# Local Quantities Analysis of Turbulent Premixed Flames Using DNS Databases

Kazuya Tsuboi<sup>1</sup>, Shinnosuke Nishiki<sup>2</sup>, Tatsuya Hasegawa<sup>1</sup>

<sup>1</sup>EcoTopia Science Institute, Nagoya University, Furo-cho, Chikusa-ku, Nagoya 464-8603, Japan

<sup>2</sup>Department of Mechanical Engineering, Nagaoka University of Technology, 1603-1 Kamitomioka, Nagaoka, Niigata 940-2188, Japan

#### **1** Introduction

The enhancement of energy efficiency and the reduction of combustion emission with harmful effects are required for engines of aircraft and automobiles. To design the engines, it is necessary to understand the detailed mechanism of flow and combustion and to predict their behaviour exactly. In the engines, turbulent combustion mainly takes place. To research more quantitatively the mechanism of turbulent combustion, it is effective to utilise the DNS (Direct Numerical Simulation) databases of turbulent combustion. Recently, the studies for the mechanism of turbulent premixed flames have been carried out by using DNS (Haworth and Poinsot [1], Trouvé and Poinsot [2], Tanahashi et al. [3]). In the present work, the turbulent flame surface is identified and the local flame area is evaluated based on DNS databases of turbulent premixed flames with different density ratios (Nishiki et al. [4]) and with different Lewis numbers. The turbulent burning velocity obtained by the flame area is compared with that obtained by the reaction rate.

#### 2 Analysis method

Two kinds of DNS databases are used for the analysis of flame area and turbulent burning velocity: (1) with different density ratios  $\rho_u/\rho_b$ , where  $\rho_u$ ,  $\rho_b$  denote the density of fresh mixture and that of burnt gas, respectively; 2.50, 5.00, 7.53, (2) with different Lewis numbers; 0.8, 1.0, 1.2. Details of these databases are tabulated in Table 1, where  $u_L^0$  denotes the laminar burning velocity without flame stretch and u' the intensity of turbulence. These databases were constructed by using the 6th-order central finite difference scheme and the pseudo spectral method for the spatial discretisation. The Runge-Kutta method was used for the time development and the overall single step irreversible reaction for the chemical kinetics. The boundary conditions are the inflow and outflow conditions based on NSCBC (Navier-Stokes Characteristic Boundary Conditions) (Poinsot and Lele [5], Baum et al. [6]) for the upstream and downstream boundaries respectively, periodic conditions for the lateral boundaries. The computation domain of these databases is shown in Fig. 1. Lengths of each direction are 8 mm × 4 mm × 4 mm, grid points of each directions are 512 × 128 × 128. Firstly turbulent flame surface at each sampling time is identified as the iso-surface of the prescribed progress variable defined as

$$c = \frac{T - T_u}{T_a - T_u} = 1 - Y_u,$$
 (1)

where T denotes temperature,  $T_u$  temperature of fresh mixture,  $T_a$  adiabatic flame temperature,  $Y_u$  mass fraction of fresh mixture. For example, in the case of c = 0.8, the turbulent flame surfaces for different Lewis numbers are shown in Fig. 2, where  $u_{T_{\alpha}}$  denotes the turbulent burning velocity obtained from the reaction rate. Upper

Correspondence to : ktsuboi@esi.nagoya-u.ac.jp

	Different density ratios			Different Lewis numbers		
$ ho_u\!/ ho_b$	2.50	5.00	7.53	5.00	5.00	5.00
Le	1.0	1.0	1.0	0.8	1.0	1.2
$u_L^0$ (m/s)	0.416	0.523	0.600	0.523	0.523	0.523
$u'/u_L^0$	0.88	1.01	1.26	1.01	1.01	1.01

Table 1. Relevant conditions of DNS databases.



Figure 1. Computation domain.



Figure 2. Turbulent flame surfaces defined by the progress variable: c = 0.8. In a left-to-right fashion, Le = 0.8, 1.0, 1.2, and upper figures are the largest  $u_{Too}$  lower ones are the smallest  $u_{Too}$  in each case.

figures are at the time with the largest  $u_{T\omega}$  and lower ones are at the time with the smallest  $u_{T\omega}$ . It can be seen that the flame surface for higher Lewis number is more wrinkled and unstable than that for lower Lewis number.

Geometry of the turbulent flame surface at every grid cells is estimated from the set of the intersecting points obtained by the linear interpolation of progress variable. Then the local flame area at every grid cells is evaluated. It is deduced that geometry of the turbulent flame surface is one or two polygons. In this analysis local geometry of flame is a triangle, or a quadrangle, or a pentangle, or a hexagon for most cases, but it is two triangles, or a triangle and a quadrangle, or two quadrangles for the rare occasion. The area of these polygons is evaluated after dividing into some triangles. The evaluated area depends on how to divide the polygon into triangles. In this work, it is assumed that every dividing patterns have an equally probability of appearing, then the mean value of them is evaluated as the local flame area at a cell.

Two ways to evaluate turbulent burning velocity are performed. One is evaluated by the total sum of the local flame surface as follows:

$$u_{Ta} = \frac{A_T}{A} u_L^0, \tag{2}$$

where  $u_L^0$  denotes the laminar burning velocity without flame stretch, A and  $A_T$  denote the area of a planar flame and the total area of a turbulent flame, respectively. The other is obtained by the reaction rate as follows:

$$u_{T\omega} = -\frac{1}{A\rho_u Y_u} \int \dot{\omega} \mathrm{d}V, \tag{3}$$

where  $\dot{\omega}$  denotes the reaction rate.

Mean laminar burning velocity is defined as the mean value of the local laminar burning velocity at the turbulent flame surface as follows:

$$\overline{u}_L = \frac{A}{A_T} u_{T\omega}.$$
(4)

#### **3** Results and Discussions

 $u_{Ta}$  obtained by Eq. 2 and  $u_{T\omega}$  obtained by Eq. 3 are compared in Fig. 3 for different density ratios and in Fig. 4 for different Lewis numbers. In Fig. 3, it can be seen that  $u_{Ta}$  agrees well with  $u_{T\omega}$  regardless of the density ratio. This means that the evaluation method for the turbulent flame area is sufficiently accurate. In Fig. 4, however,  $u_{Ta}$  differs from  $u_{T\omega}$  for Le  $\neq$  1.0. This is because of the effect of flame stretch on the reaction rate. In fact,  $u_{Ta}$  does not contain the effect of flame stretch. Thus the difference of the turbulent burning velocity between  $u_{Ta}$  and  $u_{T\omega}$  indicates the contribution of flame stretch on the turbulent burning velocity.

Comparison of  $\bar{u}_L$ ,  $u_{T\omega}$  and  $u_L^0$  is shown in Fig. 5 for different density ratios and in Fig. 6 for different Lewis numbers. In Fig. 5, it can be seen that  $\bar{u}_L$  varies temporally around  $u_L^0$  and the temporal variation of  $\bar{u}_L$  corresponds to that of  $u_{T\omega}$  regardless of the density ratio. In Fig. 6, however,  $\bar{u}_L$  varies temporally apart from  $u_L^0$  and the temporal variation of  $\bar{u}_L$  does not necessarily correspond to that of  $u_{T\omega}$  for Le  $\neq 1.0$ . This is due to the influence of flame stretch on the local laminar burning velocity.

### 4 Conclusions

DNS databases of turbulent premixed flames were analysed to evaluate flame surface area and turbulent burning velocity. Some conclusions obtained are as follows:

 $u_{Ta}$  agrees well with  $u_{T\omega}$  regardless of the density ratio. For Le  $\neq$  1.0, however,  $u_{Ta}$  differs from  $u_{T\omega}$  by the contribution of flame stretch on the turbulent burning velocity.

 $\bar{u}_L$  varies temporally around  $u_L^0$  and the temporal variation of  $\bar{u}_L$  corresponds to that of  $u_{T\omega}$  regardless of the density ratio. For Le  $\neq 1.0$ , however,  $\bar{u}_L$  varies temporally apart from  $u_L^0$  and the variation of  $\bar{u}_L$  does not necessarily correspond to that of  $u_{T\omega}$  because of the influence of flame stretch on the local laminar burning velocity.

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Figure 3. Comparison of  $u_{Ta}$  and  $u_{Tw}$ . In a left-to-right fashion,  $\rho_u/\rho_b = 2.50, 5.00, 7.53$ ; for all cases, Le = 1.0.



Figure 4. Comparison of  $u_{Ta}$  and  $u_{Tw}$ . In a left-to-right fashion, Le = 0.8, 1.0, 1.2; for all cases,  $\rho_u/\rho_b = 5.00$ .



Figure 5. Comparison of  $u_{T\omega}$ ,  $\bar{u}_L$  and  $u_L^0$ . In a left-to-right fashion,  $\rho_u/\rho_b = 2.50, 5.00, 7.53$ ; for all cases, Le = 1.0.



Figure 6. Comparison of  $u_{T\omega}$ ,  $\bar{u}_L$  and  $u_L^0$ . In a left-to-right fashion, Le = 0.8, 1.0, 1.2; for all cases,  $\rho_u/\rho_b = 5.00$ .

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