Combustion and Flame 176 (2017) 521–533

Contents lists available at ScienceDirect

Combustion and Flame

journal homepage: www.elsevier.com/locate/combustflame

Premixed jet flame behavior in a hot vitiated crossflow of lean combustion products

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ARTICLE INFO

Article history:
Received 6 May 2016
Revised 18 June 2016
Accepted 14 November 2016
Available online 9 December 2016

Keywords:
Jet-in-crossflow
Premixed combustion
Auto-ignition
Planar laser induced fluorescence

ABSTRACT

Improvement in NO_x emissions from gas turbine combustors requires development of safe and reliable lean-premixed combustion systems. In this paper, the flame stabilization behavior of a premixed ethylene–air jet injected normal to a hot vitiated crossflow (JICF) of lean combustion products was studied experimentally. The equivalence ratio of the premixed jet was varied from lean to rich conditions. Measurements of the flame were conducted using high-speed chemiluminescence imaging and simultaneous particle image velocimetry (PIV), hydroxyl (OH) and formaldehyde (CH_2O) planar laser-induced fluorescence (PLIF). From the PLIF measurements, pixel-by-pixel multiplication of OH and CH_2O fluorescence signals was conducted to estimate the heat release zone of the JICF flame front. The unsteady windward flame exhibited both attached and lifted flame behavior, while the leeward flame branch remained consistently attached to the jet exit. When the windward flame was lifted, chemiluminescence imaging showed that both flame propagation and auto-ignition kernel formation contributed to flame anchoring. From the PLIF imaging, formaldehyde signal was observed upstream of the lifted windward flame base, suggesting pre-ignition behavior due to mixing between the jet reactants and the hot crossflow. The windward flame base was always in the jet shear layer and the trailing flame remained in the shear layer under lean conditions but traversed the shear layer into the bulk jet flow for stoichiometric and rich conditions. Alignment between 2D dilatation and heat release was seen to vary depending on the location of the flame relative to the shear layer. Two-dimensional dilatation and heat release location aligned best when the flame resided away from the shear layer, where jet and crossflow mixing and out-of-plane motion are minimal.

1. Introduction

The reacting jet in crossflow (JICF) configuration has been widely studied over the past decades, due to the rapid mixing rates it provides in practical combustion systems. Though geometrically simple, the interaction between jet and crossflow generates a complex flow field and strong mixing processes, especially when compared to a free jet configuration [1]. For combustion applications, rapid mixing is desired as it enhances fuel–air mixing, reduces unwanted NO_x emissions, and helps to minimize combustor size requirements [2]. Notable examples of current combustion technology utilizing the JICF configuration include the Twin Annular Premixing Swirler (TAPS) combustor, the Rich-Burn, Quick-Quench, Lean-Burn (RQL) combustor [3,4] and the more recently considered axially controlled stoichiometry premixed combustor. In the TAPS case, the JICF configuration is used to inject fuel into an air stream upstream of a stabilized pilot flame. The rapid mixing processes in the JICF flowfield enhance the mixing between fuel and air upstream of the stabilized flame such that premixed combustion conditions are mimicked. In the RQL case, air jets are injected into a fuel-rich hot crossflow in the second stage of the combustor. This configuration helps to enhance fuel–air mixing prior to combustion, as well as minimizes the residence time of high-temperature mixtures that are primarily responsible for the formation of NO_x. The axially controlled stoichiometry combustor utilizes a main flow of combustion products into which premixed jets are injected to tailor combustion stoichiometry in the downstream direction, as opposed to RQL where downstream combustion is non-premixed. The development of such staged-mixing combustor configurations has been central to mitigating gas turbine pollutant emissions. Still, as acceptable pollutant emission standards become more stringent, more advanced combustion technologies are being developed to meet these lower emission limits and the

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http://dx.doi.org/10.1016/j.combustflame.2016.11.014

present work can elucidate flame stabilization for these new concepts using premixed fuel-air jets.

Control over the stoichiometry in the combustor is important, as it allows for increased control over the pollutant formation processes throughout the combustor. Conceptually, lean-premixed combustion systems offer advantages in terms of pollutant emissions including soot, however, concerns lie in the safety and reliability of operating a combustor at lean, premixed conditions. The experiment presented in this paper uses a novel configuration, in which a premixed ethylene-air jet is injected into a cross flow composed of the hot products from lean propane-air combustion at $\phi_{cf}=0.87$. In this paper, premixed ethylene-air jet with different equivalence ratios ranging from $\phi_j=0.8$ to 1.2 at two jet-to-crossflow momentum flux ratios of $J=\frac{\rho_j V_j^2}{\rho_\infty U_\infty^2}=5.2$ and 8.7 were experimentally studied. The jet premixing provides additional control over the combustor stoichiometry compared to pure fuel or pure air jet cases, which would enable elimination of high-temperature stoichiometric regions in the combustor and potentially lower NO_x production. The crossflow into which the premixed jet is injected in the normal direction is a non-swirling channel flow composed of lean combustion products at 1500 K. The focus of this paper is a study of the impact of jet stoichiometry and momentum on the premixed JICF flame stabilization mechanisms without the complexity of swirl on the flow field. High speed chemiluminescence imaging and simultaneous particle image velocimetry (PIV), OH and CH_2O planar laser-induced fluorescence (PLIF) were employed to investigate the flame behavior. High-speed chemiluminescence imaging provided insight into the time-resolved features of the JICF flame including visualization of ignition kernels, flame propagation, and flame blowoff. The PLIF measurements were primarily used for analyzing the flame structure, specifically the preheat and heat-release regions, and simultaneous PIV measurements were conducted to understand the interaction of the flame with the flow field.

The JICF configurations used in current combustion technology operate under non-premixed conditions, where the jet is either pure fuel or oxidizer. Therefore, experimental studies on premixed JICF configuration are very limited [5–7]. In a previous study [5] conducted using the same experimental facility as in the current paper, the JICF flame stabilization behavior of a $\phi_j=1.2$ premixed jet was examined using high-speed chemiluminescence imaging and high-speed PIV. The flame behavior was observed to differ between the upstream (windward) flame, which was unsteady and exhibited a significant dependence on J, and the downstream (leeward) flame, which was consistently anchored at the jet exit [5]. Similar results were also reported for non-premixed reacting JICF [8,9]. Based on analyses of the premixed JICF in [5] it was determined that for $J>5$, auto-ignition was the dominant stabilization mechanism for the unsteady windward flame branch, while for $J=5$, both premixed flame propagation and auto-ignition were thought to be the controlling mechanisms for flame stabilization. The windward flame also showed a strong dependence on strain rate, which as a measure of the mixing rate between jet and crossflow can affect the auto-ignition behavior [5].

Additional premixed JICF research has been presented in [6,7]. In [6] a 673 K lean, premixed natural gas and air jet was injected into a fuel-lean 1775 K crossflow. For this configuration, where $J=4$–10 and $\phi_j=0.05$–0.77, the premixed JICF flame consistently anchored uniformly around the jet exit. Burning inside the jet exit tube was also observed for the $\phi_j=0.77$ condition, as a result of entrainment of crossflow fluid by the horseshoe vortex upstream of the jet. The experiment presented in [7] continued their prior work [6] by examining a broader range of JICF conditions including variations in jet and crossflow temperature, velocity, and equivalence ratio. The primary goal in [7] was to characterize the flame stabilization location (i.e. liftoff height) based upon laminar flame speed or ignition delay scaling. Mixing between jet and crossflow upstream of the lifted JICF flame meant that the liftoff behavior could not be characterized singularly by flame speed or auto-ignition delay. Ultimately, it was determined that both premixed flame propagation and auto-ignition contribute to flame stabilization and flame-liftoff scaling was achieved by considering both mechanisms and devising an empirical relationship.

Computational studies of auto-ignition and flame propagation in a laminar, premixed methane flame in hot combustion products has also been reported in [10]. It was found that auto-ignition occurred earlier when the mass fraction of hot products in the mixture increased under perfectly mixed conditions. The work being presented in this paper expands upon the results obtained in our earlier work [5] by examining the premixed JICF flame structure in greater detail using PLIF imaging and extracting simultaneous flow-field information through PIV data.

2. Experimental methods

2.1. Experimental test facility

Details of the experimental JICF test facility are schematically shown in Fig. 1 and have been also described in detail in Ref. [5]. The test facility consisted of three main sections: a preburner to produce the hot combustion products of the cross flow, transition section, and premixed fuel–air jet injection section (test section). Vitiated crossflow conditions were selected to create crossflow temperature, species, and velocity conditions similar to those which may exist in a practical combustor system.

Compressed, dry air (at ambient temperature conditions) was supplied to the preburner through a choked orifice (O'Keefe Controls Co.). Propane (Airgas, Industrial Grade) was injected into the swirling air at the center of the swirler exit via a stainless steel tube. The propane flow was metered using a mass flow controller (Porter Model 251 0-50 SLPM). The equivalence ratio of the propane–air mixture that generated the vitiated flow was set to $\phi_{cf}=0.87$. The goal was to maintain fuel-lean crossflow conditions while ensuring the crossflow temperature at the jet injection location was 1500 K. The crossflow temperature was measured by a suction pyrometer with an R-type thermocouple (TC) to minimize radiation errors. Temperature measurements along the lateral span of the test section were taken at the jet exit location. At this crossflow condition, temperature non-uniformity along the lateral span of the test section was $\pm 1\%$. The velocity profile for the crossflow was measured experimentally using PIV [5]. The velocity measurements were made along the test section centerline which aligns with the jet centerline. The crossflow is characterized by mean velocity $U_\infty=7.6$ m/s with approximately $\pm 3\%$ variation along the lateral direction. The composition and density, ρ_∞ of the crossflow was determined using the equilibrium calculation in CHEMKIN with the USC-II mechanism [11]. The PSR simulation was run for $\phi_{cf}=0.87$ propane–air mixture using an estimation of the experimental heat loss and residence time based on the actual temperature and velocity measurements, respectively. The residual oxygen mass fraction of the cross flow based on this calculation was 3 %.

In the transition section, the 38.1-mm diameter circular cross-section at the exit of the preburner gradually transitioned to a 38.1-mm × 76.2-mm rectangular cross-section. The stainless steel transition section was lined with Kast-o-lite 97 L refractory to reduce heat losses. The outer stainless steel surfaces of the transition section were wrapped with ceramic fiber blankets (Thermal Ceramics, Cerablanket), held in place by woven ceramic tape (Cotronics, Thermez 397T), to further reduce heat loss. A 12.7-mm thick ceramic honeycomb (Induceramic – 56 cells per 100 mm) was