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Highly stabilized partially premixed flames of propane in a concentric flow conical nozzle burner with coflow

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ABSTRACT

Partially premixed turbulent flames with non-homogeneous jet of propane were generated in a concentric flow conical nozzle burner in order to investigate the effect of the coflow on the stability and flame structure. The flame stability is first mapped and then high-speed stereoscopic particle image velocimetry, SPIV, plus OH planar laser-induced fluorescence, OH-PLIF, measurements were conducted on a subset of four flames. The jet equivalence ratio $\Phi = 2$, Jet exit Reynolds number $Re = 10{,}000$, and degree of premixing are kept constant for the selected flames, while the coflow velocity, Uc, is progressively changed from 0 to 15 m/s. The results showed that the flame is stable between two extinction limits of mixture inhomogeneity, and the optimum stability is obtained at certain degree of mixture inhomogeneity. Increasing Φ, increases the span between these two extinction limits, while these limits converge to a single point (corresponding to optimum mixture inhomogeneity) with increasing *Re*. Regardless the value of Φ, increasing the coflow velocity improves the flame stability. The correlation between recessed distance of the burner tubes and the fluctuation of the mixture fraction, $\Delta\xi$, shows that at $\Delta\xi$ around 40% of the flammability limits leads to optimum flame stability. The time averaged SPIV results show that the coflow induces a big annular recirculation zone surrounds the jet flames. The size and the location of this zone is seen to be sensitive to Uc. However, the instantaneous images show the existence of a small vortical structure close to the shear layer, where the flame resides there in the case of no-coflow. These small vertical structures are seen playing a vital role in the flame structure, and increasing the flame corrugation close to the nozzle exit. Increasing the coflow velocity expands the central jet at the expense of the jet velocity, and drags the flame in the early flame regions towards the recirculation zone, where the flame tracks and matches the spatial locations of low axial velocity fluctuations. At downstream, the flame is seen to conform to the passage of large scale structure. At Uc = 10 and 15 m/s, part of the primary reaction zone is rolled up towards upstream burner nozzle, anchoring the flame to the nozzle tip. This indicates that the stabilization of these flames in the presence of the coflow is controlled by the mutual interactions between the central jet and the coflow through the recirculation zone from one side, and the degree of the inhomogeneity of the central jet mixture from the other side.

1. Introduction

Investigation of turbulent partially premixed flames with inhomogeneous mixing field has attracted many research groups during the last few decades (see Masri [1] for detailed review) because these flames represent the turbulent combustion mode in many practical combustion systems. This mode is affected by the degree of partial premixing and thus it covers a wide range of combustion regimes between the non-premixed and fully premixed modes of combustion [2]. The methods of generating turbulent partially premixed flames with well-defined inhomogeneous mixing field structure are very limited in the literature. Among those methods are the reverse flow reactor with multi side fuel jets into air jet [3], and the concentric flow burner [4–6]. The advantage of the latter burner design is the simple control mechanism providing a wide range of partial premixing and the well-defined boundary conditions. Recently, Thong et al. [7–9] have investigated the structure of the mixing field using multilateral fuel jets in a turbulent jet flow, similar to Mansour et al. [3]. Their flames are more

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Nomenclature

D	outer tube inner diameter, mm
L	mixing length or recess distance, mm
r	radial distance, mm
Uc	coflow velocity, m/s
V	mean axial velocity, m/s
V_{cen}	mean axial centerline velocity, m/s
V_{jet}	axial jet velocity, m/s
Z	axial distance, mm
ξ	mixture fraction
Φ	jet equivalence ratio

stable than those generated in the concentric flow burners. However, the mixing control mechanism is not simple to cover wide range of partially premixed flames like the concentric burner. Counter flow burners [10,11] were used earlier to generate partially premixed flames but the mixing field in those flames does not represent the inhomogeneous structure of practical combustion systems.

The published data of turbulent partially premixed flames with inhomogeneous mixing field are not sufficient to fully describe the flame structure within the expected different regimes of partially premixed flames. Previous experimental investigations covered the stability of partially premixed flames as compared to non-premixed and fully premixed flames [6,12–16]. The data showed that partially premixed flames are more stable than both non-premixed and fully premixed flames [12]. Our research group covered several turbulent partially premixed methane flames with inhomogeneous mixing field in a concentric flow conical nozzle burner, CFCN, where different flame aspects were investigated, including the flow field structure [15,17], the flame structure [16,18–20] and, recently, the mixing field structure [21]. Masri and his research group have also investigated turbulent partially premixed flames of methane and natural gas in a piloted concentric flow burner [1,6,13,22]. The stability characteristics of both burners are quite similar although the stabilization mechanism is different. This indicates that the stability depends on the nature and level of inhomogeneity of the jet at the nozzle exit. The conical nozzle in the first burner [4] and the pilot in the second burner [6] improve the range of stability but do not change the trend of the stability. Mansour et al. [21] have recently provided a detailed investigation of the effect of the mixing field characteristics on the stability and flame structure. They concluded that the range of fluctuations of mixture fraction has a significant effect on the flame stability where the most stabilized flames are created for a range of fluctuations within the flammability limits. Our previous investigations addressed the stability characteristics, flow field and flame structure of turbulent partially premixed flames of methane with inhomogeneous mixing field at the nozzle exit [12,15,16,21]. The species distribution, temperature field, and stability of LPG partial premixed flames stabilized in the CFCN burner have been investigated by Elbaz [23] However, more detailed studies are required in different flames for different fuels in order to cover a wide range of partially premixed flames.

Accordingly, the aim of this work is to further study turbulent partially premixed propane flames created in the CFCN burner with air coflow. The effects of the jet mean equivalence, Φ and the air coflow velocity, Uc, on the flame stability are first investigated. After characterization of the flame stability, the flow field and flame structure are studied in details using high speed measurements of the flow field and OH field, seeking understanding of the physical effects of the flame dynamic/flow fields interaction on the flame stability in the presence of air coflow. These measurements are conducted on four flames at jet Reynolds numbers, *Re*, of 10,000, Φ = 2, and certain level of mixture inhomogeneity, but with various Uc between 0 and 15 m/s.

2. Burner and experimental setup

2.1. The concentric flow conical nozzle burner (CFCN) with coflow

A detailed description of the CFCN burner is published in [15,21]. The burner, is shown in Fig. 1a, consists of two concentric tubes of 4 mm and 9.7 mm inner diameters with a lip thickness of 1 mm and 1.5 mm, respectively. The air flows through the inner tube, while propane passes through the outer tube. The inner tube can be recessed within the outer fuel tube, creating variable level of fuel-air mixing at the exit of the outer tube. The level of inhomogeneity is controlled by

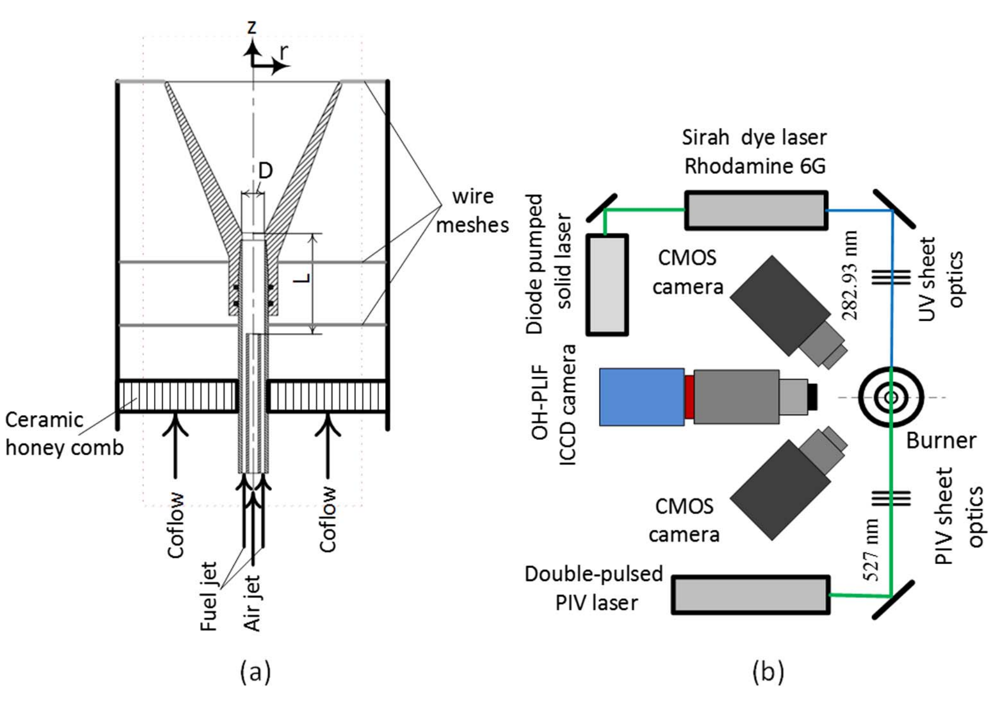

Fig. 1. (a) Concentric flow conical nozzle burner, CFCN, with air coflow arrangement, (b) Experimental set up.