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The flow field structure of highly stabilized partially premixed flames in a concentric flow conical nozzle burner with coflow

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ABSTRACT

The stability limits, the stabilization mechanism, and the flow field structure of highly stabilized partially premixed methane flames in a concentric flow conical nozzle burner with air co-flow have been investigated and presented in this work. The stability map of partial premixed flames illustrates that the flames are stable between two extinction limits. A low extinction limit when partial premixed flames approach non-premixed flame conditions, and a high extinction limit, with the partial premixed flames approach fully premixed flame conditions. These two limits showed that the most stable flame conditions are achieved at a certain degree of partial premixed. The stability is improved by adding air co-flow. As the air co-flow velocity increases the most stable flames are those that approach fully premixed. The turbulent flow field of three flames at 0, 5, 10 m/s co-flow velocity are investigated using Stereo Particle Image Velocimetry (SPIV) in order to explore the improvement of the flame stability due to the use of air co-flow. The three flames are all at a jet equivalence ratio (Φ_j) of 2, fixed level of partial premixing and jet Reynolds number (Re_j) of 10,000. The use of co-flow results in the formation of two vortices at the cone exit. These vortices act like stabilization anchors for the flames to the nozzle tip. With these vortices in the flow field, the reaction zone shifts toward the reduced turbulence intensity at the nozzle rim of the cone. Interesting information about the structure of the flow field with and without co-flow are identified and reported in this work.

1. Introduction

Partially premixed combustion is prevalent in a wide range of applications for combustion devices: e.g., diesel engines, direct injection stratified charge engines, gas turbines, and some industrial burners. A partially premixed flame (PPF) is described as a hybrid flame possessing characteristics of both premixed and non-premixed flames covering a wide range of flames including “double,” “triple” and “edge” flames where mixture is compositionally inhomogeneous. PPF’s contain multiple reaction zones which are spatially separated but actually coupled through turbulence–chemistry interactions between them, and the flame structure is strongly dependent upon these interactions [1]. Partially premixed flames are likely to be more stable than premixed or non-premixed flames [2–4]. Different techniques have been used to stabilize these flames at the nozzle exit. Examples of these techniques include the partially premixed flames [2–5], the swirl flame [6–9], the pilot flame for non-premixed [10,11]; premixed [12], and flame holder [13,14].

A Concentric Flow Conical Nozzle (CFCN) burner has been developed and modified by Mansour [4,15] in order to create well-controlled and highly stabilized partially premixed flames. The higher stability characteristic of the CFCN burner, as compared to a nozzle jet burner, is due to the conical shape of the nozzle and control of the level of partial premixing. The effects of the degree of partial premixing, the cone angle and the jet equivalence ratio on the flame stability and structure have previously been investigated [16]. Measurements and numerical study were conducted inside and downstream the conical nozzle in order to explore the stabilization mechanism and investigate the flame structure of partially premixed flames [17,18] under different equivalence ratios and degrees of partial premixed. They [17,18] concluded that the stabilization mechanism of the flames within the CFCN for high Reynolds number flames was due to a stream of air being entrained

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Nomenclature

Re	Reynolds number	V_{cen}	centerline velocity
Re_j	Reynolds number for the jet mixture	V_o	velocity at the exit of the nozzle
V	axial velocity at any radial location	V_{rms}	rms of axial velocity
V_a	axial air velocity at the exit of air tube	$V_{cen\ rms}$	rms of the axial velocity at the centerline
V_c	co-flow exit velocity	r	radial distance from centerline
V_f	fuel jet velocity at exit of the fuel tube	Z	vertical axial distance
V_j	mixture velocity at the exit of the outer tube	Φ_j	mixture equivalence ratio

along the conical nozzle wall and heated by the flame before being entrained into the early region of the flame. Additionally, they observed a recirculation zone of hot combustion products at the conical nozzle base. Thus the conical nozzle provides a good stabilization environment. In addition, an optimum level of partial premixing for the highest stability can be achieved in this burner [16]. The temperature and gas species concentrations inside and downstream the nozzle are investigated by Elbaz [19] for Liquid Petroleum Gas (LPG) partial premixed flames. This work [19] showed the same conclusions regarding the flame stability mechanism.

Large capacity burners are usually equipped with a blower for air supply. The effect of co-flow on the partial premixed flames stabilized in the conical nozzle has not yet been investigated. In addition, modeling of the burner requires quantitative data with well-known boundary conditions. With this incentive the main objective of this study is to investigate the effects of the co-flow on the flame stability and the flow field structure of turbulent partially premixed flames within the CFCN burner. The stability mapped is scanned for different degree of partial premixing and different co-flow velocities. The turbulent flow fields for partially premixed flames with and without co-flow are recorded and investigated in this work using a stereo PIV set up.

2. Experimental setup and measurement technique

2.1. Burner

The process of introducing partial premixing (inhomogeneity) is rather simple and involves two concentric pipes where the inner pipe is recessed to various distances upstream of the jet exit plane. Air passes through the inner tube while fuel (methane) passes through the annular gap between the inner and the outer tubes, as shown in Fig. 1a. The inner diameter of the inner tube "*d*" is 4 mm with 1 mm lip thickness, while the inner diameter of the outer tube "*D*" is 9.7 mm with 1.5 mm lip thickness.

The mixing between the air and the fuel starts at the exit of the inner tube and continuous downstream through the premixing length "*L*," as shown in Fig. 1b. The level of partial premixing varies by varying the distance *L*. The parameter L/D is used to describe several states of partial premixing, when the inner tube is sufficiently recessed ($L/D > 30$), the fuel and air become homogeneously mixed and the mixture is considered fully premixed. The other extreme, when both tubes are flush ($L/D = 0$), represents the non-premixed limit. The interesting partial premixed flame conditions lie between these two limits where the issuing mixtures are rather compositionally inhomogeneous. To stabilize the issuing flames, a divergent conical nozzle with a half cone angle of 26° is used at the exit of the outer tube. The length of the cone is 65 mm with a 73 mm exit diameter. The burner is located in a cylindrical wind tunnel, as shown in Fig. 1b, that provides a uniform co-flowing air from a blower. The co-flowing air velocity in the present measurements varies from 0 m/s to 15 m/s with steps of 5 m/s. The case of 0 m/s co-flow velocity is the reference case of the absence of co-flow.

2.2. Experimental technique

A stereo PIV system is used to measure the flow field structure of partial premixed flames issuing from CFCN burner. The stereo-PIV system is based on a dual cavity, diode-pumped, solid state Neodymium-doped Yttrium Lithium Fluorides (Nd:YLF) laser (LDY 300 Series) and a pair of high-speed complementary metal-oxide-semiconductor (CMOS) cameras (LaVision, Image Pro HS 4M). The laser beam wavelength is 527 nm and its power is 35 W per head at a repetition rate up to 10 kHz, with 9 ns pulse duration. The laser beam was formed into a sheet with a 0.5-mm waist along the jet centerline using three cylindrical lenses. The air and fuel jets were both seeded with titanium dioxide (TiO_2) particles with a nominal diameter of 0.5 μm via two seeding fluidized bed units. Mie scattered light from the particle-laden flow was collected using a 105 mm, f/4 objective (Nikon UV Micro-Nikkor) equipped with a 527 nm band pass filter. Two cameras were mounted equidistant from the centerline of the burner with an angle of separation of 35°. The camera was operated in two-frame burst mode at 500 fps. Image-blur due to off-axis defocusing was corrected using Scheimpflug adaptors between the objectives and the cameras. Perspective distortion was corrected using a dual plane, three-dimensional imaging target (LaVision type 22). Image de-warping between the two camera images was corrected using the image correction and distortion function. Also, with the self-calibration function, the coordinate system and the camera calibration of this stereoscopic PIV setup were adjusted so that the $Y = 0$ mm plane (see Fig. 1 for coordinates) was adjusted exactly in the middle of the laser light sheet. Vector fields were computed from particle image spatial cross correlations using the La Vision Davis 8.1 software package. An adaptive multi-pass vector evaluation technique was used, with interrogation boxes ranging from 128 pixels to 16 pixels, with 50% overlap resulting in spatial resolution and vector spacing of approximately 0.5 × 0.5 mm and 0.25 mm, respectively. The final velocity vector fields were smoothed with a 3 × 3 vector moving average filter for subsequent analysis.

3. Results and discussion

3.1. Stability limits, selected flames, and flame appearance

The stability characteristics of an earlier version of the CFCN burner indicated that partially premixed flames are more stable than premixed or non-premixed flames, and that the level of partial premixing is a critical flame stability parameter [4]. The flames created within the CFCN burner exhibit high stability levels because of the conical shape of the nozzle and the degree of partial premixing. The stability limits that were reported in