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Flame stabilization analysis of a premixed reacting jet in vitiated crossflow

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Abstract

The flame stabilization behavior of a premixed ethylene–air jet injected normal to a hot vitiated crossflow (JICF) was studied experimentally using simultaneous hydroxyl (OH) planar laser induced fluorescence (PLIF), formaldehyde (CH_2O) PLIF, and particle image velocimetry (PIV). Pixel-by-pixel multiplication of OH and CH_2O fluorescence signals was conducted to estimate the reacting JICF flame front. The simultaneous PLIF-PIV measurements allowed for an in-depth study of the interaction between the flame and the flowfield. The flame structure was divided into two branches, a windward and leeward flame branch. The unsteady windward flame exhibited both attached and lifted flame behavior, while the leeward flame branch remained consistently attached at the jet exit. In some cases, formaldehyde signal was observed upstream of the windward flame base, suggesting the build-up of a radical pool due to mixing between the jet reactants and hot crossflow. Both flame branches were anchored in the jet shear layer, but with increasing distance from the jet exit the flames moved inside the shear layers. Small scale vortices caused local wrinkling of the flame front. The windward flame was observed to wrap around the large-scale vortices that formed along the jet shear layer. The large-scale structures distorted the flame front but the associated strain-rate was typically lower than that imparted by the small-scale structures. The leeward flame edge aligned with regions of high principal extensive strain-rate and high dilatation. On the other hand, the windward flame edge was located in regions where principal extensive and principal compressive strain rate magnitudes were high and dilatation was low. The results suggest that auto-ignition is the dominant flame stabilization mechanism for the unsteady windward flame and premixed flame propagation is the more dominant stabilization mechanism for the leeward flame branch.

Keywords: Jet-in-crossflow; Premixed flames; CH_2O PLIF; OH PLIF

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1. Introduction

In the past several decades, experimental research on reacting Jet-In-Cross Flow (JICF) has been conducted primarily for non-premixed systems where the jet fluid is pure fuel or oxidizer [1–5]. Understanding of such configurations has been vital for the development of current combustion technologies such as the Rich-Burn, Quick-Quench, Lean-Burn (RQL) combustor. More recently, researchers have begun to investigate the possibility of utilizing premixed JICF systems for development of lean premixed (LPM) combustors [6–8]; however questions remain regarding the safety of operating such systems. Flame flashback, blowoff, and acoustic instabilities can arise with LPM. However, experimental studies of the LPM JICF configuration have been scarce. The objective of this study was to characterize the flame stabilization behavior of a premixed reacting jet injected into a fuel-lean vitiated crossflow. Simultaneous planar laser-induced fluorescence (PLIF) of OH and CH_2O and particle image velocimetry (PIV) were conducted for flame visualization and characterization of the flame–flowfield interaction.

While the non-premixed JICF configuration has been widely studied, very little research on premixed JICF systems has been conducted thus far. In our recent work [6], premixed JICF flame stabilization characteristics were found to depend on the jet-to-crossflow momentum flux ratio (J), defined by.

$$J = \frac{\rho_j V_j^2}{\rho_{cf} V_{cf}^2} \quad (1)$$

For the rich ethylene–air jet ($\phi_j = 1.2$) injected into a 1500 K fuel-lean crossflow, two distinct flame branches existed along the jet center plane anchored along the windward and leeward jet boundaries, respectively. For $J > 5$, the windward flame base was, on average, lifted above the jet exit, while the leeward flame remained attached at the jet exit for $J < 23$. The windward flame behavior was highly unsteady, as complete flame attachment and flame blowoff behaviors were observed intermittently. The average liftoff height increased with increasing J, and flame attachment was observed most frequently for $J \leq 5.2$ and never for $J > 8.7$. These observations differed from those presented in Schmitt et al. [7], which showed that for a premixed propane–air jet injected into a 1775 K vitiated crossflow, the flame always remained completely attached uniformly around the jet exit for $J \leq 10$. In Wagner et al. [6], similarities in experimental ignition delay time were observed for flames with J from 5.2 to 22.7. This result led the authors to conclude that the flame stabilization mechanism for the windward flame base was most likely autoignition, initiated by mixing between the jet reactants and hot crossflow.

The present study expands upon the work in Wagner et al. [6], with an emphasis on further characterization of the flame stabilization behavior through the use of simultaneous OH–CH_2O PLIF imaging and PIV. For the results shown in [6], the 2-D dilatation computed from high speed PIV measurements was used to identify the flame location in the reacting JICF flowfield. While dilatation has been used to identify the flame location in other premixed flame configurations [9,10], Najm et al. [11] found that for flames with unsteady strain-rate and curvature, dilatation may not properly indicate heat release. Instead, the authors in [11] found that HCO was a much better indicator of heat release location for a laminar-premixed flame. Following this, Paul and Najm [12] proposed using the spatial overlap of CH_2O and OH to identify the laminar-premixed flame heat release region, as HCO PLIF signals are typically weak and OH–CH_2O PLIF signals are much easier to obtain. More recently, CH_2O and OH PLIF measurements have been validated for measurements of heat release for a variety of premixed flame configurations, including turbulent flame experiments [13,14].

In the present work, pixel-by-pixel multiplication of CH_2O and OH fluorescence signals was performed to compute the premixed reacting JICF flame front structure. By simultaneously conducting PIV measurements, the flame front and flow field interaction was also studied.

2. Experimental setup

2.1. Experimental test rig

The experimental test rig consists of three primary sections: a preburner, transition section, and a jet mixing section. The vitiated crossflow was generated using a propane–air swirl-stabilized flame in the preburner. The crossflow equivalence ratio was held constant at $\phi_{cf} = 0.87$ to maintain a crossflow temperature of 1500 K at the jet exit, which was measured as described in Wagner et al. [6]. The circular cross-section at the exit of the preburner was gradually transitioned to a 3.81 cm × 7.62 cm rectangular cross-section. A 1.27 cm thick ceramic honeycomb was placed at the end of the transition section to straighten the flow entering the jet mixing section. The average crossflow velocity was measured to be $V_{cf} = 7.6$ m/s The jet tube was press fit into the floor of the jet mixing section along the centerline, such that the jet exit was flush with the bottom surface. The jet exit diameter (d) was 9.53 mm. Mass flow controllers set the flow rates of the jet fuel and air. The test section was surrounded by three quartz windows allowing for optical access from both sides and the top of the jet. Further details on the experimental setup are provided in Wagner et al. [6].

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