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Fuel density effect on near nozzle flow field in small laminar coflow diffusion flames

Yuan Xiong, Min Suk Cha *, Suk Ho Chung

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

Abstract

Flow characteristics in small coflow diffusion flames were investigated with a particular focus on the near-nozzle region and on the buoyancy force exerted on fuels with densities lighter and heavier than air (methane, ethylene, propane, and n-butane). The flow-fields were visualized through the trajectories of seed particles. The particle image velocimetry technique was also adopted for quantitative velocity field measurements. The results showed that the buoyancy force exerted on the fuel as well as on burnt gas significantly distorted the near-nozzle flow-fields. In the fuels with densities heavier than air, recirculation zones were formed very close to the nozzle, emphasizing the importance of the relative density of the fuel to that of the air on the flow-field. Nozzle heating influenced the near-nozzle flow-field particularly among lighter fuels (methane and ethylene). Numerical simulations were also conducted, focusing specifically on the effect of specifying inlet boundary conditions for fuel. The results showed that a fuel inlet boundary with a fully developed velocity profile for cases with long tubes should be specified inside the fuel tube to permit satisfactory prediction of the flow-field. The calculated temperature fields also indicated the importance of the selection of the location of the inlet boundary, especially in testing various combustion models that include soot in small coflow diffusion flames.
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Keywords: Laminar diffusion flame; Recirculation; Buoyancy; Boundary condition

1. Introduction

Small laminar coflow diffusion flames have been investigated extensively in soot studies, including a determination of the threshold soot index (TSI) for gaseous fuels [1–3]. Numerical simulations of coflow flames have been performed to validate various combustion characteristics, such as the gas-phase reaction [4], radiation [5], hydrodynamic structure [6], instability [7], and soot [8,9]. These simulations require accurate inlet boundary conditions, particularly for the fuel stream.

In a laminar coflow diffusion flame, there is appreciable influence on the flow-field when buoyancy acts on the burnt gas region. The accelerated vertical flow velocity, leading to flame flickering motions [10,11], highlight the role of buoyancy. The buoyancy can also affect the fuel flow. As the density of fuel becomes appreciably different

* Corresponding author.
E-mail address: min.cha@kaust.edu.sa (M.S. Cha).

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from air, the near-nozzle flow-field could also be significantly influenced. This has been demonstrated in propane jets with lifted flames by comparing cold and reacting flows [12].

Under a moderate Reynolds number fuel stream, the hydrodynamic structures of jet diffusion flames have been well reported [13]. Two vortical structures have been identified: one located near the flame bulge region on the oxidizer side, which leads to flame flickering, and the other identified as an inner vortex that is due to shear layer instability. These two vortical structures are widely observed in laminar jet flames regardless of fuel type [14]. In addition, a unique toroidal vortex at the end of a potential core was observed when the fuel jet velocity was less than that of coflow air in heavy hydrocarbon fuels [15–17].

For the validation of various combustion models, boundary conditions (BCs) in a simulation should be accurately specified. The inlet BC adopted in simulations for axial fuel velocity in a coflow burner usually has either a uniform or parabolic profile. Due to the strong effect of buoyancy on burnt gas, the centerline velocity in a coflow diffusion flame could reach $O(1\text{ m/s})$ when the fuel and coflow velocities are $O(0.01\text{ m/s})$ and the nozzle diameter is $O(1\text{ cm})$ [17]. For this reason, it has been suggested that a simple uniform or parabolic inlet velocity profile at the nozzle exit may be enough for predicting the overall flow-field [5,16]. However, a systematic test to confirm the near-nozzle flow-field in small coflow diffusion flames has not yet been conducted, particularly when considering the fuel density effect.

In this regard, we investigated the hydrodynamic structure of small coflow diffusion flames with various gaseous hydrocarbon fuels, taking into consideration the density difference compared with air. A complex recirculation zone structure is reported near the exit of the nozzle for fuels heavier than air. By adopting numerical simulations, the location of the inlet BC for fuel is found to be important for the accurate prediction of the experimentally observed flow-field. More importantly, the calculated temperature field can also be influenced appreciably by the location of the inlet BC.

2. Experiment

A coflow burner was used. The fuel nozzle consisted of a stainless steel tube with an inner diameter (d) of 10.8 mm and a thickness of 1.0 mm, a typical nozzle size in studying coflow diffusion flames [5]. The length of the nozzle was 855 mm to allow for the flow to be fully developed in the laminar regime. The coflow air was passed through plastic beads and a ceramic honeycomb so that the flow was reasonably uniform.

The fuels tested were methane, ethylene, propane, and n-butane (>99.5%). Compressed air was used for the coflow, which was set at 6.2 cm/s. Mass flow controllers were used for the control of the flow rate. The flame heights (defined by the soot luminous zone) for the fuels were maintained near 4.3 cm such that the mean fuel jet velocities (u_{jet}) were 4.45, 2.21, 1.40, and 1.05 cm/s for methane, ethylene, propane, and n-butane, respectively. Once the burner was thermally stabilized after sufficient time from ignition, no flame oscillation was encountered for any of the tested fuels.

An Ar-ion laser (Spectra-Physics, Stabilite2017) at 488 nm with a power of 1.5 W was used with TiO_2 particle (~0.2 μm) seeding to visualize the qualitative flow patterns of the fuel jets. A set of micro-lenses (Leica, Z16APO) was used for magnification with a digital camera. A double-pulse high-speed PIV system (LaVision, 3DFlowMaster) was used for flow-field characterization. Based on an empirical formula for a velocity shift due to gravity acting on seed particles, negligible measurement error could be guaranteed even at such low jet velocities [18].

3. Results and discussion

3.1. Flow characteristics

Photographs of the visible flames (1/500 s exposure time, F6.3) are shown in Fig. 1. The visible flame heights are approximately the same and no noticeable differences were found, except in the intensity and distribution of the yellow luminous zones. The variation in the brightness is due to fuel-specific sooting characteristics; methane (ethylene) has less (more) sooting compared with propane and n-butane [19]. These images were captured after twenty minutes of operation, such that the nozzle would be expected to have reached its thermal steady-state.

In Fig. 2, the near-nozzle flow-field is visualized from the pathlines of the seed particles by the Ar-ion laser with the exposure time of 1/160 s, together with the PIV data (with a time interval of $\Delta t = 500$ μs). In all cases, the pathlines are bent towards the centerline, an indication of strong buoyancy and acceleration of the axial

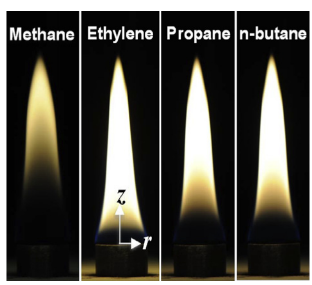

Fig. 1. Photographs of flames tested.

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