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Two-dimensional direct numerical simulation of spray flames – Part 2: Effects of ambient pressure and lift, and validity of flamelet model

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HIGHLIGHTS

- ▶ We investigate effect of ambient pressure.
- ▶ Contribution of premixed flame decreases as ambient pressure increases.
- ▶ Effect of change of ambient pressure is captured by flamelet model.

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ABSTRACT

The effect of ambient pressure on spray flames is investigated by means of two-dimensional direct numerical simulation (DNS), and the validity of an extended flamelet/progress-variable approach (EFPV) is examined under the high-pressure condition. The DNS is performed not only for a simple jet spray flame with a pilot burner but also for a lifted recirculation spray flame without any pilot burner at ambient pressures of 0.1 and 0.5 MPa. *n*-decane ($C_{10}H_{22}$) is used as liquid spray fuel, and the evaporating droplets' motions are tracked by the Lagrangian method. The results show that the behaviors of jet and lifted recirculation spray flames are strongly affected by ambient pressure. The effects of the change of the ambient pressure on these spray flame behaviors can be well captured by EFPV and EFPV coupled with *G*-equation model (EFPV-G), respectively.

1. Introduction

The effects of ambient pressure on the spray combustion behavior have not been well clarified yet mainly because combustion conditions and acquired properties are extremely limited due to the difficulty of the measurements [e.g., 1–4]. Recent progresses of direct numerical simulation (DNS) and large-eddy simulation (LES) of spray combustion fields [e.g., 5–17] enable us to numerically investigate the effects of the ambient pressure on the spray combustion behavior in detail. However, these simulations are still very expensive so that the spray combustion mechanism has not been examined enough yet. One of the important research subjects is how premixed and diffusion flames contribute in the spray flames, which could be an indication for the combustion modeling. Nakamura et al. [5] and Baba and Kurose [10] investigated the contributions of the premixed and diffusion flames in spray flames in a counterflow and a jet, respectively, by means of two-dimensional DNS, and Luo et al. [13] extended the discussion by means of three-dimensional DNS. Moreover, Baba and Kurose [10] examined the applicability of flamelet models [e.g., 18–20], which are originally proposed for gaseous combustion, to the combustion model of jet spray flames by means of two-dimensional DNS, and found that the flamelet/progress-variable approach (referred to as FPV, in this study) [20] is valid in general. However, the contributions of the premixed and diffusion flames and the applicability of FPV were mainly studied under the atmospheric pressure condition of 0.1 MPa and the effects of the ambient pressure have not been investigated enough. In addition, the flames considered in these studies by two-dimensional DNS were simple jet flames with a pilot burner because of the difficulty in maintaining the two-dimensional stable spray flames without forced ignition, but the flames observed in actual engines are swirling-recirculation flames without any pilot burner. Therefore, the study on more realistic flames is essential.

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Nomenclature

C	progress variable (–)	Y_k	mass fraction of kth species (–)
c_L	specific heat of liquid fuel ($J\,kg^{-1}\,K^{-1}$)	Z	mixture fraction (–)
c_p	specific heat of mixture gas ($J\,kg^{-1}\,K^{-1}$)	ϕ	equivalence ratio (–)
FI	flame index (–)	ρ	density ($kg\,m^{-3}$)
L	length (m)	atm	atmospheric
L_V	latent heat of droplet evaporation ($J\,kg^{-1}$)	BL	boiling point
P	gaseous pressure (Pa)	CL	critical point
s_L	laminar burning velocity (m/s)	F	fuel gas
T	gaseous temperature (K)	O	oxidizer
U	velocity (s^{-1})	0	reference value

The purpose of this study is to investigate the effects of various combustion conditions on the spray combustion behavior by means of two-dimensional DNS of spray flames. The present paper provides the second part of two investigations. In part 1 [21], the effects of equivalence ratio, fuel droplet size and radiation on the spray combustion behavior were investigated. In addition, the validity of the extended flamelet/progress-variable approach (referred to as EFPV, in this paper) was examined in various equivalence-ratio and fuel-droplet-size conditions and in the presence of the radiation. In this part 2, the effect of ambient pressure on the spray combustion behavior and the validity of EFPV in high-pressure condition are studied. The two-dimensional DNS is applied to spray flames at ambient pressures of 0.1 and 0.5 MPa and the validity of EFPV is examined by comparing with the results using the direct combustion model based on the Arrhenius formation (referred to as ARF, in this paper). The flames considered are not only a simple jet spray flame with a pilot burner but also a lifted recirculation spray flame without any pilot burner which has been established for investigating the more realistic flames. n-decane ($C_{10}H_{22}$) is used as liquid spray fuel, and the evaporating droplets' motions are tracked by the Lagrangian method.

2. Numerical simulation

2.1. Numerical methods for ARF, EFPV and EFPV-G

The set of governing equations of the carrier gaseous phase and dispersed droplets phase for ARF and EFPV are described in our previous papers [5,8–10,12] and part 1 [21] of this study. The combustion reaction of the evaporated n-decane with oxygen is described using a one-step global reaction model [22] as $C_{10}H_{22} + \frac{31}{2}O_2 \rightarrow 10CO_2 + 11H_2O$.

In order to take into account the effect of high ambient pressure, boiling temperature, T_{BL}, and latent heat of droplet evaporation, L_V, of liquid droplet at ambient pressure of P [mmHg] are given by

$$T_{BL} = \left(\frac{P^{0.119} + c}{11.9}\right)^{\frac{1}{0.119}}, \tag{1}$$

$$c = P_{atm}^{0.119} - 11.9T_{BL,atm}^{0.119},$$

$$L_V = L_{V,T_{BL,atm}}\left(\frac{T_{CL} - T_d}{T_{CL} - T_{BL,atm}}\right)^{0.38}, \tag{2}$$

respectively. Here, the subscript atm means the value under atmospheric pressure. $L_{V,T_{BL}}$, T_{BL} and T_{CL} are the latent heat of droplet evaporation, the boiling temperature and the critical temperature, respectively [5]. T_d is the droplet temperature. All thermophysical properties values and transport coefficients under various pressures are obtained from CHEMKIN [23,24]. Radiation effect [9,21] is neglected in this study.

It is known that the flame which lifts off from the nozzle or burner and stabilize at a suspended region is called "lifted flame" and that in the lifted flame, the remixed flame forms upstream of the diffusion flame and plays an important role to stabilize the lifted flame (this flame is called "partially premixed flame"). This fact suggests that EFPV based on the diffusion flame cannot be simply applied to the lifted flame. Concerning the premixed combustion, an equation describing the dynamics of a laminar flame front, known as G-equation, has been presented by Williams [25]. Accordingly, Muller et al. [26] proposed a method for the partially premixed flame, in which the premix and diffusion flame models

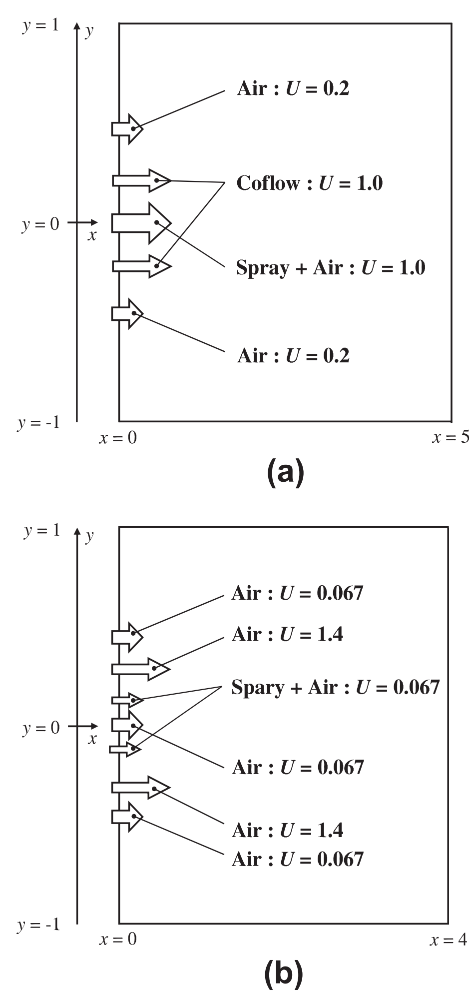

Fig. 1. Schematic of computational domains and conditions: (a) jet spray flame; (b) lifted recirculation spray flame.