THREE-DIMENSIONAL FEATURE OF H_2-AIR TURBULENT PREMIXED FLAMES

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The local flame structure in turbulence has been considered to depend on the ratios of turbulence intensity to laminar burning velocity (u'/S_L) and integral length scale to laminar flame thickness[1] (l/δ_F). From these ratios, the local flame structure has been classified into wrinkled flamelets, corrugated flamelets, thin reaction zones and broken reaction zones. Tanahashi et al.[2] conducted direct numerical simulation (DNS) of two-dimensional hydrogen/air turbulent premixed flames to clarify the effect of turbulence intensity on the local flame structure. They showed that the flame in turbulence becomes very complicated with the increase of turbulence intensity and corrugated flames and pocket structure of unburned premixed gas are observed.

Due to the recent remarkable development of computer technology, three-dimensional direct numerical simulations of turbulent premixed flames become possible. In our previous studies[3], DNS of premixed flames in homogenous isotropic turbulence has been conducted to investigate the interaction between flame and fine scale eddy and it is shown that the local flame structure depends on the angle between flame front and axis of fine scale eddy. Tanahashi et al.[3, 4] showed the local structure of turbulent premixed flames which can be classified into corrugated flamelets and thin reaction zones. Although it is believed that the local flame structure classified into wrinkled flamelets corresponds to that of laminar flame, the precise structure is not yet clarified. In this study, three-dimensional DNSs of hydrogen/air premixed flames propagating in homogenous isotropic turbulence are conducted to investigate the effect of turbulence characteristics on the local flame structure.

Details of the governing equations were shown by Miyauchi et al.[5]. Numerical parameters of DNSs conducted in the present study are listed in Table 1. Calculations are conducted for three cases that have different u'/S_L and l/δ_F. Note that δ_F is defined by $\delta_F = \nu/S_L$, where ν denotes kinematic viscosity in unburned gas. A hydrogen/air mixture in the unburned side is set to ϕ=1.0 at 0.1MPa and 700K. The inflow boundary condition for the velocity field was given as $u_{in}(y,z,t) = S_L + u'(y,z,t)$. The turbulence $u'(y,z,t)$ was obtained by the preliminary DNS of homogeneous isotropic turbulence by a spectral method and Reynolds number based on Taylor micro scale Re_λ is 37.4. In our previous study[3], it has been shown that the fine scale eddy in turbulence plays important role in determination of local structure of turbulent premixed flames. In Table 1, the ratios of the most expected diameter D of the fine scale eddy to the flame thickness δ_L are presented. δ_L is defined by $\delta_L = (T_b-T_u)/(\partial T/\partial x)_{\max}$, where T_u and T_b denote temperature in the unburned and burned side, respectively. In Case 1, this diameter is about 0.8 times of the laminar flame thickness. Locations of each case are plotted in the turbulent combustion diagram proposed by Peters[1] (Fig. 1). Case 1 and Case 2 can be classified into wrinkled flamelets and corrugated flamelets, respectively. Case 3 is located at the boundary between corrugated flamelets and thin reaction zones.

The distributions of heat release rate on a typical x-z plane for each case are shown in Fig. 2. The size of region in Fig. 2 is 5 mm $\times$ 5 mm. In Case 1, the heat release rate is fluctuating and the flame convex toward burned side shows high heat release rate compared with that of laminar flame as shown by the circle in Fig. 2 (a). In our previous study[3], it is clarified that fine scale eddy parallel to flame front transports unburned gas into the flame by strong swirling motion and generates the region of high heat release rate. These results indicate that local flame structure in wrinkled flamelets is modified by the turbulence motion. The fluctuation of heat release rate in Case 2 and Case 3 is very large as shown in Fig. 2 (b) and (c). Even though the heat release rate is highly fluctuating, its distribution shows three-dimensionally connected sheet-like structure[4]. For all cases, heat release rate tends to increase at the flame convex toward burned side. Figure 3 shows the distributions of mass fraction of O atom on a typical plane. The mass fraction of O atom tends to increase behind the flame front with high heat release rate for all cases. Tanahashi et al.[6] has clarified the mechanism of increase of heat release rate and O atom. It is suggested that heat release rate increase is attributed to the same mechanism for all cases.

The distributions of the heat release rate in Case 2 at three different times are shown in Fig. 4. The unburned mixture appears behind flame front and seems to be isolated in the burned gas from the cross sectional viewpoint. The maximum heat release rate in the unburned mixture is 1.2 times of that of laminar flame and decreases rapidly down to 0.3 times of laminar flame at 0.2 τ_l. Chen et al.[7] have been conducted two-dimensional DNS of methane/air premixed flames and shown the presence of the pocket of unburned gas even in low turbulence intensity. To investigate the three-dimensional structure of unburned mixture, identification of axis of fine scale eddy is conducted[8]. Figure 5 shows the contour surface of temperature (=1400K) and axes of fine scale eddy around the unburned mixture. As shown by the circle, the unburned mixture shows the three-dimensional structure like a handgrip and the region with high heat release rate is connected three-dimensionally. In the handgrip structure, the axis of fine scale eddy is perpendicular to the direction of mean flame propagation, which indicates that the handgrip structure is produced by the intrusion of the perpendicular eddy into the flame. The eddy transports the unburned mixture into the burned side and high heat release rate region is generated around the eddy. Figure 6 shows the distributions of heat release rate for Case 1 at three different times. While turbulent premixed flames of Case 1 is classified in wrinkled flamelets, the unburned mixture is formed behind flame front with high heat release rate. The distributions of heat release rate on the *x-y* plane and *x-z* plane with axes of fine scale eddies are shown in Fig. 7. The *x-z* plane is same as in Fig. 6. The distribution on *x-y* plane shows that the unburned mixture for Case 1 possesses spire-like structure. The perpendicular eddy at the cusp of spire structure indicates that this structure is produced by the intrusion of fine scale eddy. Three-dimensional structure like handgrip or spire is one of the important structures that enhance the local heat release rate.

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Table 1 Numerical parameters for DNS of hydrogen-air turbulent premixed flames.

	Re_λ	l/δ_F	u'_{rms}/S_L	D/δ_L	l/δ_L
Case 1	37.4	168.6	0.85	0.78	3.38
Case 2	37.4	84.3	1.70	0.39	1.69
Case 3	37.4	42.2	3.41	0.19	0.85

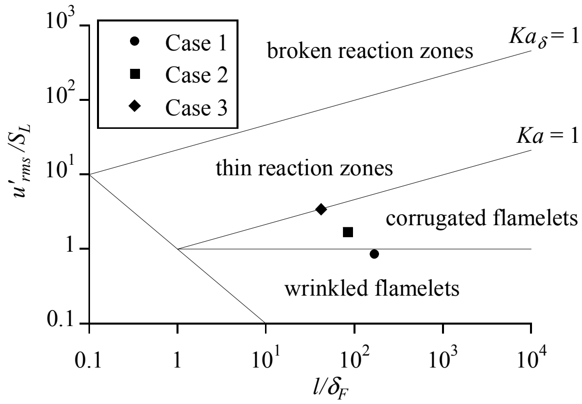


Fig. 1 Turbulent combustion diagram[1]

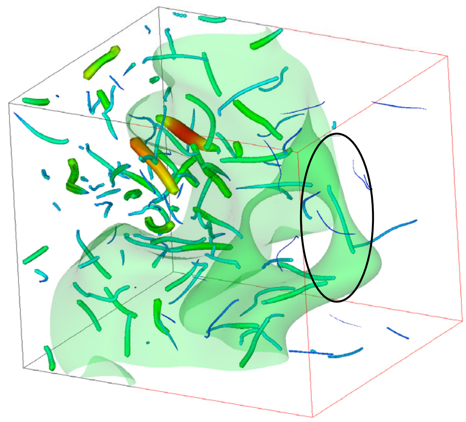
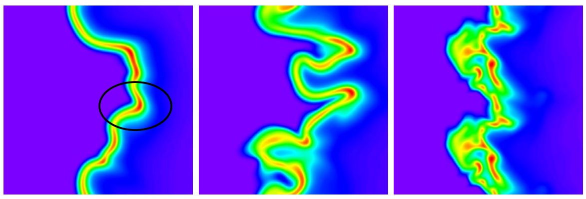


Fig. 5 Contour surface of temperature and the axes of fine scale eddies.



(a) Case 1 (b) Case 2 (c) Case 3

Fig. 2 Distributions of the heat release rate on a typical *x-z* plane.

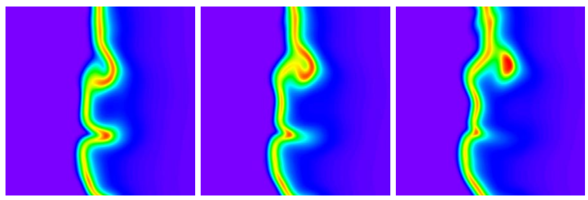
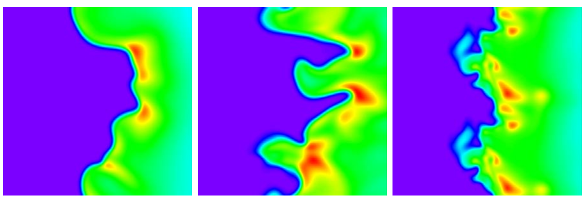


Fig. 6 Distributions of heat release rate in Case 1 at three different times (time interval =0.04 τ_l).



(a) Case 1 (b) Case 2 (c) Case 3

Fig. 3 Distributions of the mass fraction of O on a typical *x-z* plane.

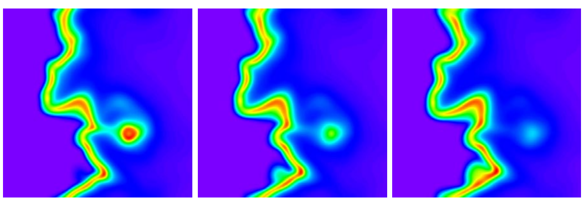


Fig. 4 Distributions of heat release rate in Case 2 at three different times (time interval = 0.1 τ_l).

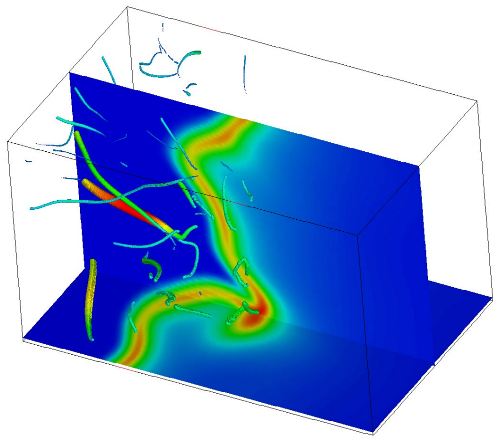


Fig. 7 Distributions of heat release rate and the axes of fine scale eddies for Case 1.