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Non-Intrusive Laser-Induced Imaging for Speciation and Patternation in High Pressure Gas Turbine Combustors

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ABSTRACT

The next generation of gas turbine combustors for aerospace applications will be required to meet increasingly stringent constraints on fuel efficiency, noise abatement, and emissions. The power plants being designed to meet these constraints will operate at extreme conditions of temperature and pressure, thereby generating unique challenges to the previously employed diagnostic methodologies. Current efforts at NASA Glenn Research Center (GRC) utilize optically accessible, high-pressure flametubes and sector combustor rigs to probe, via advanced nonintrusive laser techniques, the complex flowfields encountered in advanced combustor designs. The fuel-air mixing process is of particular concern for lowering NO_x emissions generated in lean, premixed engine concepts. Using planar laser-induced fluorescence (PLIF) we have obtained real-time, detailed imaging of the fuel spray distribution for a number of fuel injectors over a wide range of operational conditions that closely match those expected in the proposed propulsion systems. Using a novel combination of planar imaging of fuel fluorescence and computational analysis that allows an examination of the flowfield from any perspective, we have produced spatially and temporally resolved fuel-air distribution maps. These maps provide detailed insight into the fuel injection process at actual conditions never before possible, thereby greatly enhancing the evaluation of fuel injector performance and combustion phenomena.

Keywords: Combustion, Optical Diagnostics, Planar Laser-Induced Fluorescence (PLIF), Imaging, Spray Flame

1. INTRODUCTION

This report describes progress in efforts to employ existing advanced diagnostic techniques to assist in the characterization and understanding of the physical processes encountered within the flowfields of experimental gas turbine combustors at NASA Glenn Research Center. With the advent of new and stiffer limitations on emissions from aircraft powerplants, combustion researchers are being forced to examine not only novel new combustor and sub-component designs, but innovative and preferably non-intrusive diagnostic methodologies as well. A goal, established by international committee, to reduce NOx emissions by 50% over 1996 levels, and the imminent implementation of a 70% reduction, demand that future engine designs operate at much higher temperatures and pressures than current combustor designs[1]. The extreme flow conditions of these new ultralow NO_x combustor designs do not lend themselves favorably to examination by existing diagnostic methods such as thermocouples and gas extraction via gas sampling probes. Therefore combustion researchers at NASA Glenn Research Center (GRC) have successfully implemented a suite of non-intrusive, optical diagnostic techniques to obtain spatially resolved imaging of flowfield phenomena within test rigs and flametubes, where conditions closely match the expected conditions in the new combustor designs.

The requirement to lower NO_x emissions by 50 to 75% over 1996 levels has led combustion researchers and engine designers to more closely examine the fuel injection process. NO_x formation is strongly dependent upon the local fuel-to-air ratio with research showing that NO_x production peaks near stoichiometric conditions (f/a = 0.068). This would indicate that unevenness in the fuel injection and mixing process could lead to locally fuel rich regions giving rise to nonuniform and enhanced production of NO_x. Indeed, Lyons[2] demonstrated that non-uniformities in the fuel injection process of lean, premixed flames produced localized fuel-rich regions that resulted in an increase in NO_x emissions. Current measurement methods such as gas sampling by water-cooled probes are inadequate to measure the fuel-air distribution. They can provide neither instantaneous, nor spatially and temporally resolved data, and since they are intrusive, probes adversely perturb the flow. To more closely examine the fuel injection process in lean burning engines, Mongia et al.[3] developed a fiber optic probe to make in-situ measurements of fuel-to-air ratio. Their technique, based upon the absorption of the 3.30 μm line of a HeNe laser by CH_4, was demonstrated in a turbulent, pilot-stabilized, pre-mixed flame at atmospheric pressure. While providing methane concentrations across the flow and a measure of the extent of mixing in a laboratory scale burner, this technique was limited to line-of-sight, and by physically intruding into the flow, it disturbed the very region in which the measurement was made. Furthermore, the fiber optic design would not stand-up to the extreme conditions found within an actual combustor.

Lee and Santavicca[4] also demonstrated a fiber optic probe to examine fuel-to-air distributions based upon laser-induced fluorescence (LIF). In their technique, demonstrated in a heated, non-reacting flowing cell at pressures up to 1.2 MPa, acetone was seeded into a steady flow and illuminated with the fourth harmonic of a pulsed Nd:YAG laser. The advantage of this technique is that the combustor required only one aperture through which the probe was inserted and aimed upstream, thereby possibly preventing perturbation of the area of the flow being examined. The laser excitation delivery and fluorescence capture was ingeniously accomplished using the same probe. While Lee and Santavicca's optical probe successfully demonstrated the capability to measure the mean and rms fluctuations of the equivalence ratio in a turbulent airjet, at temperatures and pressures representative of some combustors, it is basically a point measurement, and requires the addition of seed material. Another disadvantage is that while the LIF focal volume is located upstream from the probe and may not be perturbed by the probe, the probe itself intrudes into the main flow and as such, suffers from heat and depositional effects.

At NASA GRC efforts have been directed toward implementation a suite of complementary, nonintrusive, optical diagnostic methods to study the performance of gas turbine combustors and combustor subcomponents at realistic conditions[5,6]. In this previous work, imaging of fuel and OH PLIF, and planar Mie scattering (PMie)[7] was made possible through the use of thin-film, cooled windows located at the fuel injector exit plane. Using fuel PLIF and a novel software routine that allows 3-dimensional views of the flow, it has been possible to examine spray patternation and mixing efficiencies of various fuel injector designs. The present course of study was undertaken to investigate the potential for using existing imaging techniques to evaluate the fuel injection processes in high performance combustors and further, to develop a procedure to investigate fuel-to-air distribution at simulated engine conditions using Jet-A fuel. We present here fuel-to-air ratio (f/a) contour plots generated from fuel PLIF images obtained in the mixing region immediately downstream of an injector installed in a high temperature, high pressure flametube.

2. EXPERIMENTAL

2.1. Facility and Instrumentation

The engine research facilities at NASA Glenn were used to perform this study. The experimental setup is described in detail elsewhere[8]. In brief, the doubled dye output from a 10 Hz, Nd:YAG laser was tuned to UV wavelengths near 281.5 nm. Approximately 15 mJ of this laser beam, which has a divergence near 5 mrads, was allowed to freely expand through the 12 meter optical path. High damage threshold, wavelength specific mirrors operated by remote control, were used to direct the laser beam to the test rig. Prior to entering the test section, the beam was formed into a sheet by a 3 meter focal length cylindrical lens. The sheet dimensions at the focal volume was approximately 25 mm x 300 microns. The elicited fluorescence was collected perpendicular to the excitation beam through a f/4.5, 150 mm focal length UV lens and imaged using a gated, intensified CCD camera measuring 384 x 576 pixels. To isolate the various responses to the laser beam in the flow, a remotely controlled filter wheel was mounted in front of the detection lens. Up to four, narrowband interference filters were installed on this system. A 316 nm narrowband interference filter with 10.8 nm FWHM was used for measuring fuel PLIF. Other filters may be used to isolate Mie scattering and OH PLIF. At each test condition, the excitation laser sheet was traversed across the width of the insertion (top) window in 1 mm increments from –20 mm to +20 mm as measured from a predefined zero point located at the rig centerline. A computer program synchronized the movement of the ICCD camera with the laser sheet to maintain focus. In this manner, forty-one images were obtained for each one of a set of specific test conditions. The resulting set of data blocks were used to defined a particular injector's performance.

Figure 1 shows a schematic of the optically accessible test section used for this study. In the figure, the flow is from right to left. Excitation and data collection is accomplished through UV-grade, fused silica windows which measure 3.8 cm along the axis of the test section, 5.1 cm in the cross flow direction, with 1.3 cm thickness. A thin film of nitrogen cools each window maintaining an inner surface temperature below 977 K. Typical conditions used during this series of experiments ranged from mass flows of 1.13 – 3.63 kg/s, preheated inlet air temperatures of 533 – 810 K, inlet pressures of 90-250 psia, and equivalence ratios (ϕ) of 0.30 – 0.60. Jet A fuel was used as the fuel for all conditions. Fuel was injected into the main combustion airflow by means of a multi-point, crossflow, centerline injector of proprietary design[9]. In this design the fuel is radially injected into the combustion air from multiple injection points. The injected fuel and air mix over a considerable distance that is totally within the view of the window. The flame front is stabilized further downstream of the window location.

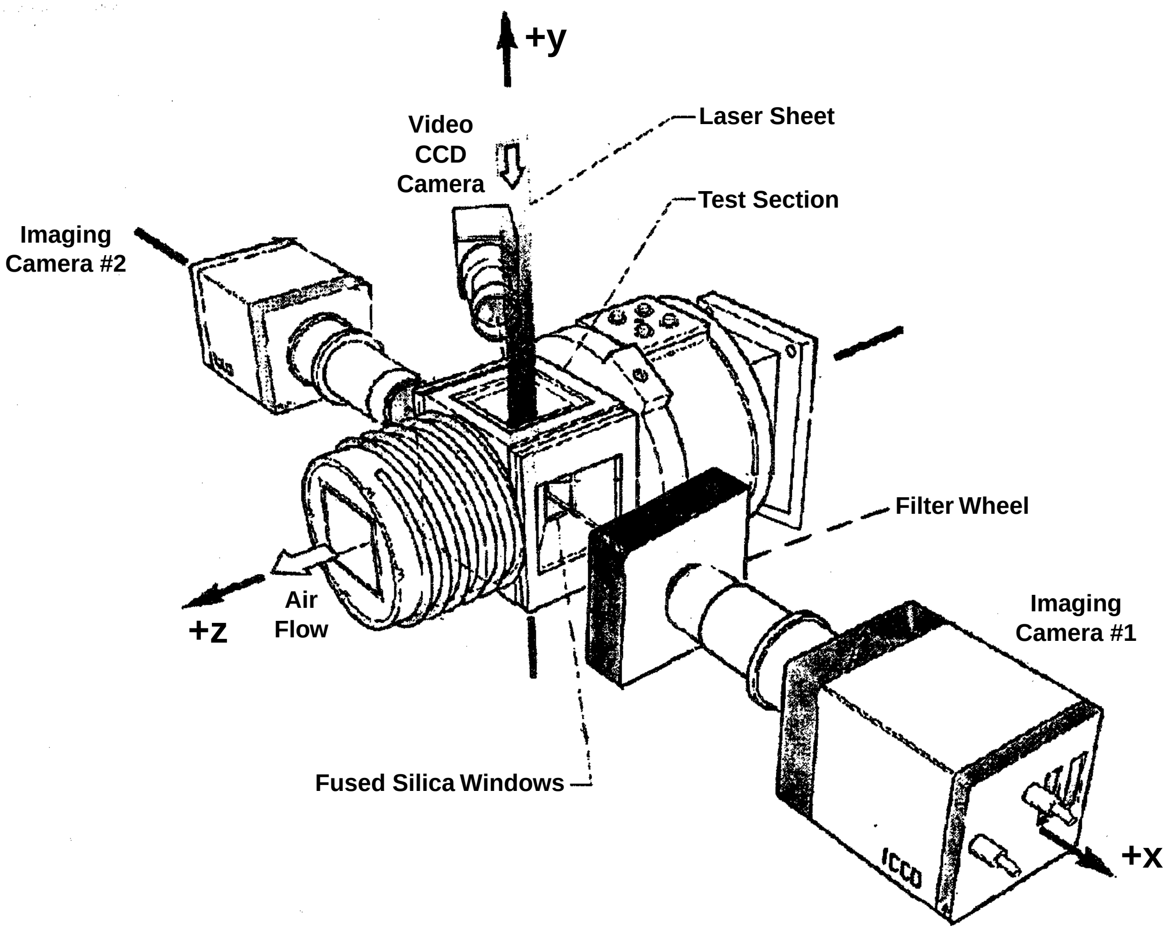
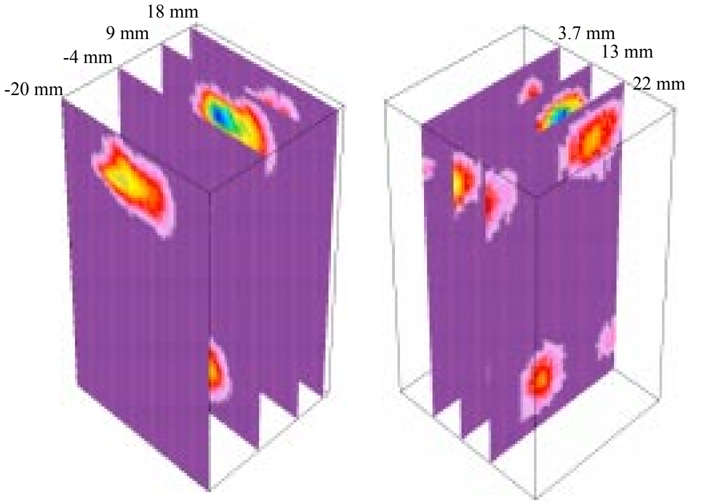


Figure 1. Schematic showing the optically accessible test section and the experimental optical setup. The flow is from right to left. In the figure, two ICCD cameras are mounted on opposite sides of the flametube perpendicular to the flow direction and to the laser insertion. Although two cameras can be used simultaneously, only one, camera #1 fitted with a remotely controlled filter wheel, was used during this series of experiments. The CCD video camera was used to record real-time video of the fuel injection process.

2.2. Imaging and Processing

Image collection was accomplished using Princeton Instrument's Winview software. The collected images were transferred to an SGI Indigo workstation for processing. Processing and image analysis on the SGI was accomplished using PV-WAVE from Visual Numerics, Inc. The gray scale images from the cameras were converted for display using a pseudocolor scale consisting of 25 color plus black (low intensity) and white (high intensity) where each color represents a span of 10 counts in a linear span of 255. The colors in the pseudocolor scale were chosen to make it easier to see details in the less intense portions of the images. Image processing includes removal of noise spikes, background subtraction, and correction for laser sheet energy distribution.

We also developed a unique image processing capability that allows us to obtain views looking upstream into the fuel injectors. These views, called cross-flow views, were developed to examine and characterize the fuel spray pattern or patternation of fuel injectors. In this process, the forty-one side-view images acquired at 1 mm increments across the flow field at each test condition, were configured by a computer program into an image stack. The program interpolates the region between each of the 41 individual images thereby filling in the gaps resulting in a smoothed 3-D image block. The image block can then be sliced in any desired orientation. Figure 2 illustrates this process. In this figure the flow exits the page to the right. The left side of the image shows, for the sake of simplicity, only a few selected side-view fuel fluorescence images in the z-y plane. The right side of the figure shows a few of the resultant cross-flow views obtained in the manner described. The images in the resulting stack are scaled together so that the highest signal level represents the 99th percentile. The images are displayed in this manner in order to accentuate the lower light level structures that would otherwise be lost in the glare of the higher intensity features.



side-view

cross-flow

Figure 2. Sequential image stacking of side-view fuel PLIF images acquired within a typical Combustor yielding cross-flow views. Test conditions: $\lambda_{exc} = 281.5$ nm, $T_{inlet} = 800$ K, $P_{inlet} = 1.46$ MPa, $\phi_{total} = 0.42$

Because the injector is positioned with its injector exit plane projecting approximately 5 mm into the window viewing area, a large amount of incident laser light scatter from the injector face is encountered. This scatter is intense enough to allow passage of a small but significant portion through the selective filters of the detectors. This scatter is eliminated by placing an external beam block over the top of the laser sheet insertion window effectively blocking any light from hitting the face of the fuel injector.

Since direct measurement of the laser sheet intensity in the downstream direction is not practical, another technique has been developed to correct for the fall off in laser sheet power at the upstream and downstream edges. We assume that the average fuel fluorescence intensity in the cross-flow images over an area enclosing the jet should be constant as we move downstream over the relatively short axial range that we can see. This is a reasonable assumption because the flow is not reacting, the fuel is completely vaporized, and the viewable distance is relatively short (approximately 40 mm). This assumption leads to the conclusion that any variation in this average is due to laser sheet energy changes. In our recent work, we have chosen to correct the xy-images by a factor that causes the within-jet average to be a constant over a range of downstream values.

To produce contour plots of fuel/air ratio we map image block pixel value to global fuel/air ratio that results in a fuel/air ratio data block. We can then slice the fuel/air ratio data block to yield 2-dimensional fuel/air ratio images and then compute the contour plots. Recall that for each test condition a data block is created consisting of 41 images. Each image is a fuel PLIF measurement at a position 1 mm from each of its two neighbors measured along the horizontal dimension perpendicular to the flow direction. For this hardware configuration and set of test conditions, the fuel and air are premixed and the burning is observed to stabilize well downstream from the PLIF measurement location. Since there is no mechanism operating to reduce or consume the amount of fuel present, it is reasonable to assume that the total amount of fuel remains constant within the window's field of view. Therefore, all the fuel injected into the flowstream is available to participate in the production of the PLIF signal along the entire axial range in the resulting fuel PLIF image block.

In the experiment represented by the contour plots in the figures presented here, there was very little spreading of the injected stream as the viewpoint moved downstream. As a result we were able to carve from the data block a cylinder of data within which lay all of the significant fuel PLIF signal. The axis for this data cylinder was the centerline of the injector. The diameter of the cylinder was 20% larger than the injector exit. For each of the six test conditions examined during this series of experiments, the average pixel value for the data cylinder was computed. These average values were plotted against the global fuel/air ratio and mapped to a straight line using a least squares criterion. This resulted in an expression of fuel/air ratio as a function of pixel value. This function was used to create the fuel/air ratio data block from the original data block so that the contour plots could be computed.

3. RESULTS AND DISCUSSION

Figure 3 presents a sample, side view fuel fluorescence image taken at our designated zero point near the centerline of the combustor. The laser sheet enters from the top of the image. The flow as indicated is from left to right. The vertical white lines denote locations downstream of the fuel injector exit plane at which crossflow images are generated in the manner previously described. Forty-one side view images are acquired for each of the six conditions tested during this series of experiments. Each of these images has been corrected for laser sheet inhomogeneities in the manner previously described. The conditions for the image shown in the figure are: T_{inlet} = 900°F, $P_{combustor}$ = 250 psia, overall f/a = 0.030, air mass flow (m_{air}) = 1.049 lb/sec, fuel mass flow (m_f) = 0.029 lb/sec. The observed absence

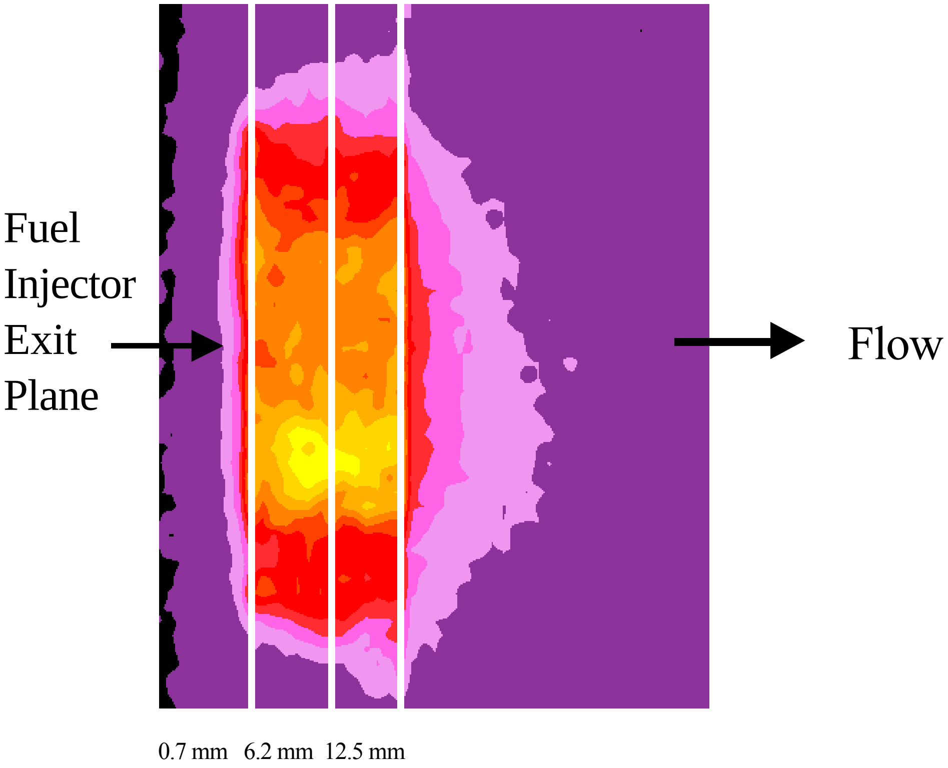
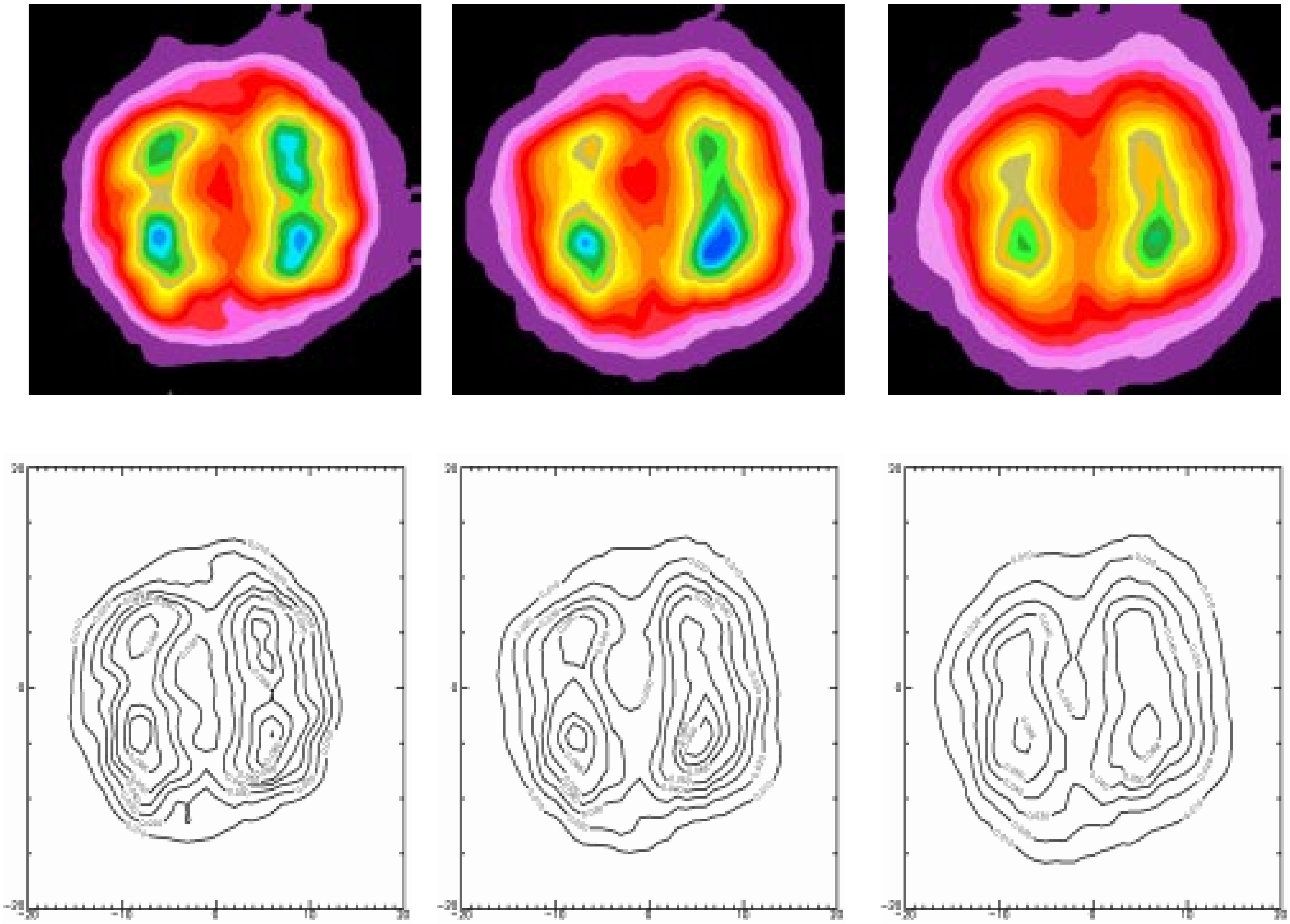


Figure 3. Side view fuel fluorescence image acquired from the optically accessible test combustor at the rig centerline. Flow is from left to right. The Laser sheet, λ = 281.0 nm, travels from top to bottom. The conditions are T_{inlet} = 900°F, $P_{combustor}$ = 250 psia, f/a = 0.030, air mass flow (w_{comb}) = 1.049 lbm/sec, fuel mass flow (w_f) = 0.029 lb/sec.

concentrations in figure three is due to fact that the main fuel injection points are off the centerline and hence are not visible in this location. Higher fuel concentrations only appear in side view images in the ±5 to ±10 mm regions of the flow.

The top portion of figure 4 presents the corresponding crossflow fuel PLIF images for the positions denoted by the white lines in figure 3; 0.7 mm, 6.2 mm, and 12.5 mm downstream of the injector exit plane. The four localized regions seen in each image at the 2, 4, 7, and 10 o'clock positions denote the location of higher fuel fluorescence signal and hence higher fuel concentrations. The areas of highest fuel concentration are positioned rather symmetrically about the center of the images and correspond with the location of the individual injection points of this particular injector design. A closer inspection of the cross-flow images of this figure reveals a small increase, on the order of approximately 10% over the 11.8 mm distance between left and right images, in the overall size of the fuel fluorescence. A second observation is that of a broadening and merging of some of the contours as the viewpoint is stepped downstream (left to right).



0.7 mm 6.2 mm 12.5 mm

Figure 4. A comparison of fuel PLIF crossflow views (top) and fuel/air contour plots (bottom) obtained for the positions denoted in figure 3; 0.7 mm (left), 6.2 mm (middle), and 12.5 mm (right) from the injector exit plane. The flow in all cases is from out of the page. The conditions are identical to those listed in figure 3 with overall f/a = 0.030.

The lower portion of figure 4 shows the contour plots corresponding to the cross-flow fuel PLIF images. The contour plots are generated in the manner previously described. As in the fuel PLIF images, an overall increase in size of the fuel spray is observed from left to right. The contours are also observed to undergo the same general broadening and merging. What is notable in these contour plots is the evidence of localized fuel rich zones with f/a ratios that are significantly greater than the overall f/a of 0.030. Contours with maxima greater than 0.090 are observed in both the left and middle plots. Fuel-to-air contours larger than 0.09 present in the left-hand figure are concentrated in the tightly drawn cell in the lower right of the image. These high concentration cells are observed to expand into much larger pockets in the middle plot. This expansion of concentrated pockets of fuel, seen in the lower right of the middle plot, is accompanied by the merging of other smaller pockets into larger cells of lower fuel concentration. This trend continues when looking from the middle plot to the right–hand plot, just 6 mm further downstream, where all pockets of high fuel concentration are gone and are replaced by broad chambers of lower fuel concentration. Each engine condition tested during this series of experiments exhibited the same trend. These contour plots provide a mechanism to perform detailed studies of the fuel-air mixing process as it evolves from the fuel injector exit plane to the downstream edge of the windows.

4. SUMMARY

A technique is presented which uses a series of fuel PLIF measurements to generate cross-flow fuel PLIF images and corresponding fuel-to-air ratio contour plots for the area immediately downstream of the fuel injector of a gas-turbine combustor, operating at actual conditions. These fuel to air ratio contour plots were possible because a fuel injector was used whose spray was wholly within the field of view of the laser illumination and detector windows, and was free of any process that reduced the amount of fuel present over the probe volume. These f/a contour plots have shown that under typical, fuel-lean operating conditions, locally fuel-rich pockets in excess of stoichiometric are produced immediately downstream of the injector exit plane. This information is vital since nonuniformities in the mixing process have been shown to be directly related to observed increases in NO_x emissions. Additional work is necessary to determine the role of fluorescence quenching and laser attenuation in making these measurements.

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13. ABSTRACT ***(Maximum 200 words)***

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