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Brief Communications

Visualization of multi-regime turbulent combustion in swirl-stabilized lean premixed flames

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ABSTRACT

Simultaneous two-species imaging using single-shot planar laser-induced fluorescence have been performed to record high quality image pairs of CH/OH, CH/CH_2O and OH/CH_2O to visualize the flame front structures in swirl-stabilized lean premixed methane/air flames. The results show that the investigated flames exhibit various flame front structures distinctly in space, which covers: (1) the corrugated flamelet at the leading front; (2) the thin reaction-zone layer with distorted preheat zone in the shear-layer downstream; and (3) quenching, re-ignition and distributed reactions further downstream. The large variation of the flame characteristics in space stems from the entrainment of ambient cold air to the flame that results in flame quenching at the trailing edge of the flame. Thereafter, the unburned fuel/air mixture in the downstream region mixes with the entrained air and the hot combustion products from the upstream leading flame front, leading to reignition with distributed reactions. The current results provide a direct experimental evidence that distributed reactions can be a common combustion mode along with the results (Ref. [1], Zhou et al., 2015) recently reported in the highly turbulent premixed jet flames.

1. Introduction

Low-swirl stabilized, lean premixed flames (hereafter named as LSFs) bear the advantage of low NO_x emission, stable flame operation and low noise; thus the LSFs have the potential to be employed for gas turbine applications [2–5]. Due to the relative simple experimental configuration, various experimental studies have been performed to investigate the fundamentals of the flow dynamics [6–8] and flame front structures [9–15] using laser Rayleigh scattering and planar laser-induced fluorescence (PLIF) of OH radicals in LSFs. Incorporated with these experimental measurements, numerical simulations have been carried out to elaborate the characteristics of LSFs [8,15–18]. Most of the experimental and numerical investigations have been focused on the region where the leading-flame-front (LFF) is stabilized, and the LFF has been shown to be thin and of typical laminar flamelet structure. In addition, both experimental measurements [7,16] and numerical simulations [18] indicate that extinction holes can appear at the flame-trailing-edge (FTE) region due to the ambient air entrainment. The fuel/air mixture diluted by the entrained ambient air can leak through the holes into the downstream regions and mix with the hot combustion products. The characteristic of the leaked unburned fuel/air mixture in the downstream region, however, has not been studied adequately by experiments. To investigate this, we perform simultaneous measurements of CH, OH and CH_2O in LSFs. The multi-scalar imaging techniques currently employed, including PLIF imaging of CH, CH_2O and OH, provide more comprehensive details for investigating the instantaneous turbulent flame structures [1]. In the present study, we focus on revealing key features of LSFs and the interplay of the mixing of hot combustion products, the unburned fuel/air mixture and ambient air through visualization of CH, CH_2O and OH species using PLIF.

2. Experimental

The low-swirl-burner (LSB) employed in present study at Lund University was developed cooperatively with Lawrence Berkeley National Laboratory and Technical University Darmstadt, serving the joint purpose of establishment of a collection of experimental data of turbulent premixed flames for model validation. Figure 1 shows a sketch of the burner. Details of the employed LSB configuration can be found in Refs. [7,8]. Two lean premixed methane/air flames (equivalence ratio, $\Phi = 0.62$) named as LSF-1 and LSF-2 with Reynolds number (Re) 20,000 (mean flow velocities of 6.2 m/s) and

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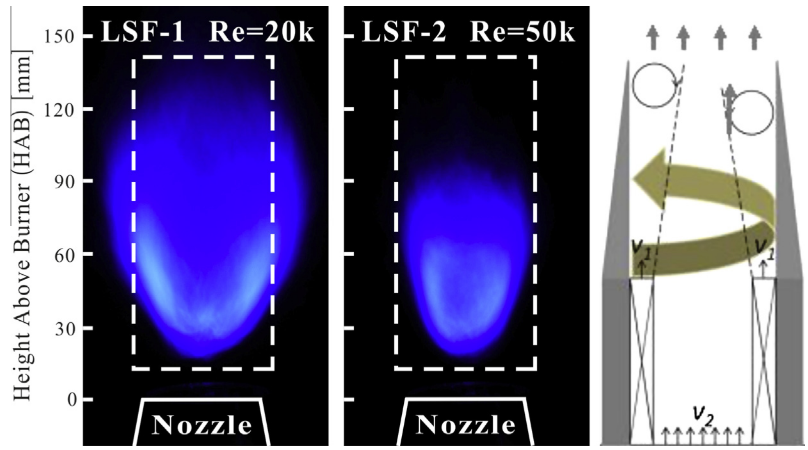

Fig. 1. Photograph of investigated flames, LSF-1 and LSF-2, taken with 200 ms exposure time. The dashed squares indicate the area that has been investigated using PLIF measurements. A sketch of the burner is shown to the right. Details of the burner configuration are referred to Refs. [7,15].

50,000 (mean flow velocities of 15.6 m/s), respectively, have been investigated here. The swirl number (see definition in Ref. [19]) of the burner employed is 0.55.

Three species, namely, CH (typical fuel-consumption reaction zone marker [20]), CH_2O (typical preheat zone marker [21]), and OH (typical oxidization and post-flame zone marker) have been selected for the PLIF measurements. An alexandrite laser (101 PAL, Light Age), an Nd:YAG laser (Quantel) and a dye laser (Cobra Stretch-G-2400) have been employed for the excitations of CH at 387 nm, CH_2O at 355 nm, and OH at 283 nm, respectively. The excitation–detection schemes for these three species adopted in Ref. [1] were utilized in this work. All the laser beams were spatially combined and shaped into a 45 mm laser sheet tightly focused on top of the LSB. The thickness of both the combined and the individual laser sheet was measured to be less than 150 μm using photon-sensitive paper. PLIF measurements of the three species have been conducted simultaneously in pairs (i.e. CH/OH, CH/CH_2O and OH/CH_2O). Two intensified CCD cameras (1024 × 1024 pixels, PIMAX III) were employed. An UV objective (B. Halle, f = 100 mm) was used for OH detection and a Nikon objective (f = 50 mm) for CH or CH_2O detection. The imaging size of both cameras was adjusted to be approximately 50 mm, and the recorded images from both cameras were spatially correlated pixel-by-pixel through imaging the same calibration target.

3. Results and discussion

Direct photographs of the two investigated flames, LSF-1 and LSF-2, are shown in Fig. 1. The two flames exhibit rather similar lift-off distance above the burner exit, while LSF-2 shows a significantly smaller flame chemiluminescence volume, which can be explained by the increased ambient air entrainment to the downstream of the flame as a result of the increased flow velocity at the burner exit. Based on the flow field measurements under similar flame conditions [8,18], the Karlovitz number (Ka) of the investigated flames has been estimated to be about unity at the LFF region and about 30 at the FTE region, thus the flame is in the corrugated flamelet/thin-reaction zone regimes of the Borghi diagram [22]. The region where the PLIF measurements have been performed was marked out by the dashed squares in Fig. 1, covering the LFF region (height above burner, HAB ~ 30 mm) and the FTE regions (~30 mm < HAB < 55 mm) and further downstream central region of the flame (HAB > 55 mm), where the leaked fuel/air mixture further diluted by the ambient air mixed with the hot combustion products from the LFF/FTE region. Figure 2 shows examples from three series of simultaneous PLIF images for LSF-1, i.e. (A) CH_2O/OH, (B) CH/OH and (C) CH/CH_2O. Each image consists of four independent instantaneous PLIF image pairs recorded at different HAB positions. It can be seen from Fig. 2(A1–A2) that the LFF of LSF-1 contains a thin CH_2O layer that partially overlaps with the high-gradient OH front, exhibiting a typical laminar flamelet structure. OH radicals prevail over a large area downstream of the LFF, signifying a region with hot combustion products where the mean temperature up to 1700 K has been measured [18]. Further downstream (HAB > 55 mm), CH_2O appears widely distributed in space with reduced peak signal level by a factor of ~2 comparing with that at the LFF, while OH appears in patchy regions where the CH_2O signal is hardly visible. In addition, from the previous acetone (as fuel marker) PLIF measurements [16], the leaked fuel has also been found to exist widely in the same region. The corresponding mean temperature (reported in Ref. [23]) along the central axis gradually decreases from 1600 K (at HAB = 55 mm) to 1000 K (at HAB = 140 mm) due to the entrainment of ambient air. These facts indicate that the leaked fuel continues to react into intermediate reactants such as CH_2O at the downstream regions where the overall temperature is still considerably high. More strikingly, Fig. 2(B and C) shows that the short-lived radicals CH can be distributed and coexists with CH_2O in wide regions downstream, while OH radicals appear not to be at a significant level in these CH and CH_2O regions. According to Driscoll [20], a distributed reaction zone can be experimentally evidenced by the observation of the distributed CH signals. At some downstream locations as marked by the circles in Fig. 2(C1–C2), CH signal disappears while CH_2O still survives, which likely signifies local quenching of distributed reactions due to the cooling of ambient air entrainment. These observations on distributed reactions are consistent with those recently reported in highly turbulent premixed jet flames [1]. Note that the occurrence of the distributed reactions also shares similarities with that of mild combustion [24] where reactants with low oxygen content were significantly heated by, for example, mixing with hot combustion products. As reported in Ref. [23], the mean oxygen concentration of LSF-1 at the regions showing distributed reactions were measured to be in the range from 9% to 15%.

The distributed CH radicals observed in LSFs can be explained by the following. The entrained ambient air in the FTE region and further downstream dilutes the leaked fuel/air mixture. The lower local equivalence ratio (<0.62) results in a lower combustion temperature and hence a longer time scale of local chemical reactions