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Experimental investigation of coflow effect on the ignition process of a methane jet diffusion flame

Qian Wang[a,*], Yang Zhang[b], C.Y. Zhao[a]

[a] School of Mechanical Engineering, Shanghai Jiao Tong University, Shanghai 200240, China
[b] Department of Mechanical Engineering, the University of Sheffield, Sheffield S1 3JD, UK

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ABSTRACT

The coflow air effect on the ignition process of a methane jet diffusion flame has been investigated using high speed colour/schlieren imaging and image processing techniques experimentally. The methane flow rate is kept at constant (Re = 55.4), while the coflow air flow rate changes (Re from 171 to 5985), creating a wide range of the air/fuel velocity ratios varying from 0.36 to 12.5. Special digital image processing techniques are applied to visualise the weak blue flame and weak yellow flame, which is often difficult to view in the presence of the bright orange diffusion flame, during ignition process. The processed images have shown clearly that a sooty diffusion flame is initially formed inside a blue flame pocket at low air velocities. When the coflow air flow rate exceeds 75 l/min, only blue flame can be observed. The equivalence ratio of blue flame has been evaluated based on colour characteristics, which is close to 1 during the ignition process for all the cases. Moreover, the fuel flow, flame and hot gas interactions with the cold air flow are investigated by visualising the schlieren images. It is found that a hot gas bulge is formed due to the excessive fuel exiting before ignition and a hot laminar central jet is formed with the help of coflow effect. The hot gas bulge tip and bottom moving velocities are found to increase with the coflow air flow rates. Besides flow visualisation based on high-speed schlieren imaging sequences, the velocity fields during ignition process have been evaluated quantitatively using optical flow method.

1. Introduction

Laminar gas jet diffusion flames have been intensively studied in combustion science [1–6]. Diffusion flames are widely used in industrial systems for safety consideration, since the oxidizer and fuel can be stored separately. In order to improve the stability of diffusion flames, adding coflow is often considered to be an effective and easy implementation method. Characteristics of diffusion flames in laminar jets have been investigated extensively to understand the stabilization mechanism both for lifted and attached flames. The lift-off characteristics in coflow jets with highly diluted propane were studied experimentally [7]. The gravity effects on the oscillation mechanisms of a lifted flame have been tackled under coflow conditions in [8]. A combined computational and experimental investigation that examines the relationship of soot and NO formation in coflow ethylene air diffusion flames is presented in [9]. The coflow effect on the interaction between the visible flame and outside vortices of the non-lifted methane diffusion flames have been studied systematically through experimental visualisation methods [10]. It is found that coflow air can help to push the initiation point of toroidal vortex to exceed the flame tip; the flame oscillation induced by the vortex is then suppressed. However, the aforementioned research mainly focused on the well-established flame dynamics; the ignition process of diffusion flame with coflow is rarely studied.

The ignition of a flammable mixture is a fundamental problem in the field of combustion science, which involves complex chemical reactions and flow variations. Many technological applications requires detailed investigation on the combustion transition from a non-reacting (forced ignition) or a slow reacting state (auto ignition) to a fully burning state; for example, the relighting of an aviation gas turbine, the spark-ignition engine and diesel engine, etc. The initiation of turbulent non-premixed flames through auto ignition and spark ignition has been reviewed by Mastorakos [11]. Phuoc et al. [12] investigated the laser spark ignition of a jet diffusion flame experimentally. It is reported that the success of ignition depends on whether the spark initiated reacting gas could undergo a transition from hot plasma to a propagating flame or not. The simulation work by Richardson and Mastorakos [13] indicates that the ignition can be prohibited by excessive strain rates in a non-premixed flame. The ignition and flame propagation of a methane-air triple flame in a partially premixed jet is investigated experimentally

* Corresponding author.
E-mail address: qianwang@sjtu.edu.cn (Q. Wang).

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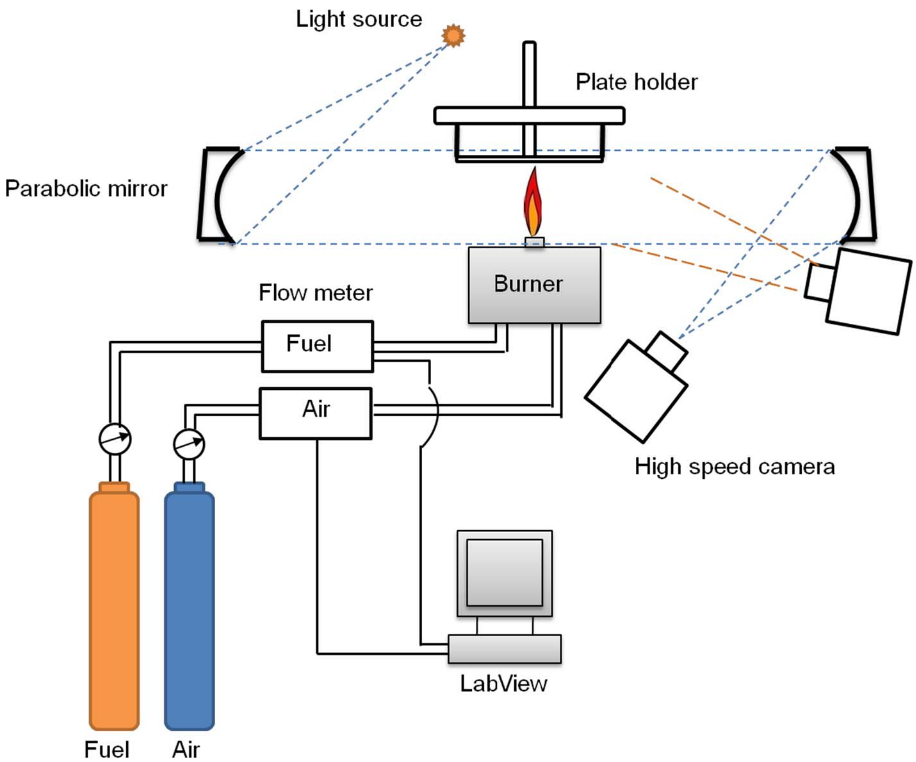

Fig. 1. Schematic of the experimental setup.

Table 1
Test conditions.

Gas type	Volume flow rate (l/min)	Velocity (m/s)	Re No.	V_a/V_f [a]
Methane(CH4)	0.182	0.216	55.4	/
Air	5	0.077	171	0.36
Air	14	0.216	479	1.00
Air	25	0.385	855	1.78
Air	50	0.772	1710	3.56
Air	75	1.155	2565	5.34
Air	100	1.540	3420	7.13
Air	125	1.925	4275	8.91
Air	150	2.310	5130	10.7
Air	175	2.695	5985	12.5

[a] V_a: co-flow air velocity; V_f: fuel velocity.

and numerically by Qin et al. [14]. It is found that during the flame propagation process, the curvature-induced stretch dominates over the hydrodynamic stretch and the flame speed decreases with the increase of stretch rate. Zhang and Bray [15] reported that different flame patterns can be formed under identical flow conditions only by varying the ignition place for a methane impinging flame. The ignition process of methane and propane diffusion impinging flame was further investigated by Wang and Huang [16,17] through high speed colour/schlieren and image processing techniques. It is found that the ignition process is sensitive to plate-to-nozzle height, fuel flow rate, ignition position and fuel type. Most of the aforementioned ignition studies focus on minimum ignition energy, strain rates effect and ignition probability, with most of which only considering premixed flames. For non-premixed flames, the forced ignition process is more complicated, as confirmed by both simulations and experiments. The experimental ignition data under particular flow conditions may help to gain more physical insights into the understanding of non-premixed ignition process. In this study, the coflow air effect on the ignition process of methane diffusion flame is explored experimentally, which has not been reported to the best knowledge of the authors.

A modern high-speed colour camera is not only able to visualise the behaviours of time-dependent flame structure evolution but also provides dynamic information on the flame colour change. For hydrocarbon flames, the visible emanating energy can be attributed to the spectra of electronically excited combustion radicals CH^* (430 nm), C_2^* (C_2^* Swan system, dominant emissive band head at 473.71 nm and 516.52 nm), CN^* (350–380 nm) and the continuous spectrum from solid carbon/soot [18]. The intensity of the energy released by these spectra is related to a number of factors such as burning condition, fuel composition and fuel-to-oxidizer ratio, which would consequently affect the colour perceived from a given flame. Thus, the colour of a flame can be used to provide information on its general spectrometric composition.