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Flowfield measurements and flame stabilization of a premixed reacting jet in vitiated crossflow

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ABSTRACT

Flow field characteristics and flame stabilization behavior are studied experimentally for a premixed ethylene-air jet injected into a vitiated hot crossflow composed of products of fuel lean combustion. The jet was injected perpendicular to the crossflow in a rectangular duct with jet-to-crossflow momentum flux ratios (J) ranging from 5 to 23. High speed chemiluminescence imaging was used to capture unsteady and average behavior of the reacting jet in cross flow (JICF). Time resolved particle image velocimetry measurements were taken to characterize the flow field of non-reacting and reacting jets injected into the vitiated crossflow. Power law correlations for non-reacting JICF trajectory from the literature were found to over-predict the experimental non-reacting jet trajectories due to the greater degree of confinement present in the experimental configuration compared to previous studies. New jet trajectory correlations were developed, to fit the experimental non-reacting and reacting trajectory data, including the effects of confinement. In the case of reacting JICF, the flame was found to have two separate stabilization points, one on either side of the jet centerline. The windward flame stabilization was characterized by three distinct behaviors: complete flame attachment, an unsteady lifted flame, and windward blowoff. The average windward flame edge was lifted for all momentum ratios tested and the liftoff height showed strong dependence on J. The leeward flame consistently stabilized above the jet exit. Experimental strain rates, flame propagation speeds, and ignition delay times were found at the instantaneous flame stabilization locations. Consistencies between strain rate and ignition delay time at the windward flame edge for varying J suggest auto-ignition dominated flame stabilization behavior.

1. Introduction

The jet-in-crossflow (JICF) has been a flow configuration of significant technological interest over many years due to its broad applicability [1,2]. In reacting flows specifically, the JICF configuration has been used for fuel injection, as well as air injection in staged combustors [3–7]. In these systems, rapid mixing between the jet and crossflow is desired. Through fast mixing processes, residence times of stoichiometric mixtures are shortened and NO_x formation is reduced. To further prevent the formation of NO_x, combustor technology is now moving toward utilization of premixed configurations. With these premixed systems comes safety and reliability issues, and thus an in-depth understanding of how such systems behave is desired.

In the present study, a premixed ethylene-air jet is injected into a fuel-lean vitiated crossflow. While the jet and crossflow mixing is known to be a controlling parameter in non-premixed systems [8–12], it is currently unknown how the jet and crossflow mixing impacts the flame stabilization behavior in premixed JICF systems. Additionally, the experimental conditions include high confinement of the JICF, as the lateral confinement was limited to four jet diameters in this study. In much of the JICF research published thus far, experiments have been conducted with little to no confinement. The highly confined flow in the experiment presented here was chosen purposefully, as high lateral confinement is found in many practical applications utilizing JICF.

2. Background

2.1. Non-reacting jets in crossflow

The non-reacting JICF flow field is broken up into the four main features as depicted in Fig. 1: the jet shear layer vortices, the horseshoe vortex system wrapping around the jet base, the counter-rotating vortex pair (CVP) and the wake vortices [13–15]. The jet shear layer vortices are found in the jet/crossflow boundary, dominating the near field portion of the jet and are inherently unstable. The upright wake vortices initiate from the wall boundary layer and connect with the main jet downstream in the wake region [13]. The horseshoe vortex system forms upstream of the jet exit and wraps around the

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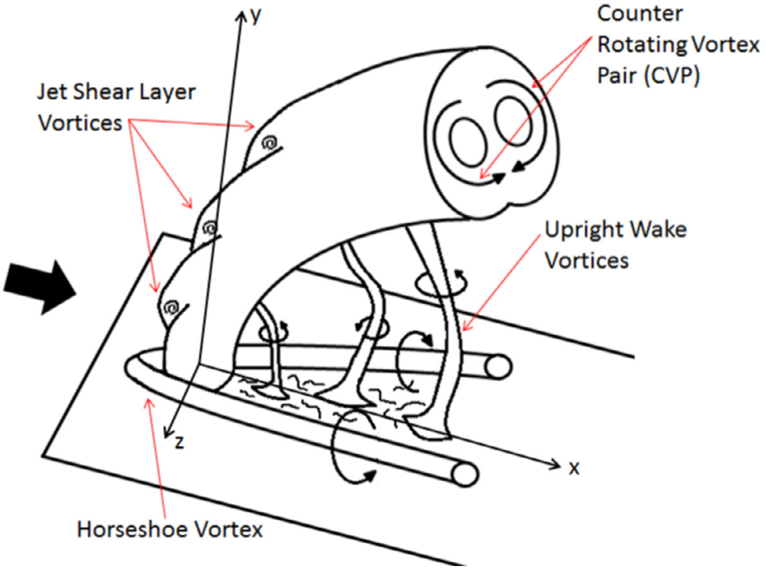

Fig. 1. Four main flow structures observed in non-reacting JICF.

main jet column. The wall boundary flow approaching the jet separates as a result of the adverse pressure gradient ahead of the jet column [13,14]. The CVP arising from the jet flow stagnation in the transverse direction is responsible for the large scale mixing, especially in the downstream region. The CVP also interacts with the jet shear layer behavior, beginning in the jet near field and growing until it is the dominating flow structure downstream [13,16–18].

The primary parameter used to characterize different behavior observed in JICF experiments is the jet-to-crossflow momentum flux ratio, J:

$$J = \frac{\rho_j V_j^2}{\rho_\infty V_\infty^2} \tag{1}$$

The jet fluid density is represented by ρ_j, the crossflow density is represented by ρ_∞, and the jet and crossflow velocity are represented by V_j and V_∞, respectively. From non-reacting JICF experiments, correlations for the trajectories of maximum jet velocity, temperature maxima and minima, as well as other scalars, have been developed. The correlations have all been found to be a function of J and other geometrical parameters [19]. The most common correlation for describing jet trajectory was developed by Pratte and Baines [19], who found that the jet trajectory is a function of the J value and the jet diameter, d:

$$\frac{y}{\sqrt{J}d} = A\left(\frac{x}{\sqrt{J}d}\right)^B \tag{2}$$

where x and y are the coordinates along the crossflow and jet injection directions, respectively. In their experiment they [19] found that the values for A and B were 2.05 and 0.28 respectively, for J values ranging from 25 to 1225; however, values of A and B reported in the literature vary over the range of $1.2 < A < 2.6$ and $0.28 < B < 0.34$ [20]. Scatter in the values of the constants can be attributed to differences in the jet exit velocity profiles, crossflow boundary layer, and definitions used for the jet trajectory. Kamotani and Greber [21] proposed another correlation after finding that the value for A was also a function of J. Their correlation takes the form,

$$\frac{y}{\sqrt{J}d} = A\sqrt{J}^{C}\left(\frac{x}{\sqrt{J}d}\right)^B \tag{3}$$

where A, B, and C are constants that depend on whether the velocity or concentration maxima is used to define trajectory. Kamotani and Greber [22] also studied the effect of confinement on jet trajectory for a single non-reacting jet in crossflow. In these experiments the velocity and temperature jet trajectories were compared for JICF configurations with no opposing wall and an opposing wall providing lateral confinement to the jet penetration. It was found that the jet trajectory was relatively insensitive to opposing wall location for $J < 20$ and only slightly affected at high J values, $J > 70$, when the jet collided into the opposing wall. In the experiment, lateral confinement was varied from 16 jet diameters down to 8 jet diameters. In addition, for $J > 70$ upstream jet flow recirculation was observed near the opposing wall.

2.2. Reacting jets in crossflow

2.2.1. Jet trajectory

While jet trajectory has been well defined in non-reacting JICF experiments, only a few attempts were made to correlate the trajectory of reacting JICF [7–9,11]. In some instances non-reacting JICF correlations have been found to fit experimental reacting JICF trajectory [7,8]. In other experiments, such as those from Hasselbrink and Mungal [9] and Sullivan et al. [11] reacting JICF trajectories were found to differ from non-reacting JICF trajectories. In these experiments it was found that nearfield jet penetration was similar between reacting and non-reacting jets; however the reacting jet tended to overpenetrate in the far field, relative to non-reacting jets. Reduction in crossflow entrainment and gas expansion due to heat release were identified to be the possible reasons for the increased penetration in the case of reacting jets. Sullivan et al. [11] also found that in the case of high momentum ratio jets, $J \sim 50$, fuel dilution was found to have no effect on jet penetration, thus suggesting that total heat release had no effect on the trajectory of reacting jets with high J values.

These differences in the literature between experimental reacting and non-reacting JICF trajectories show further characterization of the reacting JICF trajectory may be needed. The results presented in this paper will show how the trajectory of reacting jets relative to non-reacting jets can vary as a result of confinement effects and flame location. The non-reacting and reacting JICF trajectories are then characterized by separate correlations.

2.2.2. Flame stabilization

In general, JICF flame stabilization can be characterized by two distinct behaviors: attached and lifted flames. Many different factors