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The effects of nozzle geometry and equivalence ratio on a premixed reacting jet in vitiated cross-flow

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ABSTRACT

The effects of nozzle geometry, jet equivalence ratio (ϕ_j), and momentum flux ratio (J) on the flow field, stability characteristics, and flame topology of a premixed ethylene–air jet injected transverse to a vitiated cross-flow are investigated experimentally. Cross-flow conditions of 900 K and 100 m/s were chosen to simulate the environment of a secondary combustor in a staged combustion system. The dependence of the flame liftoff height on J suggests that at these conditions the flame stabilization process is flame-propagation controlled rather than autoignition assisted. A circular nozzle and high aspect ratio slotted nozzle of identical exit area were investigated for jet to cross-flow momentum flux ratios ranging from 5 to 65 for jet equivalence ratios of up to $\phi_j = 5.0$. High-speed particle image velocimetry was utilized to study the time-averaged flow field and OH* chemiluminescence was used to capture time-averaged and instantaneous features of the flame behavior. The nozzle geometry was determined to have a significant effect on RJICF flame stability, with substantially expanded blow-out limits for the slotted nozzle. Enhanced operability of the high aspect ratio slotted nozzle was shown to be attributable to the substantially larger and stronger recirculation zone on the leeward side of the jet when compared to the circular nozzle. This area is characterized by a more disperse region of elevated vorticity levels, resulting in the entrainment of more hot combustion products with a longer residence time in the recirculation zone, which in turn provides a stronger and more stable ignition source to the oncoming, unburned reactants. A correlation for the isothermal JICF trajectory was modified to account for gas expansion effects and found to satisfactorily capture the jet trajectory for both the non-reacting and reacting slotted nozzle. The jet trajectory was demonstrated to be independent of ϕ_j, whereas the jet flame penetration decreases as ϕ_j increases, indicating that where the flame situates itself is determined by the local mixture concentration rather than changes in the flow field. Nevertheless, ϕ_j was also found to have an effect on the mean flow field, with slightly higher magnitudes of reversed flow velocity and an increase in mean recirculation zone length observed as the fuel content of the jet is increased.

1. Introduction

The jet in cross-flow (JICF) has received extensive attention due its wide range of applications [1–5]. Its characteristically high levels of turbulence, enhanced mixing and entrainment properties, and unique flow structures have made it particularly attractive for fuel injection and flame stabilization in staged combustion gas turbines. The reacting JICF (RJICF) is an efficient means to quickly introduce and mix fuel with the cross-flow and has been shown to enhance the combustion process when compared to traditional bluff body flameholders [6]. Additionally, the fast mixing times that result from elevated turbulence levels can reduce the residence times of stoichiometric mixtures, reducing the formation of thermal NO_x [7].

Multiple studies have investigated the flame stabilization properties of the reacting JICF configuration for a range of operating conditions. Most have focused on diffusion jet flames and only several have examined premixed jets. Surprisingly, almost all of the studies involving a vitiated cross-flow have operated in the autoignition or "autoignition-assisted" burning regimes with relatively low cross-flow velocities. The aim of the current study is to examine the flame stabilization properties of the reacting JICF where the core velocity is high but the temperature is relatively low. Such conditions are representative of the outflow of the high pressure turbine of a staged combustion system, where the reduced temperature increases the autoignition timescale [8]. Under

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Nomenclature

d_c	diameter of the circular nozzle jet exit
$\overline{E_l(x)}$	average leeward boundary
$E_l(x,\ t)$	instantaneous leeward boundary
$\overline{E_{l,mp}(x)}$	average distance of leeward flame boundary normal to $z_{mp}(x)$
$E_{l,\ mp}(x,\ t)$	instantaneous distance of leeward flame boundary normal to $z_{mp}(x)$
$E_{l,\ n}(x,\ t)$	instantaneous leeward boundary displacement normal to $\overline{E_l(x)}$
$E_l^{RMS}(x)$	RMS of instantaneous leeward boundary displacements normal to $\overline{E_l(x)}$
$\overline{E_w(x)}$	average windward boundary
$E_w(x,\ t)$	instantaneous windward boundary
$\overline{E_{w,mp}(x)}$	average distance of windward flame boundary normal to $z_{mp}(x)$
$E_{w,\ mp}(x,\ t)$	instantaneous distance of windward flame boundary normal to $z_{mp}(x)$
$E_{w,\ n}(x,\ t)$	instantaneous windward boundary displacement normal to $\overline{E_w(x)}$
$E_w^{RMS}(x)$	RMS of instantaneous windward boundary displacements normal to $\overline{E_w(x)}$
J	jet-to-cross-flow momentum flux ratio
Re_j	jet Reynolds number
r_{corr}	Pearson's correlation coefficient
u	streamwise component of velocity
U_j	jet velocity
U_∞	cross-flow velocity
v	transverse component of velocity
w	vertical component of velocity
$w(x)$	time-averaged jet flame width
w_{sl}	spanwise width of the slotted nozzle jet exit
x	axial position
y	lateral position
z	height from jet exit wall
z_{lo}	average flame liftoff height
$z_{mp}(x)$	time-averaged midpoint jet flame trajectory
$z_{mv}(x)$	time-averaged maximum velocity jet trajectory
ϕ_j	jet equivalence ratio
ρ_j	jet density
ρ_∞	cross-flow density
ω_z	out-of-plane vorticity

these conditions autoignition is of only secondary importance and the flame stabilization process is expected to be flame-propagation controlled [9–11].

2. Background

2.1. Isothermal JICF

The non-reacting JICF flow field is both three-dimensional and highly unsteady in nature. It consists of four primary vortical systems: the jet shear-layer vortices, the counter-rotating vortex pair (CVP), the wake vortices, and the horseshoe vorticies [12]. The jet shear-layer vortices are formed at the interface between the jet and the cross-flow in the near field. The CVP is the dominant structure in the far field. Smith and Mungal demonstrated that it is the development of the CVP in the near field rather than its presence in the far field that enhances mixing when compared to the free jet [13]. The wake vortices span the distance of the jet injection wall to the jet. Although their vorticity originates in the cross-flow boundary layer upstream of the jet, interaction with the jet reorients it to a direction perpendicular to the jet exit wall [12]. The jet shear layer vortices and wake vortices, which exhibit alternating behavior similar to that of the Bènard-von Kàrmàn (BVK) instability, are inherently unsteady. The other two vortex systems can be distinguished in the mean flow, though they can also have unsteady components.

The most common parameter used to classify different characteristics of the JICF is the jet-to-cross-flow momentum flux ratio, J:

$$J = \frac{\rho_j U_j^2}{\rho_\infty U_\infty^2} \tag{1}$$

where ρ is density, U is the velocity, and the subscripts j and ∞ denote properties of the jet and cross-flow, respectively. Many aspects of the mean and instantaneous jet behavior are dependent on the magnitude of this ratio.

Multiple correlations that are typically a function of J have been developed for the mean jet trajectories. These correlations are most often expressed as the locus of maximum velocity in the plane of symmetry [14], but have also been defined as the locus of maximum local temperature and concentration decay [15,16]. The most commonly quoted trajectory is that given by Pratt and Baines [17]:

$$\frac{z}{rd} = A\left(\frac{x}{rd}\right)^B \tag{2}$$

where z is the distance from the jet exit perpendicular to the cross-flow, x is the streamwise distance from the jet exit, r, also known as the blowing ratio, is $\sqrt{J}$, d is the jet exit diameter, and A and B are constants. Though Pratt and Baines defined $A = 2.05$ and $B = 0.28$ for r values ranging from 5 to 35, data from various studies have resulted in the general conclusion that $1.2 < A < 2.6$ and $0.28 < B < 0.34$ [16]. Kamotani and Greber showed that different definitions of the jet centerline can result in significantly different jet trajectories [14]. Different trajectory shapes for different studies conducted at ostensibly similar conditions led Muppidi and Mahesh to consider other parameters when developing a correlation, specifically the velocity profile at the jet exit and the cross-flow boundary layer thickness immediately upstream of the jet orifice [18]. Their correlation results in a significant collapse of data from different experimental facilities, showing the dependence of the jet trajectory on flow field conditions.

2.2. Reacting JICF

The RJICF differs from the isothermal JICF in several fundamental ways. The primary differences are (1) higher velocity magnitudes downstream of the jet injection point, (2) highly divergent streamlines on the lee side of the jet, and (3) a larger recirculation region on the leeward side of the jet [19]. These differences can all be attributed to the significant decrease in density caused by heat release.

Though the trajectory of the isothermal JICF has been heavily investigated and the factors influencing its shape are well understood, relatively few studies have developed correlations for the reacting JICF. Hasselbrink and Mungal attributed slightly deeper flame penetration over their non-reacting counterparts to the reduced cross-flow entrainment of the jet flames [16]. Lamont et al. employed the Holdeman correlation [20] in order to account for confinement effects and found poor correlation with their experimental premixed flames [21]. They suggest this is due to an effective increase in jet momentum caused by heat release. Steinberg et al. found that hydrogen jets injected into an electrically heated cross-flow follow the scaling in Eq. (2) for $1.2 < A < 1.3$ and $0.42 < B < 0.43$ for J values varying from 2 to 8.4 [22]. A study based on CH* chemiluminescence images by Sullivan et al. found reasonable correlation with Eq. (2) for $25 < J < 100$ protruding jets