Effects of Strain Rate on Heat Release Rate of Hydrogen–Air Premixed Turbulent Swirling Flame

M. Shimura¹, S. Ogawa¹, K. Aoki¹, N. Fukushima², M. Tanahashi¹ and T. Miyauchi³

¹ Tokyo Institute of Technology, 2-12-1 Ookayama, Meguro-ku, Tokyo, Japan
² The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo, Japan
³ Meiji University, 1-1-1 Higashimita, Tama-ku, Kawasaki, Kanagawa, Japan

mshimura@navier.mes.titech.ac.jp

1 Introduction
In industrial combustors such as gas turbine combustor, swirling flow is applied to create recirculation zone, which plays an important role in flame holding. To develop high-efficiency and low-emission combustors, characteristics of swirling flow and flame structures need to be clarified. Direct Numerical Simulation (DNS) of hydrogen-air turbulent swirling premixed flame in a small cuboid combustor has been conducted to study the differences of the flame and vortical structures with different swirl numbers in our previous study (Tanaka et al., 2011). Wang et al. (2011 and 2012) have conducted DNS of hydrogen–air swirling premixed flame and investigated flame characteristics on the relation among heat release rate, curvature and strain rate. However, local flame structures and effects of strain rate on heat release rate have not been investigated and revealed yet.

Therefore, in the present study, DNS of turbulent swirling premixed flame at different swirl number cases is performed, and relations between heat release rate and strain rate in turbulent swirling premixed flame are investigated based on reaction progress variable and contributions of elementary reactions to heat release rate.

2 DNS of Turbulent Swirling Premixed Flame
Details of the numerical method are found in our previous study (Tanaka et al., 2011). Detailed kinetic mechanism with 12 reactive species (H₂, O₂, H₂O, O, H, OH, HO₂, H₂O₂, N₂, N, NO₂ and NO) and 27 elementary reactions for hydrogen–air mixture are picked up from the works by Miller and Bowman (1989), Smooke and Giovangigli (1991) and Kee et al. (1989). Transport and thermal properties are calculated by CHEMKIN packages (Kee et al. 1986 and 1989) with modifications for vector and parallel computations.

The size of the cuboid combustor is 15 mm in the flow direction (Lₓ) with 10 mm×10 mm cross section (Lᵧ×Lₜ). The shape of the inlet is a concentric annulus with 0.6 mm inner and 2.5 mm outer diameters. Temperature of the wall is assumed to be 700 K. Equivalence ratio, pressure and preheating temperature is set to 1.0, 0.1 MPa and 700 K, respectively. Velocity profile at the inlet is given analytically under assumption 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. In order to reproduce the realistic inflow boundary condition, the velocity perturbations are given at the inlet, which are composed of the banded white noise and have its lifetime. The RMS value of the inlet velocity perturbation is 13.2 m/s. Number of grid points (Nₓ×Nᵧ×Nₜ) is determined to resolve flame thickness and flame-wall interactions enough, and is 769×513×513.

3 Flame Structures of Turbulent Swirling Premixed Flame
Figure 1 shows instantaneous contour surfaces of the second invariant of velocity gradient tensor (Q) and distributions of heat release rate illustrated by volume rendering method. The threshold of Q is set to 1.0% of the maximum value (Qmax). As shown in our previous study (Tanaka et al., 2011), large-scale helical vortical structures and the distributions of heat release rate significantly depend on swirl numbers. For S = 0.6, the large-scale helical vortical structures are formed in upstream region and fine-scale eddies emerge in the downstream. The shape of the region with high heat release rate is cylindrical in the upstream region, whereas it is complex downstream. As for S = 1.2, the large-scale ring-shaped and fine-scale vortical structures are generated near the inlet, since strong shear layer is formed and turbulence develops rapidly compared to the case of S = 0.6. As a result, combustion process is almost completed in the upstream region.

Figure 2 shows the flame classification in turbu-
Figure 1: Instantaneous contour surfaces of $Q = 0.01Q_{max}$ (gray) and distribution of heat release rate illustrated by the volume rendering method (red) for $S = 0.6$ (left) and $S = 1.2$ (right).

Figure 2: Flame classification in turbulent combustion diagram proposed by Peters (2000) at each streamwise direction position for $S = 0.6$ (upper) and $S = 1.2$ (lower). The turbulent combustion diagram proposed by Peters (2000) at each position in the streamwise direction, $u'_{rms}$, $S_L$, $l$ and $\delta_L$ represent turbulent intensity, laminar burning velocity, integral length scale of turbulence and nominal flame thickness based on kinematic viscosity and the laminar burning velocity, respectively. The plot of the classification starts from laminar flame regime for $S = 0.6$ and wrinkled flamelets regime for $S = 1.2$. The large part of turbulent swirling premixed flame for $S = 0.6$ is classified into wrinkled flamelets and corrugated flamelets regimes, whereas that for $S = 1.2$ is in thin reaction zones regime. It can be inferred from these classifications that there are differences between flame inner structure for swirl numbers.

Figure 3: Instantaneous two-dimensional distributions of heat release rate on the center $x - y$ plane for $S = 0.6$ (left) and $S = 1.2$ (right).

Figure 4: Probability density functions of heat release rate at flame front. The flame front is defined by the position where temperature gradient has the local maximum. Here, local heat release rate $\Delta H$ is normalized by $\Delta H_L$. For $S = 0.6$, the existence
probability of flame front which have $0.4 \sim 0.8$ times of $\Delta H_L$ is constant and the maximum of $\Delta H$ reach 1.2 times of $\Delta H_L$. For $S = 1.2$, the number of flame front which have $0.4 \sim 0.5$ times of $\Delta H_L$ is more than that for $S = 0.6$ and the number of flame front monotonically decreases with the increase of $\Delta H$.

To investigate characteristics of flame inner structure, contributions of elementary reactions to heat release rate are analyzed. Here, elementary reactions, which contribute significantly to heat release rate in the laminar flame, R1 ($H + O_2 \leftrightarrow OH + O$), R3 ($H_2 + OH \leftrightarrow H_2O + H$), R6 ($H + O_2 + M \leftrightarrow HO_2 + M$), R8 ($H + HO_2 \leftrightarrow OH + OH$) are focused. Figure 5 shows distributions of heat release rate and contributions of the elementary reactions to the heat release rate in the section A-A’ and B-B’ of Fig. 3. Conditions of strain rates tangential to flame front at the flame front in the sections are almost same. The tangential strain rates are defined as $a_t = t_1 t_2 ; \nabla u + t_2 t_2 ; \nabla u$ in which $t_1$ and $t_2$ stand for orthogonal tangential unit vectors at flame front. The flame front is under $a_t \approx -0.4 \times 10^5$ and $a_t \approx 0.15 \times 10^5$. $x^*$ is a direction which is normal to each flame front from unburnt to burnt sides. Origin of the coordinate is the flame front. In the unburnt side of flame front, contributions of R6 and R8, in which H radical is consumed and OH radical is produced, are significant independently of swirl numbers. Contribution of R3, in which produced OH reacts with $H_2$, is the largest, whereas the contribution of R3 is smaller than that of R6 in laminar condition. In the case of $S = 1.2$, reaction of R3 is more enhanced. Even though flame fronts is under the similar strain rate conditions, inner structure of flame changes with the swirl number.

4 Flame structures conditioned by reaction progress variable

The flame structure in the downstream region is
complex, and the crossline distributions as shown in Fig. 5 cannot provide understandable results, and therefore a reaction progress variable is introduced. The reaction progress variable \( c \) is defined as 
\[
c = \frac{T - T_u}{T_b - T_u}
\]
where \( T \) is temperature and subscripts \( u \) and \( b \) represents the unburnt and burnt gases. Figure 6 shows distributions of mean heat release rate with respect to the reaction progress variable. Mean heat release rate of turbulent swirling premixed flames is very low in the whole region. The maximum value of the mean heat release rate is about \( 0.5 \Delta H_L \) for \( S = 0.6 \) and \( 0.25 \Delta H_L \) for \( S = 1.2 \). The distribution of heat release rate for \( S = 0.6 \) has a singular peak at slightly lower progress variable than the laminar case. As for \( S = 1.2 \), the distribution shows nearly zero up to \( c \approx 0.06 \), and has two peaks at \( c \approx 0.14 \) and \( c \approx 0.44 \).

Figure 7 shows distributions of mass fraction of H radical with respect to the reaction progress variable. For \( S = 0.6 \), mass fraction of H radical is prone to be lower in the region with high reaction progress variable and larger in the low reaction progress variable region \( (c \leq 0.2) \) than the laminar case. Contrarily, for \( S = 1.2 \), the mass fraction shows low value especially in the region with low reaction progress variable. This relation between the mass fraction of H radical and reaction progress variable leads to the difference of contribution of reactions to heat release rate in Fig. 5. Here, analysis on contributions of the elementary reactions to heat release rates is conducted by introducing the reaction progress variable, which is shown in Fig. 8. The distribution for \( S = 0.6 \) is similar to the example shown in Fig. 5. However, for \( S = 1.2 \), contributions of \( R_6 \) and \( R_8 \) are very low even in the region with low reaction progress variable, and take peaks in the high temperature region similar to the contribution of \( R_3 \). This trend of contribution of elementary reactions to heat release rate is attributable to shortage of H radical in flame.

5 Effects of Strain Rates on Contributions of Elementary Reactions to Heat Release Rate

To investigate strain rate effects on heat release rate, joint probability density functions of tangential strain rates at flame front with conditional mean heat release rate are shown in Fig. 9. The relation between the maximum and minimum of tangential strain rates categorizes flame front to stretching-stretching (S-S), stretching-compression (S-C) and compression-compression (C-C). The contributions to heat release
rate are normalized by $\Delta H_L$. The probability difference between neighboring contour lines is 2.0 times. The probabilities of the flame elements that are affected by two-dimensional strain, and almost all the flame elements are stretched into one direction at least.
As for both cases, the most expected flame elements are stretched only in one tangential direction, which is the same trend with the premixed flames freely propagating in homogeneous isotropic turbulence revealed in our previous study (Shim et al., 2011). For $S = 0.6$, the mean heat release rate increases from $0.5 \Delta H_L$ in S-S regime to about $0.7 \Delta H_L$ in S-C regime, while for $S = 1.2$ they increase from $0.4 \Delta H_L$ in S-C to $0.5 \Delta H_L$ in S-S.

Figures 10 and 11 show the averaged contributions of the elementary reactions which are conditioned by the tangential strain rates for $S = 0.6$ and $S = 1.2$, respectively. The contributions are normalized by the same manner with Fig. 9. For both swirl number cases, contribution of R3 to heat release rate is the largest independently of the strain rate condition, and contribution of R6 and R8 increases from S-S to S-C. For $S = 0.6$, contributions of R1 and R3 increase with the increase of strain rate. On the other hand, for $S = 1.2$, contribution of R3 is larger than that for $S = 0.6$, especially in the flame fronts which are exposed by strong stretch in two directions. This is because $H_2$, of which mass fraction is larger than that in laminar case contrary to mass fraction of H radical, is supplied readily to flame front by the stretch in two directions. With increase of consumption of $H_2$ by R3, H radical increases and R1 is also enhanced, which results in the decrease of total heat release rate. These results indicate that the inner structure of hydrogen-air turbulent swirling premixed flame with high swirl number is significantly different from the laminar premixed flame.

6 Summary and Conclusions

In this study, DNS of hydrogen–air premixed turbulent swirling flame was conducted. Relations between heat release rate and strain rates were investigated based on reaction progress variable and contributions of elementary reactions. For the case with high swirl number, the inner structure is different tremendously from the laminar flame. For the case with high swirl number, the inner structure is different tremendously from the laminar flame. For the case with high swirl number, the inner structure is different tremendously from the laminar flame. For the case with high swirl number, the inner structure is different tremendously from the laminar flame. For the case with high swirl number, the inner structure is different tremendously from the laminar flame. For the case with high swirl number, the inner structure is different tremendously from the laminar flame. For the case with high swirl number, the inner structure is different tremendously from the laminar flame. For the case with high swirl number, the inner structure is different tremendously from the laminar flame.

Society for the Promotion of Science.

References


