Combustion and Flame 191 (2018) 66–75

Contents lists available at ScienceDirect

Combustion and Flame

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

# Near-field flow stability of buoyant methane/air inverse diffusion flames

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ARTICLE INFO

*Article history:*
Received 13 September 2017
Revised 5 January 2018
Accepted 5 January 2018

*Keywords:*
Inverse diffusion flame
Buoyancy
Near-field
Shear flow
Instability

ABSTRACT

Experiment and simulation were performed to investigate buoyant methane/air inverse diffusion flames, with emphasis on the near-field flow dynamics under non-reacting and reacting conditions. In the non-reacting flow, the initial shear flow and the buoyancy effect induce opposite-direction vortices, which interact with each other and cause flow instability similar to the mechanism forming the von Karman vortex street. The instability is greatly intensified at around unity Richardson number, when the two vortices are comparably strong. In the reacting flows, the density gradient is reversed due to chemical heat release and so is the buoyancy-induced vortex that has the same direction with the vortex of the initial shear flow. As a result, the buoyancy-induced vorticity generation would facilitate the growth of the initial shear layer, thus the near-field flow remains stable. However, the growing shear flow would eventually lead to the development of the Kelvin–Helmholtz instability in the far field.

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## 1. Introduction

Buoyant diffusion flames exist in a wide range of industrial combustion devices and accidental fires. The research of buoyant diffusion flames is of great significance in optimizing combustion performance, controlling environmental pollution and reducing fire damage. In buoyant diffusion flames, flow instability and laminar-turbulent transition are evident in the near-field where fuel and air mix with each other [1]. The distinct flow and flame dynamics of buoyant diffusion flames have been attributed to combustion heat release, fuel–air density difference, and fuel and air Reynolds numbers [2–4], where the former two are the main factors contributing to the buoyancy effect and greatly influence the flame dynamics at low Reynolds numbers [5].

A number of investigations have been performed to understand the flame or flow instabilities of buoyant normal diffusion flames (NDFs) [6–10], where the flames oscillate at the relatively low frequencies typical of 10–20 Hz [6,11,12]. It was also found that the oscillation frequency is slightly affected by the fuel type, the fuel nozzle size, or the fuel inlet velocity [1,13–17]. Because of the coupling of inertial instability, buoyancy, vortex dynamics, and chemical heat release, it is usually difficult to isolate one factor from another in the study of buoyant NDFs. As a result, the existing literature does not consent on the mechanism of the flow and flame instability in reacting or even non-reacting conditions [18]. Cetegen and Kasper [19] attributed buoyant flow instability to Rayleigh–Taylor instability, but Coats [1] and Buckmaster and Peters [20] to Kelvin–Helmholtz instability. Buckmaster and Peters [20] proposed that the buoyant flow instability is a convective instability that is controlled by the thermomechanical properties of the hot and cold gases under the gravitational acceleration, but others considered the buoyant flows absolutely unstable [21–23]. Jiang and Luo [2,24–26] studied the formation of large vortex structures in buoyant reactive plumes and found that the enhanced tendency of flow transition to turbulence in buoyant NDFs is due to combustion induced buoyancy, in contrast to the relaminarization effect of chemical exothermicity in non-buoyant NDFs.

Inverse diffusion flames (IDFs), where oxidizer is surrounded by fuel in contrast to fuel being surrounded by air in NDFs, have been extensively investigated in laboratory with emphasis on soot formation [27–30]. However, to the authors' knowledge, relatively limited research attention was focused on the flow and flame dynamics in IDFs. Santoro et al. [31] assumed that the flow field in IDFs is similar to that of NDFs, in which air co-flow entrainment dominates the near-field of the flame base and results in a radial inflow from the side of the main injection together with a vertical buoyant flow. Blevins et al. [32] gave a schematic of the IDF flow field, where the inward flow in the near-field has a slight expansion, resulting in a small radial out flow after a short distance of development. By using laser Doppler velocimetry, Kang

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https://doi.org/10.1016/j.combustflame.2018.01.009
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et al. [33] found that the air flow in IDF tends to move outward to the fuel side. Shaddix and Williams [34] provided the velocity field data for ethylene IDFs and used the velocity data for soot formation analysis. Recently, Sen et al. [35] adopted dynamic systems analysis to understand the connection between flame dynamics and thermoacoustic characteristics of a ducted IDF. In spite of these worthy studies, limited details were provided on the flow or flame oscillation of IDFs in most literature.

In their early study, Wu and Essenhigh [36] gave a detailed map for the structure of methane IDFs. They found that, with a very low fuel inlet velocity (<1 cm/s), the IDFs started to oscillate with a frequency of 1–2 Hz, probably because of the relatively important buoyancy effect. Katta et al. [37] investigated the dynamics of an IDF, for which the main focus was on the role of flow dynamics in the polycyclic-aromatic-hydrocarbon (PAH) and soot formation. According to their simulation results, the advection of vorticities at 17.2 Hz enhanced the mixing of the species and contributed to a more uniform distribution of PAH in the downstream. In both works, no further analysis was provided to address the flame or flow dynamics of the IDF, e.g. the main factor determining the instability.

IDFs have been recently adopted in synthesizing carbon nanotubes (CNTs) [38,39], for which an unstable flow may deactivate the catalyst particles by the transportation of polycyclic aromatic hydrocarbons(PAH) or soot to the catalytic substrate, thus impeding the growth or degrading the purity of CNTs [40]. Since flow exerts an important influence on soot formation of IDFs [29,34] and flow instability may cause difficulty to accurate soot sampling [28,41], it is necessary to understand the IDFs from the flow dynamics perspective [31–33,36].

In the present study, the non-reacting and reacting flows of methane/air IDFs were examined through both experiment and numerical simulation. Particle image velocimetry (PIV) system was used for the measurement of non-reacting flows. Large eddy simulation (LES), which has been sufficiently validated by the PIV experiment, was applied to analyze the unsteady flow and flame dynamics. The main goal of the study is to explore the fundamental physics responsible for the flow and flame oscillations in buoyant IDFs. The structure of the paper is organized as follows. Experimental facilities are described in Section 2, followed by experimental observations of flow and flame oscillation in Section 3 and the specifications of the present LES in Section 4. Results and detailed discussions for the non-reacting and reacting flows are provided in Sections 5 and 6, respectively.

## 2. Experimental specifications

In the present work, a co-annular burner consisting of two concentric stainless-steel tubes was built up to generate IDFs, similar to that used by Sidebotham and Glassman [41]. As shown in Fig. 1, the air flow is injected through the central tube with a diameter of 10 mm and a length of 200 mm, and the fuel flow is injected through the annulus between the outer tube and the central tube. The tip of the central tube is sharpened to 0.3 mm thickness to reduce the blockage effect that causes wake. The upper segment of the central tube is encircled by the outer tube, which has an inner diameter of 40 mm, a thickness of 15 mm, and a length of 150 mm. To create a uniform inflow velocity profile for the injecting fuel, the annulus is filled with steel wire gauze and small steel beads which was also adopted by Sidebotham and Glassman [41]. To isolate the flames from the ambient oxygen, a quartz glass tube is installed above the burner to serve as a chimney. The tube has the same diameter as the outer burner tube with a length of 300 mm.

The air flow is supplied by a compressed air tank, which has a capacity of 320 L and a maximum working pressure of 18.9 bar. A central air supply system is used to deliver air to the tank while maintaining pressure. Pure methane (purity 99.9%) stored in Dewar tanks is released to provide the fuel flow. Pressure control valves and flow meters are combined to control and monitor air and fuel flow rates. The laboratory conditions for all the present experiments were 293 K and 101 kPa.

PIV measurement was employed to obtain the non-reacting flow field information and hence to validate the present LES results. A schematic of the PIV system is shown in Fig. 1(b), where the IDF burner is mounted vertically. The fuel flow is injected directly into the outer annulus, whereas the air flow is pre-mixed with PIV particles in a separate tank before entering the central air tube. A Quantel dual cavity Nd:Yag laser (EverGreen 600 mJ/pulse, 532 nm wavelength) is used to generate laser pulses at 5 Hz. The point laser beam is transformed into a plane laser sheet through a series of sheet forming optics. By adjusting the angle of the mirror placed above the burner, the laser sheet is aligned with the axis of the burner to enable the flow measurement in the *xy*-plane, as shown in Fig. 1(b). A TSI Incorporated$^{TM}$ 9307-6 aerosol generator is applied to generate olive oil droplets of 1 µm diameter to seed the air flow. The PIV images are captured by a high-speed camera (Hisense 4 M, 2048 × 2048 pixels), which is synchronized with a Berkeley Nucleonics Corporation 575 pulse/delay generator, and the time delay between two frames is fixed at 200 µs. The spatial resolution for the present PIV measurement is 37 pixels/mm. The PIV images are processed by the Dantec Dynamic Studio software to obtain the corresponding velocity data.

For visualizing the reacting IDFs, the flow and flame images are captured using a digital camera (Nikon D5200) and a lens (Tamaon 1800 mm Macro 1:1). The aperture is adjusted to f5.6 and the IOS value was fixed at 1000 to reduce the interference of external light. The exposure time for flame image is 1/10 s for all of the flame images in the present work.

## 3. Experimental observations of flow and flame oscillation

The first experimental evidence for oscillation of IDFs was reported by Wu and Essenhigh [36], who found that with sufficiently low fuel velocity the IDFs would become unsteady and start to oscillate. Following their observation, we reproduced a series of oscillating IDFs and present the instantaneous flame images for a representative case in Fig. 2. To characterize the air and fuel inlet flows, we defined two Reynolds numbers by

$$Re_i = \frac{\rho_i v_i d_i}{\mu_i}, \quad Re_o = \frac{\rho_o v_o d_o}{\mu_o}, \tag{1}$$

where $\rho$, $v$, and $\mu$ are the density, velocity, and viscosity; the subscripts $i$ and $o$ represent the properties for the air and fuel flows; $d_i$ and $d_o$ are the inner diameters of the center air tube and the outer fuel tube. For the IDF in Fig. 2, the air inlet velocity is $v_i = 30$ cm/s ($Re_i = 192$) and the fuel inlet velocity is $v_o = 2$ cm/s ($Re_o = 46$). It is observed that flame oscillation only occurs in the upper portion (i.e. the yellow cap) of the flame, where the direction of the flame tip swings and the height varies, while the blue region at the bottom remains stable.

To understand the source of flame oscillation, we also examined the non-reacting flow characteristics for comparison. Here, the non-reacting flow refers to the one with the same flow conditions as Fig. 2 but without ignition. Fig. 3 shows the instantaneous non-dimensional vorticity ($\tilde{\Omega}_z$) contour obtained from the PIV measurement for the non-reacting flow, hereinafter, the non-dimensional vorticity is defined as $\tilde{\Omega}_z = \frac{\Omega_z}{2v_i/d_i}$. It is seen that the flow is also highly unsteady as the shear layer between fuel and air wiggles and deforms dramatically. Qualitatively, the non-reacting flow seems to be more unstable than the reacting flow as the bottom half of the shear layer also tends to be unsteady. Further justification for this observation will be provided in Sections 5 and 6. In

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