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Coupled dynamics of lift-off and precessing vortex core formation in swirl flames

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ABSTRACT

The lift-off mechanism of swirl stabilized premixed flames was investigated using high repetition rate OH planar laser induced fluorescence (PLIF), particle image velocimetry (PIV), and OH* chemiluminescence. At steady operating conditions, the studied flames stochastically transitioned between attached and lifted configurations, with an increasing percentage of time spent in the detached state with increasing velocity. Neither the percentage of time spent in the detached state nor the final detachment conditions were predicted by the Damköhler number. The lift-off process involved several coupled phenomena, namely local flame extinction near the flame base, development of a helical precessing vortex core (PVC), and eventual total extinction of the flame base. Wavelet analysis demonstrated the correspondence between the flame lift-off height and the strength of the PVC. Furthermore, it showed that the initial local extinction preceded the PVC formation. Hence, the lift-off mechanism involved a stochastic local extinction event near the flame base altering the combustor density field and promoting formation of the PVC. The PVC increased the strain-rate on the flame base, which eventually led to total detachment.

1. Introduction

While lean premixed combustion often is used in power generation gas turbine engines to meet NO_X emission regulations, issues of flame stability remain a major practical challenge [1–8]. An important aspect of predicting flame stability is understanding the configurations in which the flame may stabilize in a gas turbine combustor and the mechanisms by which it transitions between configurations. This paper investigates such transitions.

Flame stabilization transition, including lift-off and blow-off, have been extensively studied in the past for bluff-body stabilized flames. Several studies have identified localized extinction, triggered by high local strain-rate/dissipation-rate on the flame sheet, as the first stage leading to the eventual blow-off [9–11]. Complete blow-off occurred when the strain-rate was sufficiently high that the heat release could not sustain reaction. It also was demonstrated that entrainment of unburned reactants into the recirculation zone and wake behind the bluff-body resulted in a transition to a hydrodynamically unstable flow field and emergence of a vortex shedding behavior that was previously suppressed by the heat release. This change in flow-field was associated with a change in the flame topology and large-scale unsteadiness approaching blow-off.

In gas turbine combustors, formation of recirculation zones by which to stabilize the flame often is achieved through vortex breakdown of swirling flow, as opposed to bluff-bodies [12–14]. Of particular importance is the central recirculation zone (CRZ), also sometimes termed the inner recirculation zone (IRZ), formed downstream of the nozzle exit, which provides a low-speed region in which the flame can anchor and serves as a continuous ignition source through recirculation of hot products [15]. Commonly reported swirl flame configurations include flames that are stabilized in the shear layers, and flames that are aerodynamically stabilized near the stagnation surface between the inflowing gas and the CRZ [16–18]. The former attach to some feature of the nozzle geometry, whereas the latter are lifted.

The specific aim of this paper is to elucidate the transition mechanism between attached and lifted swirl flames. Several different swirl-flame configurations often are reported in the literature, which are shown schematically in Fig. 1. The combustor studied here transitioned from the attached V-shaped flame (Fig. 1a) to the lifted M-shaped flame (Fig. 1b). An important aspect of this transition process is local flame extinction. Using high-speed laser diagnostics, Stöhr et al. examined the lift-off dynamics of partially premixed swirl flames [19]. They found that flame root extinction was closely related to the interactions between the flame and the precessing vortex core (PVC), which is a coherent structure that

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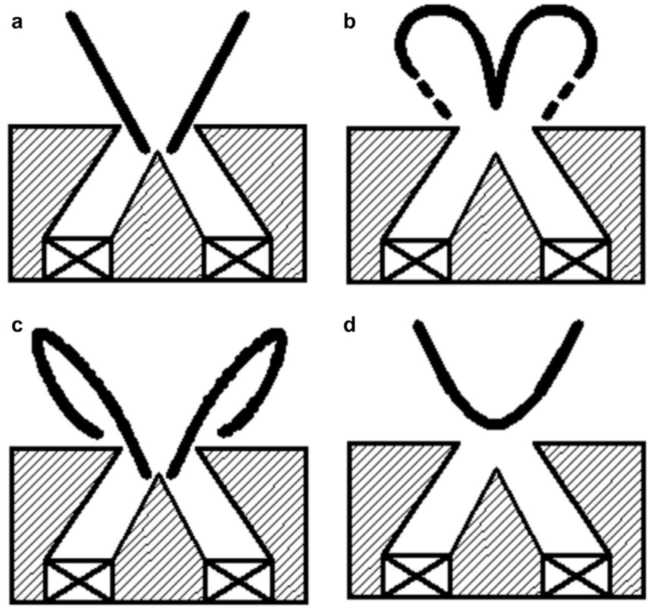

Fig. 1. Commonly reported swirl flame configurations, among which the transition from flame shape (a) to (b) is the focus of this study.

often occurs in swirling flows [20–25]. Based on a comparative study of experiments and linear stability analysis, Oberleithner et al. proposed that the PVC is a manifestation of a global hydrodynamic instability mode. Data from their geometry showed that the PVC always occurred in non-reacting flows and M-shaped lifted flames, but not in burner-attached V-shaped flames [26]. This study also showed that the density field above the nozzle exit, which was directly affected by the flame stabilization mode, played a key role in PVC formation. In another study conducted by Manoharan et al., it was also confirmed that the PVC could be suppressed under several configurations due to the flame-induced density gradient [27]. Boxx et al. proposed that local extinction in partially premixed swirl flames was associated with high 2D principal compressive strain-rate applied to the flame surface for sufficient duration [28].

In this paper, the links between local flame extinction, dynamic formation of the PVC, and flame-state transition are elucidated for a series of turbulent premixed swirl flames by using multi-kHz repetition-rate laser diagnostic techniques. Section 2 describes the experimental setup and diagnostics. Results are then presented to describe the nature/limits of the flame transitions, localized extinction, and the correspondence between the flame lift-off and PVC formation using wavelet analysis.

2. Experimental setup

2.1. Combustor and test strategy

The experimental setup and conditions investigated here were previously described by An et al. [29], and only a brief overview is provided. Figure 2 shows the gas turbine model combustor used in this work, which has been the subject of numerous previous studies, e.g., [21,26,30–32] . Fuel and air were mixed in a commercial premixer, fed through a plenum (78 mm diameter, 100 mm length) to a radial swirler (12 swirl vanes), before entering the combustion chamber through a nozzle (diameter $D_n = 27.85$ mm) with a conical center body. The measured swirl-number was 0.55, which was sufficient to produce a strong CRZ at all conditions studied [30]. The optically accessible combustion chamber was 97 × 97 × 114 mm, ending in a conical contraction to an exhaust tube. In this study, the burner was operated with a fuel composed of 60% CH_4 and 40% CO_2 by volume, which is representative of a typical biogas or acid gas. Use of a diluted fuel also has the advantage of lowering the bulk velocities at flame lift-off.

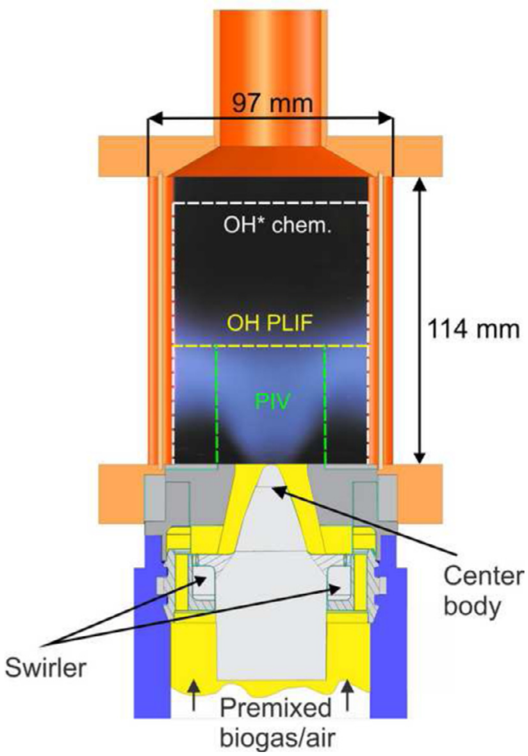

Fig. 2. Schematic of swirl burner.

Table 1
Test matrix for this study, χ_i is the mole fraction of species *i* in the fuel/air mixture.

Case #	T_{ad}	T_{preh}	ϕ	χ_{Air}	χ_{CH_4}	χ_{CO_2}
1a	1700	300	0.66	0.896	0.062	0.042
1b	1700	400	0.62	0.902	0.059	0.039
1c	1700	500	0.58	0.908	0.055	0.037
2a	1800	300	0.73	0.887	0.068	0.045
2b	1800	400	0.68	0.893	0.064	0.043
2c	1800	500	0.64	0.899	0.061	0.040
3a	1900	300	0.80	0.878	0.073	0.049
3b	1900	400	0.75	0.884	0.070	0.046
3c	1900	500	0.71	0.890	0.066	0.044

The test matrix consisted of three target adiabatic flame temperatures (T_{ad}) and three preheat temperatures (T_{preh}), for a total of 9 test cases, which are listed in Table 1. Air was preheated using an in-line electric air heater (Farnam Heat Torch) to a temperature slightly greater than the target T_{preh} and then mixed with fuel about 1 m upstream of the plenum. The mixture temperature was monitored at the entrance to the plenum using a Type K thermocouple, where it was maintained at T_{preh}. It is noted that Case 3c exhibited strong thermoacoustic oscillations that affected the flame-state transitions, and is not included in the analysis below.

The fuel/air equivalence ratio (ϕ) for a particular test condition was set by the fuel composition, preheat temperature, and target adiabatic flame temperature. Each test case was started at a bulk velocity ($\bar{U}$, volumetric flow rate divided by nozzle exit area) at which the flame was attached near the center conical

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