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Technical Notes

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OH Imaging in a Lean Burning High-Pressure Combustor

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Introduction

THE next generation civilian aircraft combustors will operate at conditions of higher pressures and temperatures than do current combustors. Although providing greater engine efficiency, these conditions not only create significant challenges to emissions reduction[1] but also pose unique challenges to all established combustor diagnostic techniques. Classical diagnostic methods, although they provide valuable information on stable molecular species as well as unburned hydrocarbons, are incapable of measuring chemical intermediates or elucidating flame structure. Planar laser-induced fluorescence (PLIF) measurements have demonstrated the capability to provide quantitative, temporally resolved, nonintrusive two-dimensional species, temperature, and velocity measurements in combustion environments.[2] Obtaining this type of information is critically important for advanced combustor design and evaluation and flame code development. In this Note we present PLIF images of OH obtained from an optically accessible flame tube combustor burning JP-5, with high temperature, pressure, and airflow capabilities. The present study was motivated in part by a need to better understand the combustion process in large-scale, high-pressure combustors and to provide design evaluation feedback to combustor and fuel injector designers.

Experimental Apparatus

The combustor test facility at NASA Lewis Research Center is designed to deliver nonvitiated air at flow rates up to 4.5 kg/s at temperatures of 866 K and pressures up to 1723 kPa. The combustion section, illustrated in Fig. 1, is 74 cm long with a 7.62 × 7.62 cm flow cross section. The lean direct injection (LDI) scheme[3] used in this study is one of several under consideration for the NASA High-Speed Research Program (HSR). In brief, the LDI concept deposits fuel directly into the flame zone using air swirl for flame stabilization and efficient fuel/air mixing. Typical conditions sampled in this series of experiments ranged from inlet temperatures of 866 K, mass flow rates up to 0.68 kg/s, rig pressures approaching 1450 kPa, and flow velocities of 24–45 m/s. These parameters were selected because they simulate a range of HSR cruise conditions and, as such, are of critical interest to the combustor designers.

The optically accessible portion of the flame tube is located approximately 12 cm downstream from the fuel injector manifold. One fused silica window was placed at the same axial position on each of the four combustor walls. The windows afford a clear aperture of 5 cm radially by 3.8 cm axially, resulting in a 67% view of the flow cross section. The windows are able to withstand temperatures approaching 2033 K by means of thin film cooling. The nitrogen film cooling mechanism provides no more than 10% of the aggregate combustor mass flow rate that has a maximum of 1.47 kg/s.

For the PLIF measurements the output of the Nd:YAG-pumped dye laser was frequency doubled to provide uv output near 282 nm (~16 mJ/pulse) with a bandwidth of approximately 1.0 cm^{-1} as measured by a Burleigh wavemeter. The dye laser was tuned to the $R_1(1)$, $R_1(10)$, and $Q_1(1)$ transitions of the OH A ← X (1, 0) band by directing a portion of the laser beam through the flame of a Bunsen burner and observing the fluorescence with a photomultiplier tube/boxcar averager system.

The doubled dye output was expanded, collimated, and directed through a series of high damage threshold, wavelength-specific mirrors to the test cell. The laser beam was then directed to the test section by means of a beam positioning system immediately above the test section. To reduce complexity, a computer program was written to coordinate remote positioning of both the laser sheet and detector system.

The laser sheet (33 × 0.3 mm) at 9 mJ/pulse was transmitted vertically through the flowfield. Fluorescence was collected normal to the incident excitation sheet using a Princeton Instruments intensified charge-coupled device (ICCD) camera with a resolution of 576 × 384 pixels, coupled with a 105 mm, f4.5 Nikon uv lens. The camera intensifier was synchronously triggered with the laser pulse and was gated for 50 ns. Elimination of flame luminosity and

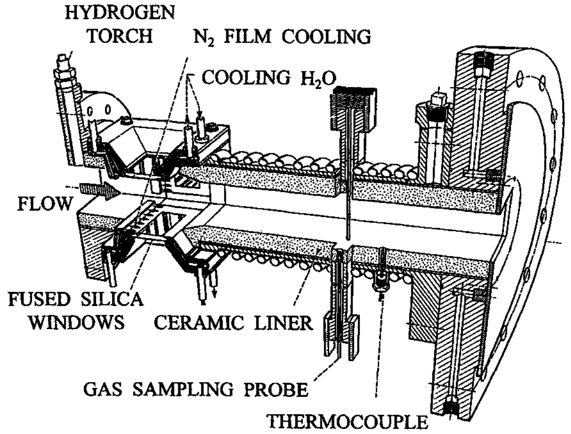

Fig. 1 High-pressure, high-temperature square cross section of flame tube.

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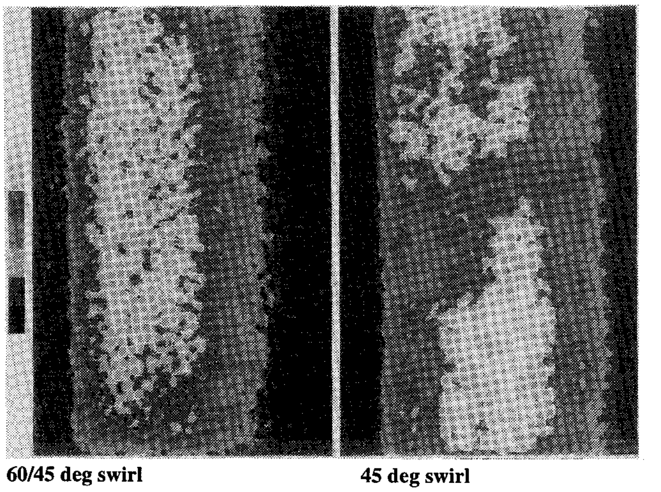
scattered laser light was accomplished with a WG-305 Schott filter and a narrow band interference filter from Andover, having a peak wavelength of 315 nm. In all images, flow is from left to right with laser sheet propagation from top to bottom.

Results

Figure 2 is a comparison of three OH PLIF images obtained by tuning the dye laser to three different resonant wavelengths while maintaining steady operating conditions: 9 point LDI with 60/45 deg air swirl (an alternating combination of 45 and 60-deg swirlers) at 1034 kPa, 866 K inlet air, and $\Phi = 0.53$. The left image, with R_1 (1) excitation at 281.458 nm, shows a relatively uniform flow and exhibits no sign of laser sheet attenuation across the flowfield. The center image, excited with $R_1(10)$ at 281.591 nm, and the right image, excited with $Q_1(1)$ at 281.970 nm, show evidence of moderate to strong laser sheet attenuation, respectively, but otherwise uniform flowfields.

The plots immediately below each image in Fig. 2 give the relative pixel intensity from top to bottom along the vertical lines drawn at the same position through each respective image. The plot for $R_1(1)$ excitation again displays no evidence of laser sheet attenuation. The $R_1(10)$ excitation displays attenuation of the laser sheet on the order of 25%, whereas the right-hand plot shows significant attenuation, approaching 40%. Adiabatic equilibrium code calculations for LDI injection at these conditions predict OH concentrations of $N_{OH} \approx 3.0 \times 10^{16}$ cm^{-3}. Performing a simple Beer's law calculation using the right-hand image yields an OH concentration of $N_{OH} \approx 1.3 \times 10^{16}$ cm^{-3}. The choice of excitation wavelengths was made to minimize beam walking effects produced by the long beam path while tuning the dye laser. Future experiments will use transitions such as $R_1(12)$, $P_1(7)$, and $Q_2(11)$, which will minimize laser sheet attenuation as well as temperature sensitivity.

Figure 3 contrasts two PLIF images for different LDI fuel injector air swirl angles at identical operating conditions of 1034 kPa, 866 K inlet air, and $\Phi = 0.53$. Each image is a 10-shot average obtained by exciting the $R_1(10)$ transition. The image on the left, using 60/45 deg swirl, shows a nearly uniform flowfield and is representative of all other images, including single shot, acquired with this configuration. The image on the right, obtained with 45-deg swirl, displays a highly nonuniform flowfield, again characteristic of all other images obtained in this study using 45-deg air swirl. From Fig. 3, it is immediately apparent that with 45-deg swirl the greater fraction of OH and hence higher flow temperatures are located along the walls of the combustor. The significance of this observation is that, before application of LIF imaging techniques, these injector configurations were both believed to possess uniform flowfields. The images revealing evidence of poor mixing and localized hot spots for the injector with 45-deg air swirl have demonstrated the strength of the PLIF imaging technique to address questions concerning these combustors. By delineating the actual flowfield via species and temperature distributions, the PLIF technique has been shown to provide valuable feedback to injector and large-scale combustor designers.



60/45 deg swirl **45 deg swirl**

Fig. 3 Comparison of 10-shot averaged OH PLIF images for different fuel injector configurations with 9-point LDI at 1034 kPa and $\Phi = 0.53$ and resonant excitation of $R_1(10)$ 281.591 nm.

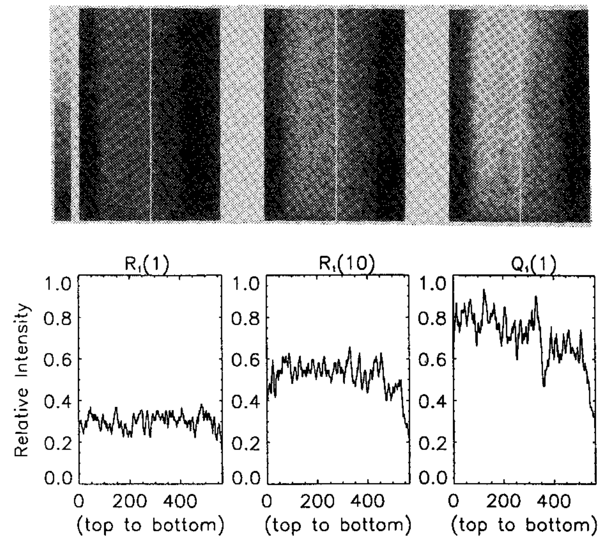


Fig. 2 Comparison of 10-shot averaged OH PLIF images for different resonant excitation: left: $R_1(1)$ 281.458 nm; middle: $R_1(10)$ 281.591 nm; right: $Q_1(1)$ 281.970 nm. Nine-point LDI injection with 45/60 deg swirl at 1034 kPa and $\Phi = 0.53$.

Conclusions

PLIF images of OH were obtained at a range of test conditions duplicating those to be experienced by HSR-type combustors at cruise. Although all images shown here were 10-shot averages, similar results were obtained for single laser shots. Images resulting from off-resonant excitation displayed no evidence of elastically scattered laser light or contributions attributable to complex fuel chemistries and/or polycyclic aromatic hydrocarbons. Lack of evidence of hydrocarbon interference is not surprising because the combustor is fuel lean and the windows are well downstream of the primary combustion zone. Therefore, all images obtained in this study were attributed to the fluorescence of OH.

Quenching was shown to play no major role in hindering the capture of the OH images at pressures approaching 1500 kPa. Additionally, no evidence of fluorescence trapping was observed, perhaps because of the relatively short fluorescent path length (3.8 cm) utilized in our combustor. Quagliaroli et al.[4] determined fluorescence trapping to be strongly fluorescent path length dependent and to be problematic to some extent for all $(0 \leftarrow 0)$ and $(1 \leftarrow 0)$ excitation schemes. For combustor concepts with longer path lengths, fluorescence trapping must be considered during diagnostic preparations and viable reduction strategies investigated.

Although the images obtained in this study were qualitative and only portray relative fluorescent yields, these results have established the suitability of the PLIF diagnostic technique to large-scale high-pressure combustor applications. The ability to portray the relative concentration distribution of OH and other species of interest provides a unique opportunity to view large-scale combustor flowfields and to provide valuable feedback to powerplant designers. Furthermore, implementation of recent advances developed in other laboratories[5,6] will allow determination of quantitative concentration distributions for OH, NO, and other species of interest, as well as flowfield temperature distributions.

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Single-Pulse Temperature Measurement in Turbulent Flame Using Laser-Induced O_2 Fluorescence

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Introduction

TEMPORALLY resolved measurements of flowfield variables, such as temperature, density, velocity, and species concentration, are important for the study of turbulent reacting and nonreacting flows. Such measurements can provide data on probability distributions that are unattainable with time-averaged techniques. Short-duration impulse facilities such as shock tubes, shock tunnels, or combustion bombs that are employed in high-speed aerodynamic and combustion research require instrumentation with precise timing as well as high time resolution. As temperature is an important parameter in these studies, several time-resolved laser-spectroscopic thermometry techniques have been developed and demonstrated. Unfortunately, only a few techniques are sufficiently versatile for widespread use. In general, these techniques are tailored to specific measurement requirements, exploit certain thermodynamic conditions or constraints in the gas flow under study, and/or are applied to problems for which their strengths are particularly suited.

A new single-pulse, two-line laser-induced O_2 fluorescence temperature measurement technique has recently been developed[1] for use in unseeded high-temperature (1500–3000 K) reacting and nonreacting airflows where temperature, pressure, and species concentrations are subject to turbulent fluctuation. The technique has been characterized and calibrated in a high-temperature atmospheric air furnace. Here, we demonstrate its potential for use in high-temperature reacting flows with measurements in the turbulent postflame gases of a premixed, atmospheric propane–O_2 flame.

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Temperature Measurement Technique

The technique is based on the simultaneous excitation of the spectrally coincident $v'(0) \leftarrow v''(6)P(13)$ and $v'(2) \leftarrow v''(7)R(11)$ absorption lines in the $B^3\Sigma_u^- - X^3\Sigma_g^-$ Schumann–Runge system of O_2 using a tunable KrF laser. The peaks of these lines near 40,251 cm^{-1} (248.44 nm) overlap each other within ~0.05 cm^{-1}. Because of their close proximity, a single laser with a bandwidth of approximately 1 cm^{-1} can excite both lines simultaneously. As a result, the fluorescence from both upper states reached by absorption is emitted simultaneously as well. Although separation of the two fluorescence contributions by time-resolved detection is not possible, unique features of their emission spectra allow them to be separated spectroscopically. By using a spectrometer equipped with a multichannel array detector, the fluorescence spectrum resulting from the excitation of both lines can be recorded on a single-pulse basis. Thus, by analyzing each single-pulse dispersion spectrum, time-resolved thermometry is realized. Although limited to point or line measurements, this approach is simpler than alternative two-line laser-induced fluorescence (LIF) approaches,[2,3] where two lasers and two detection systems are needed for time-resolved thermometry. Unlike single-pulse Rayleigh or Raman techniques, which require high laser pulse energies (~200 mJ) to produce a sufficiently high single-pulse signal-to-noise ratio, this LIF technique requires only 5–10 mJ and thereby precludes problems associated with particle incandescence as well as with exceeding damage thresholds of window materials. Owing to the high predissociation rate of the upper states, quenching corrections are unnecessary for pressure up to approximately 2 atm—an important consideration in turbulent reacting flows where the local gas composition is subject to considerable fluctuation. However, the low fluorescence conversion efficiency and restrictions on the incident laser flux present with this O_2 LIF technique[1] may limit its use to high-temperature flows with greater than trace concentrations of O_2. Although LIF detection limits are intimately tied to particular experimental configurations, the detection limit realized in the present experiment was estimated to be ~0.5% mole fraction at 2500 K and 1 atm.

The technique was calibrated in a high-temperature atmospheric air furnace where independent thermocouple measurements were available.[1] Mean temperatures and their variances were obtained from 100 single-pulse measurements at furnace temperatures from 1300 to 1800 K, and the mean temperatures were compared with the corresponding thermocouple measurements. For 100-pulse averages, typical measurement error over this range was 1.3%. Photon shot noise was found to be the primary source of error in the fluorescence measurements. The measured standard deviation in the single-pulse LIF temperature measurements in the furnace agreed well with the predicted uncertainty computed using the mean temperature and fluorescence signals. Single-pulse temperature measurement uncertainties (1σ) in atmospheric air ranged from approximately 13% at 1300 K to 7% at 1800 K. The theoretical model[1] that was used to accurately interpret the temperature dependence of the fluorescence signals measured in the furnace was also used in the present demonstration to determine temperatures outside the calibration range. Since the coefficients that were determined from the calibration measurements are temperature independent, such extrapolation outside of the calibration range is justified. In addition, systematic errors in the temperature measurement due to uncertainties in the model parameters were found to be small relative to propagated uncertainties in the single-pulse fluorescence signal measurement.[4]

Turbulent Flame Temperature Measurements

To demonstrate the technique's viability for measurements in reacting gas flows where the O_2 concentration and temperature are subject to turbulent fluctuation, temperature measurements were obtained in the turbulent high-temperature gases of a premixed propane–O_2 jet flame. The flame was produced by a commercially available, atmospheric pressure blast burner commonly used for glass and metal shaping. The intense, axisymmetric turbulent flame was approximately 15 mm in length and was located approximately 5 mm above the burner tip ($D = 1$ mm). The luminous region of the postflame gases extended approximately 150 mm above the base of