Turbulent Transport Properties of Wrinkled Flames

Shinnosuke Nishiki¹, Tatsuya Hasegawa¹, and Ryutaro Himeno²

¹Department of Environmental Technology and Urban Planning, Graduate School of Engineering, Nagoya Institute of Technology, Gokiso-cho, Showa-ku, Nagoya 466-8555, Japan
²Computer and Information Division, The Institute of Physical and Chemical Research, 2-1 Hirosawa, Wako-shi, Saitama 351-0198, Japan

Summary. Direct numerical simulation of a turbulent premixed flame with a single-step irreversible Arrhenius-type reaction is performed at \( u'/u_L = 0.88 \), \( l/\delta = 15.9 \) and \( \rho_u/\rho_b = 7.53 \), and turbulent transport properties are evaluated. A fully developed stationary wrinkled flame is obtained in a domain of 8 mm x 4 mm x 4 mm. Turbulent fluctuations generally increase in the flame region, but streamwise component increases more than transversal components. This results in the generation of anisotropic turbulence in the flame region. Analysis based on the Favre-averaged transport equation of turbulent kinetic energy shows that pressure gradient term and pressure work term increase turbulent kinetic energy in the flame region, while diffusion and dissipation term and velocity gradient term decrease it in the flame region. The counter-gradient diffusion dominates turbulent scalar flux in the DNS data, and the BML model well predicts it. Analysis based on the Favre-averaged transport equation of turbulent scalar flux shows that mean pressure gradient term, velocity-reaction rate correlation term and fluctuating pressure term play important roles on production of counter-gradient diffusion, while mean velocity gradient term, mean progress variable gradient term and dissipation terms suppress it.

Key words. Wrinkled Flames, DNS, Flame-Generated Turbulence, Counter-Gradient Diffusion

Introduction

Numerical simulation becomes to play an important role in design of practical combustors, but turbulent combustion models are still required even by using modern supercomputers. The structure and characteristics of turbulent premixed flames are progressively made clear experimentally, for example, by Kobayashi et al. (1997, 1998), Furukawa et al. (2000). However, it is impossible to measure all...
variables in time and in space experimentally. Therefore DNS takes an important place in order to evaluate and develop turbulent combustion models.

There are a few databases of three-dimensional turbulent premixed flames with a simple reaction. For example, Trouvé and Poinsot (1994) calculated a propagating premixed flame in a decaying turbulence with one-step irreversible reaction, and studied the effect of Lewis numbers on statistical properties such as the turbulent burning velocity and the local flame structure. The initial characteristics of turbulence are $u'/u_L = 10.0$ and $l_t/\delta = 5.2$ and the density ratio of the flame is 4.0. Rutland and Cant (1994) also calculated a stationary premixed flame in an incoming turbulence using one-step irreversible reaction and low Mach number approximation. The initial characteristics of turbulence are $u'/u_L = 1$ and $l_t/\delta = 30$ and the density ratio of the flame is 3.3. Besides these simple reaction cases, Tanahashi et al. (1999) performed three-dimensional DNS of H2-air turbulent premixed flames with detailed kinetic mechanism including 12 reactive species and 27 elementary reactions. The initial characteristics of turbulence are $u'/u_L = 3.0$ and $l_t/\delta = 1.74$.

Hasegawa et al. (1999) and Nishiki et al. (2000) studied turbulence, flame structure and transport properties of turbulent premixed flames on the basis of DNS with one-step irreversible reaction, though flames were not enough developed. The initial characteristics of turbulence are $u'/u_L = 4.8$ and $l_t/\delta = 8.0$ and the density ratio of the flame is 7.53. In this study, a fully developed stationary wrinkled flame is obtained in a turbulent flow of $u'/u_L = 0.88$ and $l_t/\delta = 15.9$ with a flame of $\rho_u/\rho_b = 7.53$. In the following sections, simulation method will be described and evolutions of turbulence and turbulent scalar flux through the flame are discussed.

**Direct numerical simulation**

**Basic equations**

Following assumptions are used in the simulation: 1) The chemical reaction is a single-step irreversible one with heat release, where the molecular weights of reactants and products are the same. 2) The bulk viscosity, the Soret and the Dufour effects, and the pressure gradient diffusion are neglected. 3) The specific heat at constant pressure and the specific heat ratio are constant. 4) The equation of state of the burned and unburned gases is that of an ideal gas. Following the above assumptions, basic equations are written as follows:

\[
\frac{\partial \rho}{\partial t} + \frac{\partial (\rho u_i)}{\partial x_i} = 0
\]