DNS of a lifted spray flame in a mixing layer

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1   Introduction

Spray combustion is utilized in numerous practical equipments such as energy conversion and propulsion devices. It is therefore needed to understand the mechanism to improve the efficiency and develop the advanced systems. Recently, the characteristics of spray flames have been investigated in terms of droplet group combustion and flamelet modeling by two-dimensional direct numerical simulations (DNS) [1–4].

The purpose of this study is to investigate the detailed behavior of a lifted spray flame by comparing with a lifted gaseous flame. DNS is applied to the lifted flames in mixing layers. The premixed and diffusion flames in the lifted flames are studied. In addition, in terms of the flamelet modeling, the flamelet behavior in the lifted flames are discussed.

2   Direct numerical simulation

Phase coupling between carrier gaseous phase and dispersed liquid phase is conducted by Eulerian/Lagrangian method. For the carrier phase behavior, non-averaged and non-filtered conservation equations of mass, momentums, energy and mass fractions of species:

$$\frac{\partial \rho}{\partial t} + \frac{\partial \rho u_j}{\partial x_j} = -\frac{1}{\Delta V} \sum_N \dot{m}_d, \tag{1}$$

$$\rho \frac{\partial u_i}{\partial t} + \rho u_j \frac{\partial u_i}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \frac{\partial \tau_{ij}}{\partial x_j} - \frac{1}{\Delta V} \sum_N \frac{d}{dt}\left(m_d v_i\right), \tag{2}$$

$$\rho \frac{\partial h}{\partial t} + \rho u_j \frac{\partial h}{\partial x_j} = \frac{\partial}{\partial x_j}\left(\rho D_h \frac{\partial h}{\partial x_j}\right) - \frac{1}{\Delta V} \sum_N \left[\frac{1}{2}\frac{d}{dt}\left(m_d v_i v_i\right) + \frac{d}{dt}\left(c_L m_d T_d\right)\right], \tag{3}$$

$$\rho \frac{\partial Y_i}{\partial t} + \rho u_j \frac{\partial Y_i}{\partial x_j} = \frac{\partial}{\partial x_j}\left(\rho D_i \frac{\partial Y_i}{\partial x_j}\right) + \dot{m}_i - \frac{1}{\Delta V} \sum_N \dot{m}_d, \quad \text{for} \quad Y_i = Y_V, \tag{4}$$

are simultaneously solved [3], where ρ is the density, u_i is the velocity, h is the enthalpy and Y_i is the mass fraction of i-th species. In addition to the above equations, transport equation of mixture fraction Z is solved. Last terms on the right-hand sides of the equations are the phase coupling terms, where $\sum_N$ represents contributions of droplets to the control volume of the carrier phase. ΔV is the control volume. m_i is the consumption or production rate of i-th species. A one-step global reaction of n-decane oxidation is given by Arrhenius law. Species considered here are $C_{10}H_{22}$, O_2, N_2, H_2O and CO_2, and their thermodynamics and transport properties are given by Chemkin database.

On the other hand, formulation for the dispersed liquid phase behavior is as follows [5]:

$$\frac{dX_i}{dt} = v_i, \quad \frac{dv_i}{dt} = \frac{F_i}{m_d} = \frac{f_1}{\tau_d}\left(u_i - v_i\right),$$ (5)

$$\frac{dT}{dt} = \frac{Q_d + \dot{m}_d L_V}{m_d c_L} = \frac{Nu}{3Pr}\left(\frac{f_2}{\tau_d}\right)\left(\frac{c_p}{c_L}\right)\left(T - T_d\right) + \frac{\dot{m}_d}{m_d}\frac{L_V}{c_L},$$ (6)

$$\frac{dm_d}{dt} = \dot{m}_d = -\frac{m_d}{\tau_d}\left(\frac{Sh}{3Sc}\right)\ln\left(1 + B_M\right),$$ (7)

where X_i is the droplet position, v_i is the droplet velocity, T_d is the droplet temperature and m_d is the droplet mass. f_1 is the correction for drag force. In spray combustion, blowing from the droplet surface is known to reduce the drag force. Kurose et al. [6] proposed the following correction to consider the reduction effect,

$$f_1 = \frac{1 + 0.054Re_{sl} + 0.1Re_{sl}^{1/2}\left(1 - 0.03Re_{sl}\right)}{1 + b|Re_b|^c},$$ (8)

$$b = 0.06 + 0.077\exp\left(-0.4Re_{sl}\right), \quad c = 0.4 + 0.77\exp\left(-0.04Re_{sl}\right),$$ (9)

where Re_{sl} is the particle Reynolds number based on slip velocity $u_{sl} = |u_i - v_i|$, and Re_b is the Reynolds number based on blowing velocity. B_M is the transfer number defined by $B_M = (Y_V - Y_{V,s})/(1 - Y_V)$, where $Y_{V,s}$ is the mass fraction of fuel vapor at the droplet surface and computed from mole fraction surface $X_{V,s}$. To estimate the value of $X_{V,s}$, non-equilibrium effect is taken into account by Langmuir-Knudsen evaporation law.

Figure 1 shows the schematic of the computational domain. The computational domain is two-dimensional square with streamwise (X direction) and spanwise (Y direction) lengths of L_x=0.075 m and $2L_y$=0.06 m, respectively. The staggered grids with 400×500 grid points are non-uniformly arranged in the domain. The inlet velocities of fuel and oxidizer are U_F=7.0 m/s and U_O=0.1 m/s for the gaseous flame, and U_F=8.5 m/s and U_O=0.1 m/s for the spray flame, respectively.
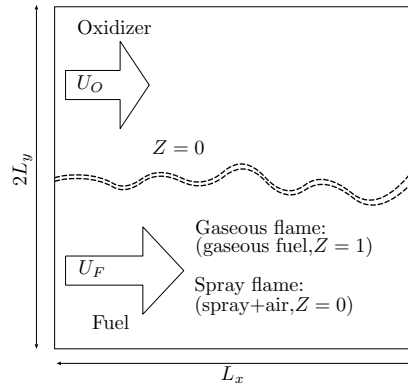

Figure 1: Schematic of the computational domain.

The fourth-order fully conservative finite difference scheme for Navier-Stokes equations [7] is applied to nonlinear terms of NS equations. Scalar convections are computed from a QUICK scheme. Other differentials of governing equations are approximated by a second-order central finite difference method. Time advance follows fractional step method and a second-order explicit Runge-Kutta method is used for the fractional time advance.

3 Results and discussion

Figure 2 shows the instantaneous distributions of temperature T^* (non-dimensionalized by reference temperature of T_0=300K as $T^* = T/T_0$), flame index FI and mixture fraction Z of the gaseous flame. FI is a diagnostic tool

to distinguish between premixed and diffusion regimes in flames [8]. The positive and negative values indicate the premixed and diffusion flames, respectively. It is found that a lifted flame is formed in the mixing layer and is stabilized mainly by the premixed flame appearing at the front edge of the flame. In the downstream region, the diffusion flame becomes marked, and the premixed and diffusion flames expand on the oxidizer and fuel sides, respectively. This shows that the lifted flame is a partially premixed flame. It is known that there appear lean- and rich-premixed-flame branches in the lifted jet flames [9]. In this study, however, only the lean-premixed-flame branch is observed.
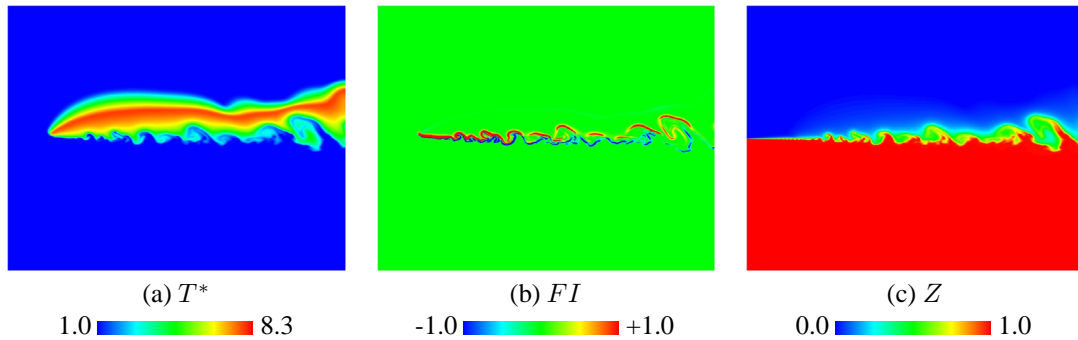

(a) T^* (b) FI (c) Z

1.0 ▭ 8.3   -1.0 ▭ +1.0   0.0 ▭ 1.0

Figure 2: Instantaneous distributions of T^*, FI and Z of lifted gaseous flame (U_F=7.0 m/s).

(a) T^* (b) FI (c) Z

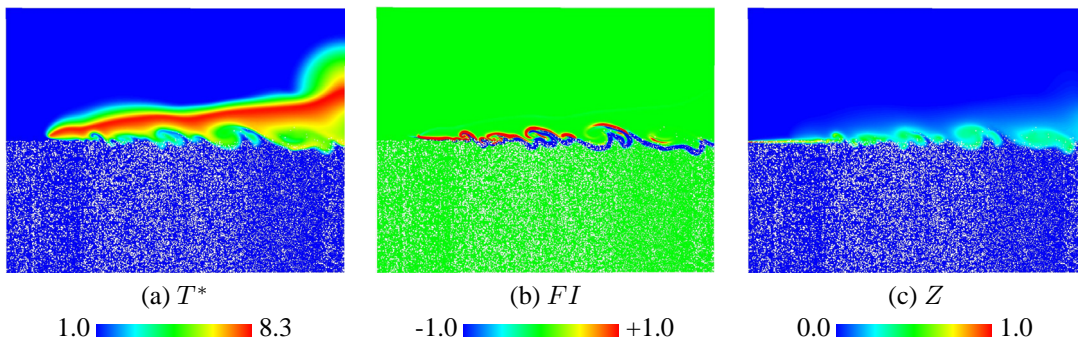1.0 ▭ 8.3   -1.0 ▭ +1.0   0.0 ▭ 1.0

Figure 3: Instantaneous distributions of T^*, FI and Z of lifted spray flame (U_F=8.5 m/s).

Figure 3 shows the instantaneous distributions of temperature T^*, flame index FI and mixture fraction Z of the spray flame. Droplet positions are superimposed on the distributions. Like the gaseous flame, the spray flame is observed to be lifted. The scales of vortices generated in the mixing layer are found to be larger than those of the gaseous flame. This is because Reynolds number of the mixing layer for the spray flame is smaller than that for the gaseous flame. The mixture fraction Z for the spray flame distributes only in the mixing layer, whereas that for the gaseous flame indicates unity in the lower fuel side and diffuses towards the upper oxidizer side.

Figure 4 shows the instantaneous spanwise profiles of temperature T^* against mixture fraction Z at X/L_x=0.5. For the gaseous flame, $Z = 0$ and $Z = 1$ correspond to the oxidizer and fuel sides, respectively. The T^* profile of the gaseous flame against Z is similar to that in a planar diffusion flame, although it does not match exactly because of the existence of the premixed flame. Contrary to the gaseous flame, the T^* profile of the spray flame is quite different from that of the planar diffusion flame. The profile consists of two branches corresponding to the fuel and oxidizer sides and the value of T^* is not characterized by the value of Z. This trend is a noteworthy characteristic of spray flames found by Watanabe et al. [4].
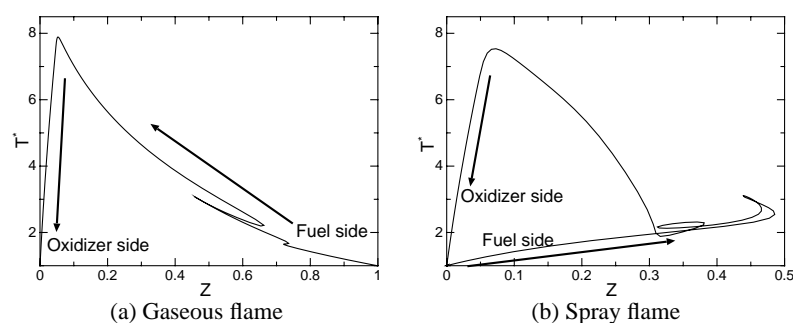
Figure 4: Instantaneous spanwise profiles of T^* against Z at X/L_x=0.5.

4   Conclusions

The behavior of a lifted spray flame in a mixing layer was investigated by DNS, and compared with that of a lifted gaseous flame. It was found that both the lifted gaseous and spray flames were partially premixed flames, which were stabilized mainly by premixed flames. It was also found that the gaseous temperature was characterized by the mixture fraction for the gaseous flame, whereas not for the spray flame. This means that the conventional steady flamelet model can not be simply applied to the lifted spray flame.

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