensional DNSs with detailed kinetic mechanism have been conducted for statistically-planar, freely-propagating turbulent flame and turbulent V-flame of hydrogen-air mixture.

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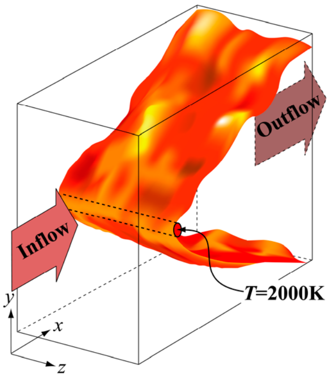

Figure 1. Schematic of the flow geometry for DNS of turbulent V-flame.

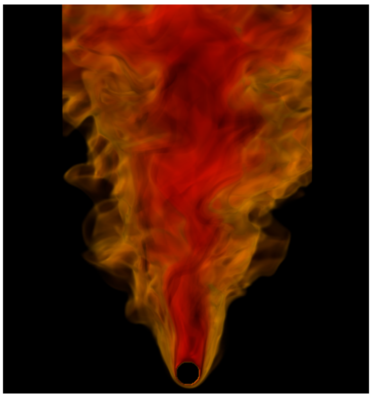

Figure 2. Volume rendering of reaction progress variable for Re_λ=60.8 (view from *z* direction).

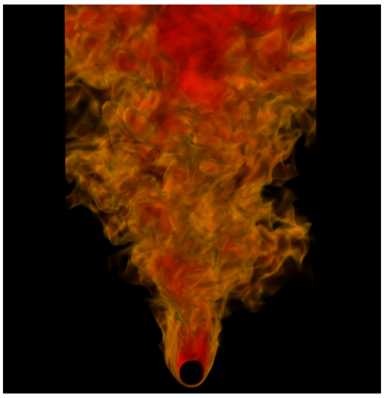

Figure 3. Volume rendering of reaction progress variable for Re_λ=97.1 (view from *z* direction).

From the results of two different configurations, eigen values of strain tensor are evaluated to investigate characteristics of the strain near the flame and alignment of the principal strain and flame.

2 DNS of Hydrogen-Air Turbulent Premixed Flames

In this study, Soret effect, Dufour effect, pressure gradient diffusion, bulk viscosity and radiative heat transfer are assumed to be negligible. The DNS code has been developed in our previous study [3]. A detailed kinetic mechanism which includes 27 elementary reactions and 12 reactive species (H_2, O_2, H_2O, O, H, OH, HO_2, H_2O_2, N_2, N, NO_2 and NO) is used to represent hydrogen-air reaction in turbulence. The temperature dependence of the viscosity, the thermal conductivity and the diffusion coefficients are considered by linking Chemkin II packages with several modifications for vector/parallel computations.

DNS are performed for statistically-planar turbulent premixed flame propagating in three-dimensional decaying turbulence, which is the same configuration reported in our previous study [3], and turbulent premixed V-flame. DNS of statistically-planar turbulent premixed flame are conducted for two different Reynolds number cases: one is Re_λ=60.8 [3] and other is Re_λ=97.1, where Re_λ is Reynolds numbers based on Taylor micro scale. The results in statistically steady state are used for the present analysis. For Re_λ=60.8, u'/S_L is set to 3.39 and l/δ_F is 89.8 and for Re_λ=97.1, the conditions are set to 5.78 and 122. Here, u', S_L l and δ_F denote turbulent intensity, laminar burning velocity, integral length and laminar flame thickness, respectively.

Figure 1 shows a schematic of the flow geometry for V-flame used in this study. Computational domain is selected to be 1.0cm × 0.5cm × 0.5cm. 513 × 257 × 257 and 769 × 385 × 385 grid points are used for Re_λ=60.8 case and Re_λ=97.1 case, respectively. The governing equations are discretized by 4th-order central finite difference scheme in all directions. To eliminate high frequency oscillations higher than spatial resolution of finite difference scheme, 4th-order compact finite difference filter is applied in the *x* and the *y* directions and cutoff filter is implemented for *z* direction. The boundary conditions in the *x* and the *y* directions are NSCBC and those in the *z* direction are periodic. The flame is held by the hot-rod of which temperature is set to 2000K and the velocity at the rod is fixed to zero. Time integration is performed by the third-order Runge-Kutta scheme. A hydrogen-air mixture in the unburnt side is set to ϕ =1.0 at 0.1MPa and 700K. The inflow boundary condition for the velocity field is given as $u_{in}(y,z,t)=10S_L+u'(y,z,t)$ for Re_λ=60.8 case and as $u_{in}(y,z,t)=20S_L+u'(y,z,t)$ for Re_λ=97.1 case, respectively. The turbulence $u'(y,z,t)$ was obtained by the preliminary DNS of homogeneous isotropic turbulence with a spectral method. Figures 2 and 3 show a distribution of reaction progress variables by a volume rendering method for V-flame case of Re_λ=60.8 and 97.1. These figures suggest that different flame structures might be created due to Reynolds number and convection.

3 Principal Strain Rates near the Flame

To investigate the strain field near the turbulent flame, one has to know detailed information of that in non-reactive turbulence. Figure 4 shows probability density functions (PDF) of eigen values of the strain tensor for non-reactive decaying homogeneous isotropic turbulence for different Reynolds number. In this study, the maximum, intermediate and minimum eigen values are denoted by α, β and γ, respectively. The eigen values are normalized by Kolmogorov length and velocity scale (η and u_k). Due to this normalization, PDF of each eigen value coincide very well, which shows that principal strain rates can be scaled by Kolmogorov scales. In Fig. 5, near-flame behaviors of eigen value are shown for V-flame with Re_λ=60.8. In general, flame front is often defined from wide range of the reaction progress variable ($0.2 < c < 0.4$). However, with the increase of the progress variable which is defined from temperature in the present study, the absolute value of the maximum and minimum eigen values decrease and the intermediate one approaches to zero. For c=0.70 which is nearly behind the flame front, strain field can be treated as simple two-dimension. This result suggests that each eigen value should be treated separately for each progress variable. Figure 6 shows PDF of three eigen values of two statistically-planar turbulent premixed flames (Re_λ=60.8 and 97.1) and V-flame (Re_λ=60.8) at the same progress variable (c=0.20). The eigen values ratio gives effects of dilatation, Reynolds number and convection. These PDFs show strong dependency of each eigen value on Reynolds number. In addition, even in same Reynolds number, there is difference between planar

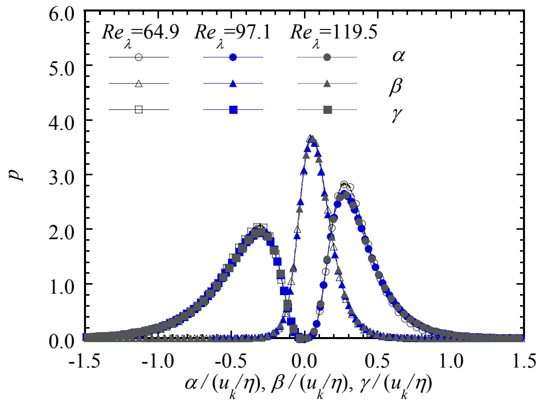

Figure 4. PDF of the eigen values of strain rate tensor for non-reactive incompressible homogeneous isotropic turbulence (Re_λ=64.9, 97.1 and 119.5).

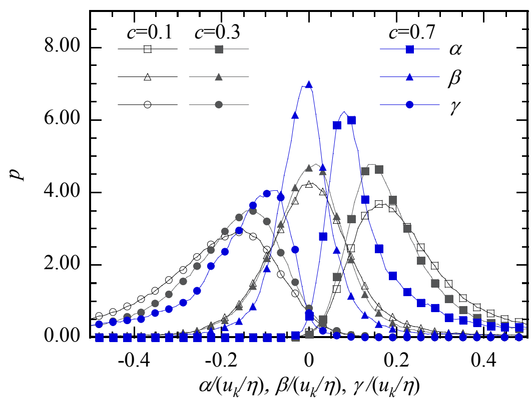

Figure 5. PDF of the eigen value of strain rate tensor for different progress variable (c = 0.10, 0.30 and 0.70) for V-flame (Re_λ=60.8).

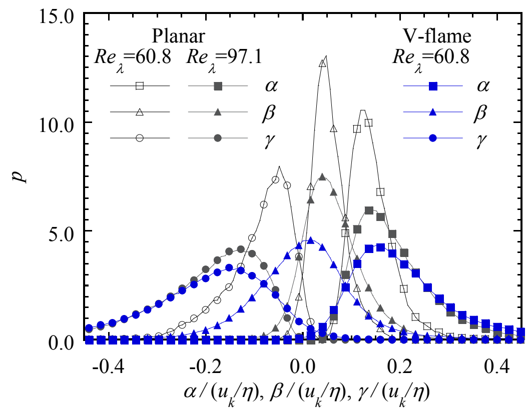

Figure 6. PDF of the eigen value of strain rate tensor near the flame (c=0.20) for statistically planar turbulent premixed flame (Re_λ=60.8 and Re_λ=97.1) and V-flame (Re_λ=60.8).

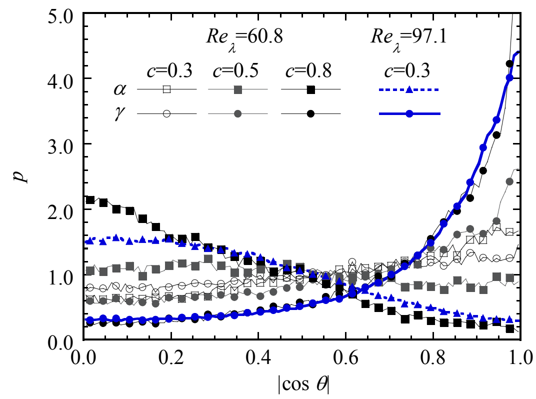

Figure 7. PDF of the cosine angle between the flame normal direction and eigen vectors in statistically planar turbulent premixed flame for c = 0.30, 0.50, 0.80 (Re_λ=60.8) and c = 0.30 (Re_λ=97.1).

flame and V-flame. This might be caused by strong convection and wake behind the hot-rod. This result implies that these eigen values are underspecified in complicated numerical configuration. The alignment between eigen vectors and the flame normal direction is important for the gradient-type turbulent combustion models. Figure 7 shows PDF of the cosine angle between the flame normal direction and eigen vectors in statistically planar turbulent premixed flame for different c value. For small c, probability of the maximum eigen vector alignment with flame surface is slightly high. It is known that the maximum eigen vector well align in the low Reynolds number flow. However, in relatively high Reynolds number cases, alignment between the maximum eigen vector and the flame surface (or gradient of c) decreases and negative correlation is observed for large c. As for the minimum eigen vector, these correlation for small c is very weak. However, with the increase of c, most of the minimum eigen vectors are perpendicular to the flame front. In Fig. 7, the alignments at c=0.30 for Re_λ=97.1 is also shown for comparison. The comparison of two different alignments between Re_λ=60.8 and 97.1 also supports above suggestion. More specifically, alignment of maximum eigen vector with flame surface become weaker in higher Reynolds number turbulence. Therefore, the characteristics of alignment also depend on Reynolds number.

4 References

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