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Time-averaged characteristics of a reacting fuel jet in vitiated cross-flow

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ABSTRACT

This paper describes an experimental study of reacting jets in a high-temperature (1775 K) vitiated crossflow at 6 atm. We present an extensive data set based on high speed chemiluminescence imaging and exhaust gas sampling showing the characteristics of the time-averaged trajectory, width of the flame, flame standoff (or ignition) location, and NO_x emissions over a momentum flux ratio range of $0.75 < J < 240$. Key observations are: (1) Depending upon ignition times, reaction can initiate uniformly around the jet, initiate on the leeward side of the jet and spread around to the windward side farther downstream, or initiate further downstream. (2) The time-averaged trajectory generally follows nonreacting trajectories, but penetrates further in the far-field than for what would be expected of a nonreacting jet. (3) The width of heat release zone increases monotonically with downstream location, J, and flame flapping amplitude, but seems to be dominated by the size of the counter-rotating vortex pair. (4) The measured ignition locations were of the same order of magnitude as values based on calculated ignition time scales and mean jet exit velocities, but with some additional variability. (5) The incremental NO_x emissions were controlled primarily by the global temperature rise associated with burning the jet fuel (for the fixed crossflow conditions studied here), and the NO_x emissions increased roughly linearly with the temperature rise.

1. Introduction

Jets in crossflow (JICF) find application in many combustion systems due to their rapid mixing characteristics. Common application areas include gas turbine fuel/air pre-mixers, film cooling jets, dilution air jets, and fluidic flame stabilization [1–3]. The reacting JICF problem can consist of either fuel injection into an oxidizing stream, such as in a fuel injector or flare [4,5], or air injection into a fuel-containing stream, such as in the quench section of an RQL combustor [6,7]. The specific configuration investigated here, that of a fuel jet injected into a vitiated, oxidizing crossflow, is motivated by concepts for achieving low NO_x emissions with higher combustor outlet temperatures [3,8,9]. In combined cycle power plants, thermal efficiency is proportional to turbine inlet temperature. Historically, turbine inlet temperatures have limited the maximum combustor outlet temperatures, but steady improvements in coatings and turbine cooling have led to significant increases in allowable combustor outlet temperatures and consequently higher minimum NO_x levels that are achievable with lean, premixed combustion technologies [10]. One approach for increasing combustor outlet temperatures without significant NOx increases is to use staged combustion devices where a more conventional lean, premixed burner supplies hot, vitiated gases to a secondary combustor utilizing a reacting jet in crossflow configuration. These high temperature combustion configurations in the secondary combustor offer important advantages, including the ability to burn fuels in a reduced oxygen content environment with low residence time, improved fuel flexibility, and inherent flame stabilization.

In addition to its many industrial applications, JICF are an important unit problem for studying turbulence/chemistry interaction [11], hydrodynamic stability in reacting flows [12,13], and evaluating computational combustion models [14,15]. The nonreacting transverse jet flow field is highly unsteady and three-dimensional, containing several coherent vortical structures arising from underlying hydrodynamic instabilities in the flow, namely, the counter-rotating vortex pair (CRVP), the horseshoe vortex system associated with the separating approach flow boundary layer, the jet shear-layer vortices (SLV), and the wake vortices [16,17]. The CRVP and horseshoe vortices are present in the time-averaged flow field, whereas the wake and shear-layer vortices are inherently unsteady features that are not [16]. The CRVP is the dominant flow structure in the far-field of the jet and is thought to be responsible for much of the enhanced mixing and entrainment seen in JICF. A fundamental parameter characterizing JICF is the momentum flux ratio (defined in Eq. (2)), which represents the ratio of two conserved quantities in the flow field (at least in the nonreacting case) and factors prominently in many of the time-averaged and instantaneous flow features.

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Nomenclature

J	jet-to-crossflow momentum flux ratio	x	axial position
P	pressure	z	vertical position
Re_d	jet Reynolds number	z_{ign}	vertical flame standoff location
T	temperature	$\zeta_L(x,t)$	instantaneous leeward edge position
Z	mixture fraction	$\overline{\zeta_L(x)}$	time-averaged leeward edge position
Z_{MR}	most reactive mixture fraction	$\zeta_{n,L}(x,t)$	instantaneous normal leeward edge displacement
Z_{st}	stoichiometric mixture fraction	$\zeta_W(x,t)$	instantaneous windward edge position
c_d	dark core based chemiluminescence trajectory	$\overline{\zeta_W(x)}$	time-averaged windward edge position
c_m	midpoint based chemiluminescence trajectory	$\zeta_{n,W}(x,t)$	instantaneous normal windward edge displacement
d	injector inner diameter	ρ_j	jet density
h	jet width	ρ_m	crossflow density
r	Karagozian vortex half-width	τ_c	calculated chemical ignition time
s	arc-length distance	τ_f	measured flow time to ignition point
u_j	jet velocity		
u_m	crossflow velocity		

While a variety of issues regarding unsteady features of reacting JICF remain to be worked out, such as its hydrodynamic stability characteristics [12,13], degree of premixing [18], flame flapping, flame-wall interactions [19], the key focus of this paper is on its time-averaged features where a number of important fundamental issues and characteristics require clarification and data. In particular, while the basic scalings for iso-density nonreacting JICs are well understand, the inter-related roles of density variations, gas dilatation, and baroclinic vorticity production introduced by the combustion problem introduce important new physics whose influence is not understood. The key focus of this paper is to provide data to address these questions.

In order to motivate the key time-averaged JICF features, which are the focus of this paper and considered in the rest of this introduction, consider Fig. 1, which compares an instantaneous and a time-averaged image of a flame. The focus of this work is on four time-averaged flame features: the jet trajectory, $c_m(x)$, the flame liftoff height, z_{ign}, the flame width, $h(x)$, and NO_x emissions. The first three are illustrated directly in Fig. 1.

2. Background: time-averaged JICF flame features

Consider first the jet and flame trajectories. The jet trajectory is particularly important in reacting flows, as high temperature reaction zones should be located far from combustor walls for durability reasons. Many combustion system performance metrics, such as combustion efficiency, emissions levels, and pattern factor, are also sensitive to jet trajectory. Multiple trajectory measures can be defined based on velocity, scalar concentration, heat release, or flame luminosity. Previous studies have characterized the jet trajectory and mixing enhancement of the nonreacting JICF [20–22], where it is well known that there are important differences between velocity and scalar-based trajectory definitions. For example, concentration-based trajectories penetrate less than velocity-based trajectories [20,23]. The basic scaling for the time-averaged trajectory and concentration field of momentum-dominated, subsonic, nonreacting JICF is well understood [21,22]. Most analytically derived correlations for the jet trajectory, based on either jet velocity or concentration, take the form [1]:

$$\frac{z}{d\sqrt{J}} = A\left(\frac{x}{d\sqrt{J}}\right)^B \quad (1)$$

where z is the centerline distance from the wall, x is the distance in the cross-stream direction downstream of the injector centerline, and d is the jet diameter (see Fig. 1). In addition, J is the momentum flux ratio given by

$$J = \frac{\rho_j u_j^2}{\rho_m u_m^2} \quad (2)$$

where ρ is density, u is velocity and the subscripts j and m denote the jet and crossflow values, respectively. The coefficients, A and B, typically vary between the ranges $1.2 < A < 2.6$ and $0.28 < B < 0.34$, depending on such parameters as the velocity profile of the jet exit [24,25], the thickness of the boundary layer [24], and the specific definition used to identify the jet trajectory. Shan and Dimotakis [26] showed that jet trajectory is effectively independent of Reynolds number for $1.0 \times 10^3 \leqslant Re_d$ (tested up to $Re_d = 20.0 \times 10^3$).

The limited data for reacting jets indicates that the time-averaged jet trajectory is quite close to the nonreacting jet [27,28].

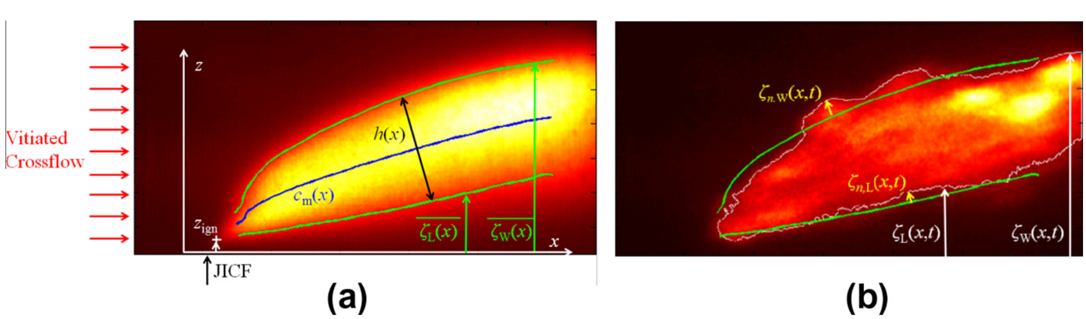

Fig. 1. Chemiluminescence image of a reacting $J = 19$ CH_4 jet in a vitiated, 6 atm crossflow: (a) time-averaged image with luminance-based trajectory in blue, ignition point marked as white cross, time-averaged edges shown as green lines, and jet width shown in black; (b) instantaneous image with edges labeled, instantaneous edge indicated with white line and time-averaged edge in green line. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)