ARTICLE IN PRESS

Combustion and Flame xxx (2014) xxx–xxx

Contents lists available at ScienceDirect

Combustion and Flame

journal homepage: www.elsevier.com/locate/combustflame

Behaviors of tribrachial edge flames and their interactions in a triple-port burner

Kazuhiro Yamamoto [a,*], Yusuke Isobe [a], Naoki Hayashi [a], Hiroshi Yamashita [a], Suk Ho Chung [b]

[a] *Department of Mechanical Science and Engineering, Nagoya University, Furo-cho, Chikusa-ku, Nagoya, Aichi 464-8603, Japan*

[b] *Clean Combustion Research Center, King Abdullah University of Science and Technology, Thuwal 23955-6900, Saudi Arabia*

ARTICLE INFO

Article history:
Received 2 July 2014
Received in revised form 20 November 2014
Accepted 20 November 2014
Available online xxxx

Keywords:
Non-premixed flame
Lifted flame
Liftoff height
Tribrachial edge flame
Numerical simulation

ABSTRACT

In a triple-port burner, various non-premixed flames have been observed previously. Especially for the case with two lifted flames, such configuration could be suitable in studying interaction between two tribrachial flames. In the present study, the flame characteristics have been investigated numerically by adopting a reduced kinetic mechanism in the triple-port burner. Four different types of flame configurations, including two attached flames, inner lifted/outer attached flames, inner attached/outer lifted flames, and twin lifted flames, were successfully simulated depending on the flow conditions. The representative edge propagation speed of a single lifted flame or an upstream lifted flame in the case of twin lifted flames increased as the liftoff height became higher. In the twin lifted flames, the inner lifted flame was affected appreciably when the other flame was located further upstream such that the lifted flame located further downstream encountered the axial velocity acceleration induced by the gas expansion from the lifted flame located upstream, while thermal effects were not observed since the temperature of the incoming flow toward the lifted flame was not affected. A unique flip–flop behavior between the inner and outer flames, observed experimentally previously, was successfully captured in the simulation such that the inner lifted flame became attached to the nozzle as the liftoff height of the outer lifted flame grew higher with an increase in the outer air velocity.

1. Introduction

Non-premixed flames in a mixing layer play interesting roles under various combustion conditions. An example is a lifted flame in a jet in which the fuel and the oxidizer are partially premixed. The flame edge typically has a tribrachial (or triple) flame structure, consisting of a lean and a rich premixed flame wings and a trailing diffusion flame [1–6]. This type of lifted flame is stabilized by the balance between the propagation speed of the edge flame and the local axial flow velocity. Many fundamental studies have been conducted to investigate the liftoff height behavior [7–12].

Particle image velocimetry (PIV) techniques have revealed that the velocity along the streamline direction in a tribrachial edge flame gradually decreases toward the leading-edge of the lifted flame to a minimum value [13–15], which is reasonably close to the laminar burning velocity [1,3,8,16,17]. The streamline divergence toward the convex premixed flame wings reduces the local velocity in front of a tribrachial flame. As a result, the propagation speed of the edge flame can be larger than a laminar burning velocity, resembling the Landau's hydrodynamic instability phenomenon [6,11,12,14].

Typically, isolated lifted flames either in a uniform flow of a two-dimensional rectangular system or an axisymmetric configuration have been considered [1–6,11]. Recently, direct numerical simulations (DNS) of turbulent lifted flames [18–20] have demonstrated that the incoming flow balances with the local burning velocity of the lifted flame.

In advanced direct-injection spark ignition (DISI) engines operated under stoichiometric conditions, mixtures are typically stratified. In such a situation, the flame propagation after ignition may be controlled by tribrachial edge flames. Because a large number of flamelets could exist under such turbulent conditions, the interaction between flames (flamelets) and flow is expected to be very complex [20–25]. Therefore, a relatively simple flow configuration is desirable to investigate the interaction among tribrachial flames with flow fields. Examples are two lifted edge flames in a slot burner with multiple inlets of fuel and air [26] or a triple port burner [27].

A triple port burner has three concentric tubes. Air flows through both the central and outermost tubes and fuel flows through the annulus between the two air tubes. Since there are

* Corresponding author.

http://dx.doi.org/10.1016/j.combustflame.2014.11.028
0010-2180/© 2014 Published by Elsevier Inc. on behalf of The Combustion Institute.

Please cite this article in press as: K. Yamamoto et al., Combust. Flame (2014), http://dx.doi.org/10.1016/j.combustflame.2014.11.028

central and outer airflows next to the fuel flow, two (an inner and an outer) flames are formed [27]. Compared with a typical co-axial burner, the contact area between the fuel and air in a triple port burner is larger because of the introduction of the central air jet, which promotes mixing of the fuel and air and subsequently reactions [28]. Depending on the flow conditions, four different flame configurations have been observed previously in a triple port burner. These include attached flames, inner lifted/outer attached flames, inner attached/outer lifted flames, and twin lifted flames. One of the interesting finding was a flip–flop behavior between the inner and outer flames, which is shown in Fig. 1. These photos of flames were recorded at 15 fps by changing U_{3A} from 1.0 to 1.1 m/s at U_{1A} = 0.6 m/s and U_{2F} = 0.6 m/s, where U_{1A}, U_{2F}, and U_{3A} are the average velocities of central air, fuel, and outer air, respectively. The result indicates that the inner lifted flame becomes re-attached, while the outer flame is lifted with the small change in the outer air velocity. The objective of the present study is to numerically simulate such behaviors observed previously in the triple port burner [27].

2. Numerical analysis

Figure 2 shows the computational domain and coordinate system. The numerical model, including the scheme and boundary conditions, was discussed in detail previously [27]. Time-dependent conservation equations of momentum, energy, and species were solved by the SIMPLE method [10] on an axisymmetric configuration with methane fuel. A finite difference procedure with staggered grids was adopted. The third-order upwind difference scheme was used for convective term. The time advance was made by using Euler's fully implicit method [4,29–31]. The computational domain was 16.8 mm in the radial direction and −1 to 200 mm in the axial direction. Similar to the experimental conditions [27], the radii of the central air nozzle, the fuel nozzle and the outer air nozzle were 5, 7 and 13.5 mm, respectively. The thickness of each nozzle was 1 mm. The grid size was 0.1 mm, and a grid dependence was confirmed in preliminary tests. When the grid was coarse, the grid size dependence was observed. They were converged when the grid size was smaller than 0.1 mm. At the nozzle exits, parabolic velocity profiles were assigned. The temperature of the fuel and air was 297 K. A methane–air skeletal kinetic mechanism was used for the consideration of computational time, consisting of 16 chemical species and 25 elementary reactions, which has been proposed during the workshop on "Reduced Kinetic Mechanisms and Asymptotic Approximations for Methane–Air Flames" held at the University of California at San Diego in 1989 [32]. The calculated stoichiometric laminar burning velocity was 0.43 m/s, which is in reasonable agreement with various

Fig. 1. Photos of the flip–flop behavior between inner and outer flames by changing U_{3A} from 1.0 to 1.1 m/s at U_{1A} = 0.6 m/s, U_{2F} = 0.6 m/s, recorded at 15 fps.

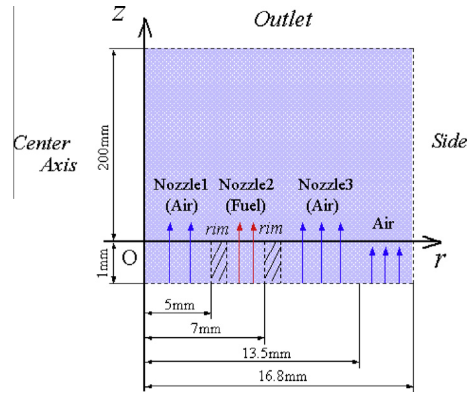

Fig. 2. Computational domain and coordinate system.

experimental data reported. This skeletal mechanism has also been successfully used previously for relatively large scale non-premixed methane jet flames [33] and highly turbulent premixed flames [34].

In the simulation, the average fuel velocity, U_{2F}, was fixed at 0.6 m/s, and the central air velocity, U_{1A}, was 0.4 m/s (case A) or 0.7 m/s (case B), while the outer air velocity, U_{3A}, was varied. The air outside the outermost tube was ambient air with a uniform velocity (0.01 m/s). At the outlet and the side boundaries, the convective boundary condition was set, where the gradient of a scalar such as temperature was zero.

3. Results and discussion

3.1. Flame transition in case A

First, the flame transition from nozzle-attached to outer lifted flame (case A) is discussed. Distributions of the heat release rate at U_{3A} = 0.2, 0.5, and 0.8 m/s are shown in Fig. 3. To show the flame structure clearly, these images are enlarged in the radial direction. As the outer air velocity (U_{3A}) increases, a transition from two

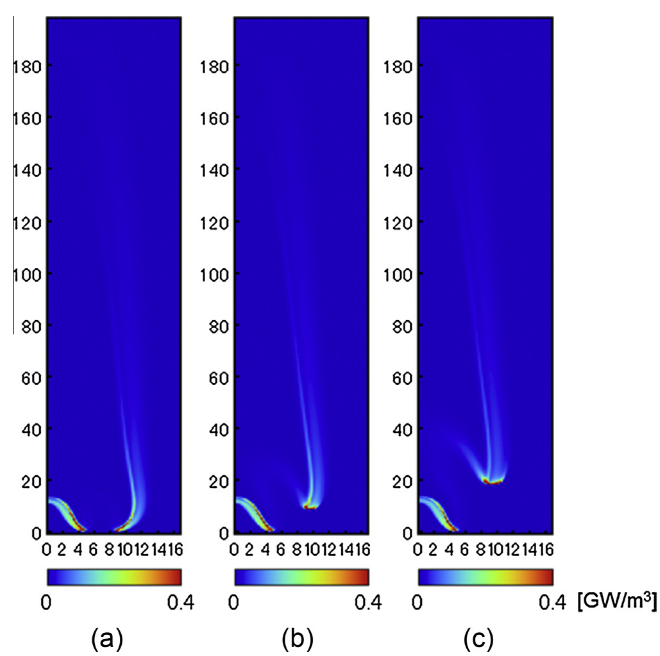

Fig. 3. Distributions of the heat release rate in case A for U_{3A} = 0.2 (a), 0.5 (b), and 0.8 m/s (c).

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