High-Repetition-Rate Planar Measurements in the Wake of a Reacting Jet Injected into a
Swirling Vitiated Crossflow

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Abstract

Staged combustion has been explored for power generation gas turbine engines to increase engine efficiency with minimal contribution to pollutant formation. Secondary fuel injection into the vitiated flow from the primary combustion process is one approach. In this work, advanced diagnostic measurements were performed on an experimental representation of such a system, with a transverse jet injection into a swirling vitiated crossflow. High-repetition-rate simultaneous particle image velocimetry (PIV) and OH planar laser-induced fluorescence (PLIF) were performed at three measurement planes perpendicular to the jet axis. The measurements provided qualitative as well as quantitative information on the evolution of complex flow structures and transient events such as re-ignition, local extinction and vortex-flame interactions in the turbulent reacting flow. Transverse jets composed of H_2 mixed with N_2 and premixed natural gas and air were injected through a tube protruding into the crossflow. The vitiated crossflow is produced by a low swirl burner (LSB). The crossflow exhibits considerable swirl at the location of the transverse jet injection. Two momentum flux ratios, $J=3$ and $J=8$ were employed to study the effect of momentum flux ratio on the stabilization of reaction fronts. The time-averaged flow field show a pair of steady wake vortices, which were found to be much larger for $J = 8$ than for the $J=3$ case. The region with the maximum time-averaged OH-PLIF intensity was found to be localized between the wake vortex pairs. The wake Strouhal number was found to be invariant with respect to the momentum flux ratio. Based on the experimental data, it is hypothesized that the shear layer and wake field vortices play a significant role in stabilizing a steady reaction front within the near-wake region of the jet.

Keywords: Staged Combustion System (SCS), Reacting Jet in Crossflow (RJICF), High Repetition Rate (HRR), Counter Rotating Vortex Pair (CVP), Wake Vortices, kHz, OH-PLIF, 2D PIV, Auto-Ignition, Turbulent Kinetic Energy (TKE), Wake Strouhal Number (St_{wake})

1. Introduction

The search for clean energy sources has motivated the design and development of advanced energy conversion systems that can meet the current and future energy needs with minimal impact on the environment. Emissions from natural-gas-fueled power generation gas turbines are regulated by environmental legislation, which places increasingly stringent limits on the emission of nitrogen oxides (NO_x) [1]. One means to achieve low NO_x emissions is to reduce peak flame temperatures, which can be attained by the premixed, lean burn approach: premixing the air and the fuel prior to combustion and burning the globally lean mixture, downstream, in the combustor [2]. However, lean combustion is often accompanied by instabilities, and the resulting pressure pulsations can lead to catastrophic mechanical damage. Secondary injection of the fuel, also referred to as staged combustion, has been identified as a means of increasing the power output of the gas turbine systems with minimal contribution to NO_x emission and also as a means of controlling combustion instabilities. Recent progress in the development and use of turbine blade materials has enabled gas turbine manufacturers to raise the turbine inlet temperatures leading to an increase in thermal efficiency of the engine [2]. One of the main motivations behind staged combustion or secondary injection of fuel is to increase the turbine inlet temperature with minimal contribution in NO_x emissions.

The jet-in-crossflow (JICF) flow field consists of several interesting vortical structures, as shown in *Fig. 1*. The counter-rotating vortex pair (CVP) is the dominant flow structure. It has been established that the vorticity distortion within the evolving jet shear layer and the pressure difference between the windward and leeward sides of the jet lead to an accumulation of vorticity sufficient to form the CVP downstream of the jet injection [3][4][5][6]. The presence of this flow structure is responsible for imparting enhanced mixing in the far-field of the jet. In addition to the CVP, flow structures associated with JICF include horseshoe vortices, shear layer loop vortices and upright wake vortices. In order to characterize the upright wake vortex dynamics, researchers have focused mainly on wake specific flow

visualization, wake Strouhal number and wake velocity deficit [7] [8]. The wake vortices appear similar to the Karman vortex street found in wake field of a cylindrical bluff body [7]. However, the source of vorticity for the wake of the JICF is fundamentally different than that from a cylindrical bluff body: it originates from the boundary layer of the nozzle walls and is then transported into the wake of the jet. In the case of the reacting JICF (RJICF), the flow encounters sharp density gradients due to heat release. The heat release causes local volumetric expansion that leads to the generation of vorticity along the shear layer between the jet and the crossflow fluid. This vorticity is then convected into the wake of the jet. There is an additional source of vorticity generation due to sharp density gradients and dynamic pressure gradients, which is termed as baroclinic torque. Thus, the near wake region of an RJICF features three sources of vorticity, namely, vorticity originating from the boundary layer of the nozzle, vorticity originating at the shear layer due volumetric expansion, and vorticity due to baroclinic torque.

Several earlier studies on the mixing and vortex dynamics of JICF are available in the literature [7] [8]. Similarly, many studies of RJICFs have focused on the jet flame structure [9] [10] [11] [12] [13]. In one of the earliest studies of RJICFs with low to moderate momentum flux ratios ($J = 1-10$), as defined in *Equation 1*,

$$J = \frac{(\rho V^2)_{JET}}{(\rho V^2)_{CF}} \quad \text{Equation 1}$$

it was observed that the flames were partially attached to the injector and were wake stabilized [10]. In another study, a wide range of momentum flux ratios and many different fuels were explored [12]. The main objective of Bandaru and Turns [12] was to obtain pollutant emission characteristics, flame dimensions and radiant fractions to gain insight into the flame structure. It was observed that flames in the crossflow field are up to 35% shorter than their counter-parts in co-flow, which is particularly important for NO_x formation.

With the rapid advancement of high-power diode-pumped solid-state (DPSS) laser systems,

coupled with high-speed CMOS detectors, it has become feasible to perform non-intrusive measurements in high Reynolds number reacting flows with high spatial and temporal resolution[14]. Researchers have reported temporally resolved particle image velocimetry (PIV) coupled with planar laser-induced fluorescence of the OH radical (OH-PLIF) to visualize flow-flame interactions in complex flows. These techniques can be used to track transient events occurring in turbulent flames and have contributed significantly in understanding the underlying physics of flow-flame interaction [15] [16] [17]. Some of the recent experimental studies on RJICF reported in the literature have focused on understanding the associated velocity field and the flame structure at crossflow Reynolds number ranging from 1000 – 50000 [18] [19] [20] [21] [22]. In an experimental study on an RJICF, PIV measurements indicated that the flame centerline penetrates slightly further into the crossflow as compared to the centerline of an isothermal jet [13] [18] [19]. It is also observed that although the heat release rate alters the instantaneous velocity field, the jet trajectory was similar to that of a non-reacting jet. Because of the enhanced mixing efficiency that the CVP provides to a JICF, most of these studies have focused mainly on the role of CVP in flame stabilization in the far-field. In a more recent study, a high-speed flame visualization technique was used to characterize the most stable and steady flame features of a reacting jet injected into a vitiated crossflow [20]. The authors reported that the bulk of the heat release occurs along the leeward side in the near-field of the jet. It was also reported that reactive jets comprised of H_2/CO mixtures were always attached to the nozzle. In another study, an auto-igniting jet of hydrogen diluted with nitrogen (70% H_2 /30% N_2) was injected into a high temperature crossflow [22]; here, simultaneous PIV and OH-PLIF were employed along with Raman scattering measurements of mixture fraction and temperature. It is observed that for a range of J values they could achieve lifted jet flames with different lifted branch configurations, including a straight-edge lifted, a merged lifted and a hooked-edge lifted branch.

For applications such as secondary injection of fuel into a vitiated gas stream in a gas turbine combustor, rapid mixing and chemical reaction in the near-field of jet injection plane are desirable. In a recent study based on high-speed CH^* and OH^* chemiluminescence imaging, vitiated crossflow, it was

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3 observed that the flame stabilizes just downstream of the injector [23][24]. The H₂/CO jet flames
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5 remained attached to the injector for all observed conditions. Based on these observations, it can be
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7 hypothesized that the near-wake region of the jet plays a significant role in flame stabilization and rapid
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9 consumption of the fuel.
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12 In a previous study, we investigated the flow field of the reacting jet using high-repetition-rate
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14 (HRR) (5 kHz), two-component PIV. The swirling nature of the crossflow was characterized in detail
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16 [25]. Premixed jets composed of natural gas and air were injected through an extended nozzle into the
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18 vitiated flow downstream of a low swirl burner (LSB) that produced the vitiated, swirled flow. The jet-
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20 to-crossflow momentum flux ratio was varied to study the corresponding effect on the flow field. The
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22 results indicate that the shear layer and wake field vortices play a significant role in stabilizing a steady
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24 reaction front within the near wake region of the jet. In this study we performed simultaneous HRR two-
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26 component PIV and OH-PLIF measurements to investigate flow-flame interaction in a reacting jet in
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28 vitiated crossflow in a combustor operating at 5.5 bars. The flow-flame interactions within the wake of
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30 an auto-igniting jet carrying fuel issuing into a swirling, vitiated crossflow are investigated. Interesting
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32 phenomena such as flame detachment and re-attachment, local extinction, and vortex-flame interactions
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34 are observed. These measurements, acquired at relevant engine conditions, are a natural utilization of
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36 high-speed diagnostic systems and provide crucial insight to the complex processes of flow-flame
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Fig. 1. showing the schematic diagram of a transverse jet, injected into a swirling crossflow through an extended nozzle. Crossflow velocity, U_∞ is in the positive X-direction, the swirling motion is in the Y-Z plane and the jet velocity, U_{jet} is in positive Z-direction [25].

2. Experimental System and Diagnostic Techniques

2.1 Experimental Hardware

The experimental test rig features a main combustion zone (MCZ) and a secondary combustion zone (SCZ). The MCZ features a low-swirl burner (LSB) fueled with premixed natural gas and air. The low-swirl burner for the MCZ is similar to that reported in the literature [26]. The design and operation of the test rig were described in detail previously [21][25]. The MCZ was operated at a pressure of 5.5 bar, an air inlet temperature of 723 K, an equivalence ratio of 0.5, and mass flow rate of 0.39 kg/s. There is a round-to-square cross section transition downstream of the MCZ. The SCZ is contained in a square-cross section assembly with optical access. The fuel jet is injected transversely into the SCZ, mixes with the in-coming crossflow and auto-ignites. The fuel is injected from a straight tube with O.D. of 15.3 mm and I.D. of 10 mm that extends 17 mm into the vitiated flow stream, as shown in Fig. 2a. The SCZ window assembly provides optical

access from three sides; one window port is used for the fuel injection into the SCZ. Each window port features a two-window configuration, a thin inner window to contain the flame gases and a thick outer window to contain the pressure. The pressure is controlled within the test section with a butterfly valve at the exit of the test rig. The cavity between the inner and outer window is pressurized by extracting a fraction of the inlet air from upstream of the main fuel injection and redirecting it into the cavity. This is done to try to match the 5.5 bar combustion pressure within the window combustor, but because of the pressure drop in the premixing section the pressure in the cavity is slightly higher than that in the combustor. The inner windows provide an optical viewing area of 98 mm x 73 mm. The window assembly has a square cross-section with dimensions of 107 mm x 107 mm. The reacting jet fluid in our study was composed of two types of fuel, i) H₂ diluted with N₂ (40%/60%) and ii) premixed natural gas ($\phi_{\text{jet}} = 0.9$). The two fluids were mixed together in a plenum before being introduced into the combustor, as shown in *Fig. 2a*. The velocity field and OH-PLIF distribution of the premixed natural gas jet ($J=3$, $\phi_{\text{jet}} = 3$) was discussed in detail previously [25]. However, the measurements were made separately at a 5-kHz data rate. The experimental data discussed here are based on simultaneous two-component PIV and OH-PLIF at 10 kHz.

Fig. 2 (a) Schematic diagram of the window assembly portion of the test rig with the extended nozzle showing the side view of the jet flame which is in X-Z plane. The green horizontal lines indicate the PIV/OH-PLIF measurement planes. (b) The flow streamlines indicating the near field wake region of the RJICF along one of the measurement planes, which is in X-Y plane.

2.2 Experimental Operating Conditions and Test Matrix

In previous work, a detailed parametric study on the staged combustion system (SCS) [21] was conducted to show the effect of J , nozzle exit diameter (D) and jet equivalence ratio (ϕ_{jet}) on the pollutant emissionse NO_x and CO . In the present study, high-repetition-rate laser diagnostic techniques are

employed to compare and contrast the effects of two J values, 3 and 8, on the structure and dynamics of the reacting (R) jet flame. For the $J = 3$ case, the fuel reacts closer to the nozzle exit with the reaction zone stabilized within the wake of the jet, while for the $J = 8$ case the jet carrying fuel penetrates deeper into the crossflow and has a higher degree of mixing. The fuel jets provide a calculated net rise in temperature of ΔT across the SCZ. A detailed test matrix is shown in *Table 1* for the simultaneous PIV/OH-PLIF study discussed in this paper. The swirling crossflow and the jet fluid are composed of hot air only for the non-reacting (NR) cases, the crossflow and jet temperatures are maintained to ensure a density ratio of $S = 1$. The simultaneous PIV/OH-PLIF measurements were performed at the $z = 5$ mm, 10 mm and 15 mm planes, as shown in *Fig. 2a*. The horizontal green lines indicate the locations of laser sheet. The distance from the nozzle exit plane is represented as Z . The nozzle exit plane is considered as the origin for this geometry, as shown by the coordinate axes in *Fig. 2a and b*. The flow streamlines indicating the near-wake region of the jet are shown in *Fig. 2b*, highlighting the steady features of the flow field. The shear layer between the crossflow and the jet is represented by the black dotted lines, and the region outside the shear layer is termed the outer wake region. The velocity measurements were performed using a laser sheet parallel to the X-Y plane which is perpendicular to the initial jet trajectory as it exits the nozzle. Henceforth, the X-Z planes will be referred to as planes parallel to the jet axis and X-Y planes will be referred to as jet cross-section planes.

Table 1, Test matrix for the simultaneous PIV/OH-PLIF study:

Crossflow Operating Condition						
Operating Pressure (bar)				5.5		
Operating Temperature (K)				723		
MCZ air flow rate (kg/s)				0.39		
MCZ equivalence ratio, ϕ_{MCZ}				0.5		
Reynolds Number (NR)				105,000		
Reynolds Number (R)				61,000		
Jet Conditions						
CASE	TYPE	Jet Type	Momentum Flux Ratio, J	Density Ratio, S	Jet Reynolds Number, Re_{JET}	
1	NR	Air	3	1	16900	
2	NR	Air	8	1	27600	
FUEL Jet					40%/60%	
3	R	H_2/N_2	3	4.25	72,000	$\Delta T = 28$ K
4	R	H_2/N_2	8	4.25	118,000	$\Delta T = 44$ K
					$\phi_{JET} = 0.9$	
5	R	Premixed NG	3	2.5	27,500	$\Delta T = 36$ K
6	R	Premixed NG	8	2.5	45,000	$\Delta T = 64$ K

2.3 Diagnostic Techniques

2.3.1 OH-PLIF System

The OH PLIF system consists of a HRR diode-pumped, Q-switched Nd:YAG slab laser (Edgewave – IS8IIDZ) that pumps a dye laser (Sirah Credo). The frequency-doubled output of the dye laser was tuned to the strong $Q_1(8)$ transition (at 283.2 nm) of the OH A-X (1,0) band. The laser system

was operated at 10 kHz with pulse energy of 0.5 mJ at 283 nm. A reference leg was integrated to continuously monitor the dye laser power output and tune the wavelength as needed. The first surface reflection from an uncoated fused silica window directed a small amount of the total beam energy through a Bunsen flame. The resulting LIF signal was collected with a photomultiplier tube and the average signal monitored with a Stanford Research Systems boxcar integrator and an oscilloscope. For measurements in the test rig, the laser beam was collimated and focused using a 1000-mm focal length spherical lens, a cylindrical lens of -25.4 mm focal length and finally by a 300 mm focal length cylindrical lens. This lens system was used to form a laser sheet that was 35 mm wide and less than 1 mm thick. A three-dimensional schematic diagram of the simultaneous PIV/PLIF system, presented in *Fig. 3*, shows the orientation of both the 532 nm and 283 nm laser sheets as they were directed into the windowed combustor. The OH-PLIF signal was focused onto a high-speed image intensifier (LaVision IRO) using a 100-mm focal length, f/2.8 ultraviolet (UV) camera lens (Soden Cerco Type-2178). An optical band-pass filter (Semrock 320/40) was fitted to the lens to transmit the fluorescence and to suppress background flame luminosity although OH* chemiluminescence can be suppressed only through intensifier gating. The intensified signal was detected using a high-speed camera (Phantom v7.4). The intensifier time gate was set to 100 ns to suppress background luminosity from OH*.

2.3.2 PIV System

The PIV laser was a HRR, dual-cavity, diode-pumped solid-state Nd:YAG laser (Quantronix Dual Hawk 80-M). Each of the laser cavities produces a 532 nm beam with a pulse energy of 3.5 mJ at 10 kHz. The time delay between the two PIV laser pulses was set to 10 μ s in order to optimize the measurement dynamic range. The PIV laser sheet was formed using a 1000-mm focal length spherical lens, a cylindrical lens of -50-mm focal length and a 250-mm cylindrical lens. The resulting laser sheet was 35 mm wide and less than 1 mm thick. The two camera systems (OH-PLIF and PIV camera systems) were installed perpendicular to each other with a second dichroic mirror to separate the signals. A

fluidized bed was used to seed the flow field with TiO₂ particles (nominal diameter of 250 nm) with the jet fluid. The scattered light from the particles was collected using a second high-speed CMOS camera (Photron SA-5) and a 105-mm focal length Nikon f/2.8 lens (operated at full aperture). A custom ultra-steep band-pass filter (3-nm FWHM centered on 532 nm) was used to suppress background luminosity.

Application of PIV in high-temperature and high-pressure flows with optical windows also faces additional challenges. Due to the presence of non-uniform temperature and density gradients in turbulent flames, PIV measurements are affected by non-uniform seeding. As a result the peak correlation values are lower as compared to an isothermal flow field. In addition, at high temperature, the quartz windows soften, causing seed particle fouling and, consequently, increased background measurement noise. Indeed, accumulation of seed on the windows limits the total measurement duration. When the scattering from particles on the windows is too intense, the experiment must be concluded and the windows replaced.

2.3.3 Laser Systems Integration

The temporal synchronization of the two lasers and the imaging systems was accomplished with an external timing pulse generator (Quantum Composer model 9520). The OH-PLIF laser pulse was delayed from the first PIV pulse by $\frac{\Delta t}{2}$ (5 μ s). Laser pulse timings were continuously monitored by photomultiplier tubes connected to an oscilloscope. A dichroic beam-splitter, with high transmissivity at 532 nm and high reflectivity at 283 nm, was used for the spatial overlap of the two laser sheets. Alignment and overlap of the lasers sheets was confirmed both in the near- and far field. Calibration of the images was accomplished (just before the start of each experiment) with a dual-plane dot target (LaVision Type 05).

Fig. 3. Schematic diagram of the high-repetition-rate simultaneous PIV/OH-PLIF experimental setup.

2.4 Data Post Processing

2.4.1 OH-PLIF Image Processing

The raw OH-PLIF images collected required image corrections to remove the background signal and to account for the non-uniformity in the laser sheet intensity profiles and fixed-pattern noise from the intensified CMOS detector. In order to correct the OH-PLIF images, three steps were followed. First, the images were calibrated and scaled to physical space. Next, background subtraction was performed using the time-averaged background image acquired after the measurements at each measurement plane were concluded. The background image was acquired with the laser sheet blocked but with the combustor operating. The non-uniformity in the CMOS detector was then corrected by flat-field correction. For this purpose, a diffuse light source was placed in front of the intensified camera and a set of flat-field images was collected. The background-corrected OH-PLIF images were divided by the ensemble-averaged flat-field image. For the laser sheet intensity correction, a set of OH-PLIF images of the vitiated crossflow were acquired at every measurement plane with the jet flow turned off. The OH distribution in the vitiated crossflow was assumed to be uniform, and thus any non-uniformity in the OH-PLIF images results from laser sheet non-uniformity and imaging artefacts such as intensifier/camera

fixed-pattern noise. The OH-PLIF images of the reacting jets at every plane were divided by the respective ensemble-averaged OH-PLIF images of the vitiated crossflow.

A MATLAB image processing algorithm was developed for flame front/edge detection in the processed images. A two-dimensional median filter and an adaptive noise removal filter (Wiener2) were used to remove the high-frequency noise in the images. A two-dimensional gaussian averaging filter of size 5x5 pixels was used to filter the fine scale structures that is not be resolved by the velocity vectors. The gradient of the filtered images were then calculated. The gradients above a fixed threshold were accepted for further processing. The OH-PLIF gradient field was binarized, and a morphological operation was applied onto the binarized images that thin objects to a single pixel lines. The output of the flame-front detection algorithm was stored as the flame-front edge.

2.4.2 Velocity Vector Field Computation

The PIV images were pre-processed before vector computation. Similar to the OH-PLIF image correction, the PIV images were spatially calibrated and then corrected by subtracting an average background image from each of the image pairs. The particle image intensity was then normalized to correct for the non-uniformity in the particle intensity field due to laser sheet intensity variations. The vector field was then computed using LaVision software, version 8.2.0. A detailed analysis based on the particle density, the time delay between the two laser pulses, and the cross-correlation was performed to balance the cross-correlation strength and resolution. A multi-pass cross correlation technique featuring an auto-adaptive interrogation window with a first pass window size of 64x64 pixels to a window size of 16x16 pixels with 50% overlap between the image pairs was used for computing the vector field.

A sequence of instantaneous Mie scattering images for the $J=8$, 40% H_2 /60% N_2 case at the $Z = 5$ mm measurement plane is shown in *Fig. 4*. The particles issuing from the jet are flowing towards the bottom right corner of the image due to the influence of the swirling crossflow. These raw image sequences provide qualitative information on the mean direction of the flow field. The non-uniformity

of the particle seeding in these images is due to mixing with the unseeded crossflow fluid as well as the local heat release. Since, the flow field is seeded through the jet fluid only, a masking function was used to mask out the regions without the particles. The masking function included a geometric mask that allowed the cross-correlation algorithm to compute vectors within a rectangular region bounded between $X = -5$ mm to $X = -27.5$ mm and $Y = -30$ mm to $Y = 15$ mm, within the white rectangular region shown in the Mie scattering images. In order to avoid vector computation from the regions without any particles a threshold function was used that ensured vector computation was performed only from the particles scattering the laser. The field of view utilized to perform the cross correlation was 35 mm x 55 mm, with a vector resolution of 0.8 mm. Based on these parameters, the total number of rejected vectors varied between 15 and 25% and the vector quality factor (Q-factor) was always maintained greater than 1.5, where the Q-factor is defined as the ratio between the two highest correlation peaks. In order to capture the turbulent statistics, a total of 10,000 image pairs were acquired for each measurement, which corresponds to a data acquisition time of 1.0 s at a rate of 10 kHz.

Fig. 4. A sequence of background subtracted PIV images in a measurement plane 5 mm from the nozzle exit plane, for the reacting jet case of $J=8$ and 40% H_2 /60% N_2 .

3. Results and Discussions

The flow field of interest in this study was a reacting jet injected transversely into a swirling vitiated crossflow. Performing PIV measurements where only the jet is seeded introduces bias in the overall magnitude of the velocity field. When a jet is injected transversely, it creates a blockage for the incoming crossflow; as a result there will be difference in the velocity magnitude obtained by seeding only the jet or the crossflow. This bias was addressed in an earlier study [25] and is quantified for these experiments as well. It was observed that the x-component of velocity was approximately 10-15 m/s lower within the shear layer regions for the jet seeded cases as compared to the crossflow seeded case. Also the crossflow seeded case did not capture the recirculation region due to the lack of particles entrained into the inner wake region. Due to this bias the velocity data needs to be carefully interpreted.

Fig. 5, shows the spatial distribution of the number of vectors computed for the $Z = 5$ mm measurement plane for the reacting jet case $J = 8$, 40% H_2 /60% N_2 . For a reliable computation of the time averaged vector field, velocity vectors at any spatial location appearing less than 1000 times out of the 10000 snapshots (or 10% of the number of snapshots) were rejected, thus, ensuring vector computation from locations with continuous seeding. It is evident from *Fig. 5* that except for region above $Y = 12.5$ mm and below $Y = -35$ mm, the number of velocity vectors computed at every spatial location exceeds 8000. This indicates that the instantaneous vector fields are computed reliably for most of the spatial locations. Furthermore, the velocity fields were extracted from three time slices of 0.2 s, i.e., 0 – 0.2 s, 0.4 – 0.6 s and 0.8 – 1.0 s, and time-averaged velocity field was computed for each of these time slices. *Fig. 6* shows the time averaged velocity vectors computed from all 10,000 images and compares it with the time-averaged field computed from velocity maps extracted from each 0.2-s slice. The time-averaged velocity fields computed from the time slices are then subtracted from the overall time average field to identify the regions with significant variation in the velocity magnitude. *Fig. 7*

shows that out of the 1620 vectors computed more than 90% of the spatial locations have a velocity magnitude difference less than 2 m/s. The velocity magnitude differences are as high as 10 m/s within the recirculation region and about 20 m/s for all three time slices above the injector and for the region below $Y = -30$ mm.

Fig. 5, Distribution of number of vectors computed at each of the spatial location in a measurement plane 5 mm from the nozzle exit plane, for the reacting jet case of J 8 and 40% H_2 /60% N_2 .

Fig. 6, The time-averaged velocity vectors overlaid on velocity magnitude averaged over (a) 0 - 1 s, (b) 0 - 0.2 s, (b) 0.4 - 0.6 s and (c) 0.8 - 1.0 s for $J = 8$; 40% H_2 /60% N_2 case measured at $Z = 5$ mm away from the nozzle exit.

Fig. 7, The difference velocity field by subtracting the time averaged velocity field of (a) 0 - 0.2 s, (b) 0.4 - 0.6 s, and (c) 0.8 - 1.0 s from the time-averaged velocity field of 0 - 1 s, for $J = 8$; 40% H_2 /60% N_2 case measured at $Z = 5$ mm away from the nozzle exit.

3.1 Time Averaged Flow Field

3.1.1 Velocity Field

The swirling nature of the crossflow velocity field has been discussed previously [25], indicating the change in the flow direction with an increase in distance from the nozzle exit. The directions of the velocity vectors in the planes $Z = 5, 10$ and 15 mm are towards the bottom corner of the image and that in the planes $Z = 45$ and 50 mm are towards the top corner of the image, indicating the swirling motion of the crossflow.

The resulting time-averaged velocity vectors, overlaid on a z -vorticity contour map for the reacting jet cases of $J = 8$ and $J = 3$ are shown in *Fig. 8* and *Fig. 9*, respectively. The jet fluid is 40% H_2 /60 % N_2 . The measurement locations correspond to the $Z = 5$ mm, 10 mm and 15 mm planes. For better clarity in the presentation of the vector field, every second vector is shown in both the x - and y -directions. A pair of counter-rotating wake vortex structures is evident at $Z = 5$ mm for both the reacting jet cases. In the contour map of z -vorticity, red represents a counter-clockwise rotation and blue represents a clockwise rotation. The nozzle exit is represented by the concentric circles centered at $X = 0$ mm, $Y = 0$ mm. The jet fluid interacts with the incoming crossflow by forming the shear layer that surrounds the wake of the jet. Within the two shear layers, there are two distinct regions. A strong recirculation region is evident between the two flows at $Z = 5$ mm. The recirculation region is a characteristic feature of the wake of the jet. The flow field can be divided into three locations identified as the lower shear layer (LSL), upper shear layer (USL) and recirculation region (RR). The wake vorticity entrains the jet fluid and the crossflow fluid within the wake of the jet, leading to chemical reactions and stabilization of a reaction zone. The magnitude of vorticity decreases as the distance from the nozzle exit plane increases, which suggests that the vortex structure is a characteristic flow structure of the wake of the jet. The zone of influence of the wake structure is smaller for the $J=3$ case, as compared to the $J=8$ case, which is an expected result because the higher J jet has deeper penetration into the crossflow. Thus, multi-plane

measurements provide an insight into the zone of influence of the wake of the jet. The time-averaged velocity fields were combined to generate a time-averaged, three-dimensional wake structure for the $J = 8$ case, as shown in *Fig. 10*. The structure shown in *Fig. 10* is a vorticity iso-surface for a z -vorticity magnitude of $\pm 5000 \text{ s}^{-1}$. The location of the nozzle is included in the figure, and the nozzle exit is at $Z = 0 \text{ mm}$. The three-dimensional perspective view of the wake structure shows its spatial evolution with respect to the jet axis.

Fig. 8, The time-averaged velocity vectors overlaid on top of z -vorticity contour map for $J = 8$; 40% H_2 /60% N_2 case measured at a) $Z = 5 \text{ mm}$, b) $Z = 10 \text{ mm}$ and c) $Z = 15 \text{ mm}$ away from the nozzle exit.

Fig. 9, The time-averaged velocity vectors overlaid on top of z -vorticity contour map for $J = 3$; 40% H_2 /60% N_2 case measured at a) $Z = 5$ mm, b) $Z = 10$ mm and c) $Z = 15$ mm away from the nozzle exit.

Fig. 10 Iso-surface of time-averaged out of plane vorticity (ω_z) for $J = 8$; 40% H_2 /60% N_2 case indicating the evolution of the wake vortex structure. The orange arrow indicates the direction of the crossflow. The wake structure is a vorticity iso-surface of $\pm 5000 \text{ s}^{-1}$

3.1.2 OH-PLIF Intensity Field

Time-averaged OH-PLIF intensity fields (each from 10,000 instantaneous images) are shown in *Fig. 11*, highlighting the mean structure of the jet flame and its variation across $Z = 5, 10$ and 15 mm. The mean OH-PLIF intensity shows the presence of the flame front along the windward side of the jet; however, OH-PLIF intensity is lower here than in the rest of the reaction zone. The core of the jet, with zero intensity, enveloped between the flame front along the windward side of the jet and the wake region reaction zone is evident at $Z = 5$ and 10 mm measurement planes. The recirculation region that entrains burnt products as well as unburnt reactants shows a broad region of OH-PLIF intensity.

Fig. 11, The time-averaged OH-PLIF intensity field for $J = 8$; 40% H_2 /60% N_2 case measured at a) $Z = 5$ mm, b) $Z = 10$ mm and c) $Z = 15$ mm away from the nozzle exit.

3.2 Length Scale and Flow Field Dynamics

3.2.1 Integral Length Scales

The two-point correlation function has been used in highly turbulent and non-homogenous flow fields, such as swirling flows, free shear jet flows, temporally evolving wakes etc., to compute the integral length scales [17][27][28]. A self-similar two-point correlation profile implies that the turbulent processes producing and dissipating energy at different length scales are in equilibrium as

the flow evolves. However, in a highly three-dimensional reacting flow field, a self-similar two-point correlation profile may not be observed. This is due to the inhomogeneity in density and temperature leading to changes in the rate of dilatation of the local flow-field. As a result, the non-reacting velocity field is considered for the computation of the two-point correlation in this case. Due to the presence of swirling motion the non-reacting flow-field will still have anisotropy and thus, the purpose of discussion in this section is to highlight the variation of integral length scale across the measurement planes.

A coordinate transformation was performed on the velocity field by rotating it by 45 degrees in a counterclockwise direction (this corresponds to the mean velocity angle calculated from the crossflow velocity vectors [25] at the planes $Z = 5, 10$ and 15 mm), with the new coordinates X' and Y' . With the coordinate transformation the two-point correlation function can be calculated along the streamwise and spanwise direction of the mean velocity vectors in the measurement planes. *Fig. 12*, shows the coordinate-transformed, time-averaged velocity field overlaid on the vorticity magnitude for the non-reacting jet case of $J = 8$ at $Z = 5$ mm. The fluctuating component of the velocity field was sampled from a windowed region, shown in the green rectangular box that includes the upper and lower shear layer region. The region of interest was from $X' = -2.5$ to $X' = 27.5$ mm and $Y' = -15$ to $Y' = 15$ mm. The two-point correlation function is defined as

$$\rho_{ij}(r) = \frac{\langle u'_i(x_o)u'_j(x_o+r) \rangle}{\langle u'_i(x_o)u'_j(x_o) \rangle} \quad \text{Equation 2}$$

The correlation function computed in the streamwise direction consists of the combined characteristics of longitudinal and transverse two-point correlation functions. However, the correlation function computed in the spanwise direction consists of the characteristics of the transverse two-point correlation function only. The streamwise (ρ_{ii}) and spanwise (ρ_{ij}) two-point correlation coefficients are plotted as a function of separation distance normalized by the jet exit diameter, r/d_{JET} , as shown in *Fig. 13a and b*. *Fig. 13a* shows that the streamwise two-point correlation coefficient for the lower shear layer region, $Y'/d_{JET} < 0$, decays to zero within one jet diameter. However, for the upper shear layer region, $Y'/d_{JET} >$

0, the correlation approaches zero within two jet diameters. This implies that the streamwise integral length scales are larger for the upper shear layer region of the flow field. *Fig. 13b* shows the spatial variation of the transverse two-point correlation function. The trend indicates that closer to the nozzle exit, $X'/d_{JET} < 0.75$, the correlation value decays faster than at greater X' . The streamwise (Λ_{11}) and spanwise (Λ_{22}) integral length scales at a given point, x_o , can be calculated by computing the area under the two-point correlation curve [29]:,

$$\Lambda_{ij} = \int_0^\infty u'_i(x_o)u'_j(x_o + r) dr \quad \text{Equation 3}$$

Fig. 14, shows the Λ_{11} and Λ_{22} computed in the streamwise and spanwise direction at measurement planes $Z = 5, 10$ and 15 mm. The Λ_{11} from all three measurement planes show two peaks at $Y'/d_{JET} = -0.75$ and 0.5 , that correspond to the LSL and USL regions of the flow field, respectively. The Λ_{22} increases monotonically along the streamwise direction, with length scales as large as the size of jet exit diameter being observed. This suggests a spatially evolving wake flow field. Across all the three measurement planes, the Λ values at $Z = 15$ mm are the smallest. In the current experiment, the final interrogation window size provides a vector resolution of 0.83 mm, which corresponds to 4 and 12 grid points over the span of the smallest and largest computed integral length scales. With this resolution, the computation of spatial gradients, vorticity and strain rate can be performed with greater accuracy; however, analysis of flow properties based on spatial gradients needs to be carefully assessed due to the risk of aliasing and bias uncertainties.

Fig. 12 Coordinate transformed time-averaged velocity vectors overlaid on top of z -vorticity contour map for non-reacting jet of $J=8$ measured at $Z=5$ mm.

Fig. 13 Spatial variation of (a) streamwise and (b) spanwise two-point velocity correlation coefficient for non-reacting jet, $J=8$ measured at $Z=5$ mm.

Fig. 14 Spatial variation of (a) streamwise and (b) spanwise integral length scale for non-reacting jet, $J = 8$ measured at $Z = 5, 10$ and 15 mm.

3.2.2 Velocity Power Spectra

In a turbulent reacting flow, the velocity field has a broad spectrum of temporal scales, and measurements at 10 kHz can resolve some of these scales. In order to extract the wake dynamics, velocity fluctuation statistics are extracted from three locations—at the LSL, the USL, and the RR, —for the $J=3$ and $J=8$ reacting jet cases for 40% H_2 /60% N_2 jet fluid at $Z = 5$ mm, as shown in Fig. 15. To characterize the dynamics of the wake of the jet, it is of interest to examine whether the vortical structures flow past a fixed point with a characteristic frequency. The power spectra of the x-component of velocity (V_x), as shown in Fig. 16 and Fig. 17, are broad with multiple peaks in the frequency domain. However, the peak frequency is found to be the same for all the three locations for the reacting jet: 552 Hz for the $J=3$ case and 565 Hz for the $J=8$ case. A wake Strouhal number (St_{wake}) is computed based on the peak frequency (f_{wake}), jet exit diameter (D) and mean crossflow velocity (U_∞):

$$St_{wake} = \frac{f_{wake} D}{U_\infty} \quad \text{Equation 4}$$

In earlier studies of the wake of an isothermal transverse jet [8] [9], the wake vortices were well characterized. The Strouhal number corresponding to the wake vortex shedding in these studies ranged

between 0.1 – 0.15. Similarly, based on our analysis, the wake Strouhal number is found to be 0.15, which could imply that this corresponds to the wake vortex shedding. Based on this observation of the characteristic frequency of the wake, it is hypothesized that the associated dynamics are the result of wake vortex shedding around the jet. Thus, with an increase in J the change in the frequency of velocity fluctuations is found to be minimal. The values of St_{wake} computed for all of the RJICF cases are shown in *Table 2*. It is interesting to see that St_{wake} is found to be within a narrow range of 0.13 – 0.15 for all the JICF/RJICF cases, irrespective of J or fuel reactivity. The peak frequencies for the non-reacting jet are found to be one-third of the peak frequencies for reacting jet cases. The crossflow mean velocities for the non-reacting and reacting cases are 13 m/s and 36 m/s, respectively. Thus, it can be concluded that the dynamics of the wake flow field of the reacting jet are more strongly dependent on the crossflow velocity than on the jet injection parameters.

Fig. 15, time averaged flow streamlines indicating the three monitor points, viz., upper shear layer (USL), recirculation region (RR) and lower shear layer (LSL) used to extract flow dynamics.

Fig. 16, Velocity power spectra of the x component of velocity (V_x) extracted from a) upper shear layer (USL), b) lower shear layer (LSL) and recirculation region (RR) for $J=3$ case at $Z = 5$ mm. The plot indicates presence of a dominant peak in frequency at $f = 552$ Hz.

Fig. 17, Velocity power spectra of the x component of velocity (V_x) extracted from a) upper shear layer (USL), b) lower shear layer (LSL) and recirculation region (RR) for $J=8$ case at $Z = 5$ mm. The plot indicates presence of a dominant peak in frequency at $f = 565$ Hz.

Table 2, Wake Strouhal number (St_{wake}) for all the test cases.

Case	TYPE	Momentum Flux Ratio, J	Jet Type	Fuel Concentration	f_{wake} (Hz)	St_{wake}
1	NR	3	Air	NA	172	0.132
2	NR	8	Air	NA	172	0.132
3	R	3	Premixed NG	$\Phi = 0.9$	540	0.15
4	R	8	Premixed NG	$\Phi = 0.9$	530	0.147
5	R	3	H ₂ /N ₂	40%/60%	552	0.153
6	R	8	H ₂ /N ₂	40%/60%	565	0.157

3.3 Flow Flame Interactions

Time-averaged data provide insight into the steady features of the flow field. A close inspection of a sequence of instantaneous measurements discussed in this section will reveal new insights into the flow-flame interactions of the reacting jet. A sequence of 10 instantaneous velocity fields and OH-PLIF images for the J = 8 reacting-jet case (40% H₂/60% N₂) is shown in *Fig. 18*. This sequence captures some of the unsteady features and transient events such as vortex-flame interactions, flame shedding, and flame-detachment due to local extinction.

3.3.1 OH-PLIF Intensity

A 1-ms sequence of images of flame-front edges is shown in *Fig. 18*. A thin reaction front above the location of the injector, corresponding to the windward side of the jet, is evident in all the OH-PLIF images. The sharp intensity gradient indicates that H₂ burns like a diffusion flame within the windward side of the jet. However, the wake of the jet promotes mixing of H₂ with the entrained hot products and vitiated crossflow. The wake of the jet provides favorable flow conditions to sustain a stable reaction zone. The sequence of images shown in *Fig. 18*, is illustrative of the complex flame structure in the wake of the reacting jet. The reaction front has a characteristic kidney shaped structure, which can be

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3 attributed to the interaction of the wake vortices with the flame front. The image sequence also shows
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5 regions with local extinction and re-ignition in the upper and lower shear layer, which could be attributed
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7 to localized high compressive strain rates. However, it has been reported that the presence of flame holes
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9 and apparent extinction/ re-ignition is sometimes attributed to through-plane motion of the flame front
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11 [30], [31]. Between 0.1 ms and 0.3 ms, at the location $X = 10$ mm, $Y = 10$ mm, flame re-ignition may
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13 be occurring, but this behavior, alternatively, might be due to through-plane flame propagation. An
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15 interesting behavior is seen between 0.6 ms and 1.0 ms, within the region $X = 15$ and 20 mm and $Y = -$
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17 20 and -25 mm: the flow field is pushing the reaction front downstream; simultaneously, it appears that
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19 the flame front is being wrapped around a vortex structure. This event continues and results in thinning
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21 of the flame front until 1.0 ms, eventually leading to a local extinction at $X = 20$ mm and $Y = -24$ mm.
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23 This transient event will be further discussed quantitatively in Section 3.2.2. The image sequence
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25 captures another interesting transient event observed between 0.3 ms and 0.6 ms where the flame front
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27 stretches, elongates and forms a neck at $X = 15$ mm and $Y = 10$ mm seen ($t = 0.5$ ms). The necked region
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29 eventually separates from the main body of the reaction zone and is convected downstream. This
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31 behavior can be related to a sudden acceleration in the flow field that causes localized high compressive
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33 strain rates, leading to flame separation from the main reaction zone. Thus, in order to extract quantitative
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35 information concerning these transient behaviors, it is also important to obtain velocity, vorticity and
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37 strain rates.
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Fig. 18, Sequence ($\Delta t = 0.1$ ms) of images in RJICF flame front edges overlaid on top of OH-PLIF images— time separation = 0.1 ms, for reacting jet case of $J=8$, 40% H_2 /60% N_2 at $Z = 10$ mm.

3.3.2 Vortex-Flame Interactions

Fig. 19 shows the flame edges, extracted from the OH-PLIF intensity field, and velocity vectors overlaid on a contour map of velocity magnitude with range between 0 m/s (blue) and 75 m/s (red). For better clarity in the vector field, every second vector is shown in both x- and y-directions. The interface between the inner and outer wake regions exhibits the highest magnitudes of velocity, and the recirculation region features a low velocity region V_x , with velocity vectors pointing against the direction of swirl. The fluid along the two shear layers pushes the reaction zone downstream, while the fluid within the recirculation-region pushes the reaction zone towards the nozzle exit. The image sequence between time 0.1 ms and 0.5 ms shows high velocity magnitude within the upper shear layer, which

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3 correlates well with the transient event of necking of the reaction front, followed by separation from the
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5 main flame body. *Fig. 20* shows the sequence of out-of-plane vorticity magnitude (-20000 s^{-1} to 20000
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7 s^{-1}), which provides additional insight into the vortex - flame interactions. The red in the contour map
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9 represents counter clockwise rotation and blue represents clockwise rotation. A vortex structure, at 0.5
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11 ms (with a counter-clockwise rotation represented by red contour), located at $X = 5 \text{ mm}$ and $Y = -15 \text{ mm}$,
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13 appears to push the flame front downstream. It is also evident that the flame front wraps around this flow
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15 structure, thus increasing the flame surface area and simultaneously thinning the reaction front. At 1.0
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17 ms a local extinction is evident at the location $X = 16 \text{ mm}$ and $Y = -24 \text{ mm}$, which could be due to the
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19 combined effect of higher instantaneous values of vorticity and high compressive strain rates. Thus, it is
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21 clear that the wake vortices have a strong influence on the flame front, causing thinning leading to local
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23 extinction. It is also evident that the wake structures entrain the surrounding hot products and unburnt
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25 fuel-air mixture into the recirculation region, which promotes mixing and helps to stabilize the reaction
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27 zone.
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Fig. 19, Sequence ($\Delta t = 0.1$ ms) of images in RJICF flame front edges overlaid against contours of velocity magnitude and velocity vectors, for reacting jet case of $J=8$, 40% H_2 /60% N_2 at $Z = 10$ mm.

Fig. 20, Sequence ($\Delta t = 0.1$ ms) of images in RJICF flame front edges overlaid against contours of vorticity, for reacting jet case of $J=8$, 40% H_2 /60% N_2 at $Z = 10$ mm.

3.3.3 Local Flame Extinction

The flame edges and velocity vectors overlaid on top of compressive strain (derived for the velocity field) are shown in *Fig. 21*. This sequence of images features an instance of flame detachment from the main reaction zone due to adverse flow conditions. It is evident that the flame front, between 0.3 ms and 0.6 ms, stretches, elongates and forms a neck. As discussed in section 3.3.2, the high-speed fluid in the upper shear layer pushes the flame front further downstream, which also increases the magnitudes of local compressive strain rates. At 0.4 ms and $X = 10$ mm and $Y = 10$ mm, the reaction front starts to wrinkle and distort. This region of high compressive strain (greater than -20000 s^{-1}) acts on the flame front for a duration of 0.4 ms, which eventually leads to detachment of a small pocket of reacting fluid from the main flame body, as seen at 0.7 ms. The relationship between the principal compressive strain rate and the scalar dissipation rate has been investigated extensively in a laboratory scale burner [32]. The highly three-dimensional nature of the flow field requires measurement of all three-components at two parallel planes for accurate computation of strain rate and vorticity. It has been postulated that if the z-axis is the principal axis, two-dimensional flow information is sufficient to compute the in-plane principal strain rate [32]. Hence, the PIV data, which provide only four out of the nine strain rate tensor components, would be sufficient for computing in-plane strain rate. Previous experimental and numerical studies have indicated that the maximum scalar gradient tends to align with the axis of the principal compressive strain [33] [34] and the strongest dissipation layers form orthogonal to this axis. The thinnest reaction fronts are also found to be normal to the axis of principal compressive strain [33]. The total duration for which the critical value of compressive strain acts on the reaction zone also dictates if local extinction will occur.

Fig. 21, Sequence ($\Delta t = 0.1$ ms) of images in RJICF flame front edges overlaid against contours of minimum principal normal strain, for reacting jet case of $J=8$, 40% H_2 /60% N_2 at $Z = 10$ mm.

3.3.4 Flame Structure Variation due to Fuel Reactivity

Fig. 22 compares the flame structure for reacting jet cases of H_2/N_2 and premixed natural gas with a momentum flux ratio of $J = 8$, measured at $Z = 10$ mm. The wake structure interacts with the flame front in a similar manner, as the flame structure for both the cases has the characteristic kidney shape. The main difference between the flame structures for the two fuels is the presence of a thin flame front on the windward side of the H_2/N_2 jet flame. For a fixed J , the in-plane strain rates are approximately same for both H_2/N_2 jets and premixed NG jets. However, the reaction zone in case of a premixed NG jet starts downstream of the jet injection point unlike with H_2/N_2 jets. This difference in the flame structure is mainly due to lower flame speed and higher propensity for strain-induced extinction in case of a premixed NG flame.

Fig. 22, Flame front edges overlaid on top of OH-PLIF image for reacting jet case of (a) $J=8$; H_2/N_2 and (b) $J=8$; premixed NG.

4. Conclusion

In this work we have presented the results of high resolution temporal and spatial measurements in an optically accessible, high-pressure staged combustion system. Simultaneous two-component particle image velocimetry (PIV) and planar laser-induced fluorescence of the OH radical (OH-PLIF) were performed at a repetition rate of 10 kHz. The test rig features a main combustion zone (MCZ) and a secondary combustion zone (SCZ). The secondary combustion zone (SCZ) features a reacting jet in crossflow (RJICF) injected into a swirling vitiated crossflow, which was optically accessible.

The measurements were performed at 3 different planes along the cross-section of the jet at planes $Z = 5, 10$ and 15 mm away from the nozzle exit. Two jet momentum flux ratios, $J=3$ and $J=8$, were studied for reacting jet cases with jet fluids consisting of either 40% H_2 /60% N_2 or premixed natural gas and air (NG/air, $\phi_{jet} = 0.9$). The PIV measurements clearly show the influence of swirling crossflow on the reacting jet. Multi-plane velocity measurements give insight into the extent of penetration of the jet, based on the size and vorticity magnitude of the wake structure. As expected, the $J=8$ case had a deeper penetration into the flow field as compared to $J = 3$ case. A three-dimensional wake vortex structure was generated using the time averaged velocity data at the three different interrogation planes for $J = 8$ case. This analysis gives an approximate size of the upright wake vortices.

The instantaneous PLIF images were processed to generate flame front edges using a MATLAB-based edge detection algorithm. The instantaneous sequences of velocity vectors (and the derived quantities) overlaid on the reaction zone and various other flow variables provided significant insight into the flow-flame interactions and local-extinctions associated with the RJICF. The wake structure distorted and elongated the flame fronts, eventually causing local extinction due to high rates of scalar

dissipation. The combined influence of high vorticity magnitude and the planar compressive strain rate were identified to be critical in causing flame detachment events. The flame structure for H₂ diffusion flames and the premixed NG flames were found to be similar within the wake of the jet. The reaction zones (in both diffusion and premixed flames) had a characteristic kidney shape, due to the interaction of the jet fluid with the wake vortex structure. The difference in the flame structure of H₂/N₂ diffusion flame and premixed NG flame is apparent in the windward side of the jet. A thin flame front is seen on the windward side for the H₂/N₂ jet. This difference in flame structure is attributed to firstly, the higher flame speed for a H₂ flame as compared to a premixed NG flame under identical conditions, and secondly, to the higher propensity for strain-induced extinction in case of a premixed NG flame.

The velocity field of the non-reacting jet cases was analyzed to extract the variation of integral length scale across the measurement planes. The two-point correlation function was computed along the streamwise and spanwise direction of the mean flow field and it was found that the correlation value decays at a slower rate in the streamwise direction than in the spanwise direction. The integral length scale is found to be non-uniform along the measurement plane; however, the spatial variation trend was consistent across all the three measurement planes.

The velocity power spectra showed a broad spectrum of temporal scales present in the flow field of the RJICF. The peak frequency of velocity fluctuation ranges between 530 – 570 Hz for all the RJICF cases. The analysis led to an interesting finding that shows that the wake Strouhal number—which is based on the peak frequency, the jet exit diameter and the mean crossflow velocity—lies within a range of 0.13 – 0.15 for all the JICF/RJICF cases studied. The crossflow mean velocities for the non-reacting and reacting cases are 13 m/s and 36 m/s, respectively, and the corresponding vortex shedding frequency for the RJICF is approximately 550 Hz and that for the JICF is 172 Hz. This suggests that the vortex shedding frequency scales with the mean crossflow velocity magnitude, but further analysis may be needed to support this statement.

The RJICF also serves as an important test case for the development of numerical models for turbulent reacting flow fields typical of gas turbine combustors. High data rate measurements similar to those discussed in this paper will provide significantly improved understanding of the complex processes of fuel/air mixing and validation data for critical development of high-fidelity turbulence-chemistry interaction models.

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