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Simultaneous planar laser-induced incandescence, hydroxyl radical planar laser-induced fluorescence, and droplet Mie scattering are used to study the instantaneous flame structure and soot formation process in an atmospheric pressure, swirl-stabilized, liquid-fueled, model gas-turbine combustor. Optimal excitation and detection schemes to maximize single-shot signals and avoid interferences from soot-laden flame emission are discussed. The data indicate that rich pockets of premixed fuel and air along the interface between the spray flame and the recirculation zone serve as primary sites for soot inception. Intermittent large-scale structures and local equivalence ratio are also found to play an important role in soot formation. © 2005 Optical Society of America

1. Introduction

Swirl-stabilized liquid-spray injectors are commonly used in gas-turbine engines to achieve compact, stable, and efficient combustion. The flow field in the primary zone of such a spray flame is characterized by high shear stresses and turbulent intensities that result in vortex breakdown and large-scale unsteady motions.1,2 These unsteady motions are known to play a key role in the formation of pollutant emissions such as carbon monoxide (CO), nitric oxide (NO), and unburned hydrocarbons.3–5 Less is known, however, about the mechanisms that lead to soot formation in swirl-stabilized, liquid-fueled combustors. Previous investigations have relied on exhaust-gas measurements and parametric studies to gain insight into the effects of various input conditions on soot loading.6–10 Much of the fundamental knowledge concerning soot formation is derived from investigations of laminar diffusion flames,11 with only a limited number of studies having focused on internal combustion engines and unsteady effects.12–14 The importance of considering unsteadiness and fluid–flame interactions was demonstrated by Shaddix et al.,14 who found that a forced methane–air diffusion flame produced a fourfold increase in soot volume fraction (as a result of increased particle size) as compared with a steady flame having the same mean fuel flow velocity.

The goal of the current investigation is to study soot formation in the highly dynamic environment of a swirl-stabilized, liquid-fueled combustor. This is accomplished by simultaneous imaging of the soot volume fraction, hydroxyl radical distribution, and spray pattern in the primary reaction zone by use of laser-induced incandescence (LII), OH planar laser-induced fluorescence (PLIF), and droplet Mie scattering, respectively. The utility of LII for twodimensional imaging of soot volume fraction has been demonstrated in laboratory investigations15,16 as well as in aircraft engine exhausts.8,10 Brown et al.17 performed planar LII for soot-volume-fraction imaging in the reaction zone of a gas-turbine combustor; their preliminary measurements employed LII alone for demonstration purposes and did not image the turbulent flame structure near the exit of the swirl cup. In this paper we extend the research of Brown et al.17 by performing LII at the exit of the swirl cup and by adding OH PLIF and Mie-scattering diagnostics.

Use of OH as a flame marker is typical in studies of soot formation in diffusion flames because of its close correlation with flame temperature.18,19 It has also been employed in a number of investigations of swirl-

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stabilized combustors. Use of laser-saturated OH laser-induced fluorescence (LIF) for quantitative measurements has also been demonstrated, although saturation is quite difficult in the case of planar measurements. In the current investigation, we demonstrate qualitative measurements in the recirculation region using excitation levels well below saturation. OH PLIF measurements in the liquid-spray region are more uncertain because of simultaneous droplet scattering and nonequilibrium conditions, although meaningful measurements are possible with careful consideration of potential errors.

The performance and accuracy of the planar LII, OH PLIF, and Mie-scattering systems are characterized in this paper and described below. The combined use of LII, OH PLIF, and droplet Mie scattering is then shown to provide insight into the unsteady physical processes that govern soot formation in gas-turbine engines. OH PLIF is employed to track the local equivalence ratio and the effects of flame chemistry. Finally, the current measurement system is demonstrated to be useful for the assessment of the performance of soot-mitigating additives.

2. Experimental Setup

A. Swirl-Stabilized Combustor

The near-field structure of swirl-stabilized flames is determined by the characteristics of the fuel injector and the geometry of the surrounding flame tube. As shown in Fig. 1, the swirl-cup, liquid-fuel injector used in the current study employs pressure atomization and dual-radial, countercircling air coflows to entrain the fuel, promote droplet breakup, and enhance mixing. The resulting three-dimensional conical flame, shown in Fig. 1(b), is composed of an outer droplet vaporization and preheat region (A) and an inner turbulent flame-brush region (B). The flame is stabilized by a recirculation zone (C) that brings hot combustion products upstream along the centerline. The 4.3-cm-exit-diameter swirl cup is installed at the entrance of a 15.25 cm × 15.25 cm square cross-section flame tube, as shown in Fig. 2. After exiting the primary flame zone, the combustion products are allowed to mix thoroughly along the 48-cm-long flame tube before entering a 43-cm-long, 5.7-cm-exit-diameter exhaust nozzle that is designed to create uniform exhaust-gas temperature and concentration profiles.

The combustor shown in Fig. 2 is used in the Atmospheric-Pressure Combustor Research Complex of the U.S. Air Force Research Laboratory’s Propulsion Directorate to study the performance characteristics of model gas-turbine engine fuels and fuel additives. An overview of the facility is available in the literature, although certain aspects relevant to the current study are described here for reference. We achieved the changes in the overall equivalence ratio from 0.5 to 1.15 by varying the pressure drop across the fuel-spray nozzle from approximately 1.5 to 10 atm, which results in fuel mass-flow rates of 1.0 to 2.2 g/s, respectively. The fuel flow rate is measured with a Max Machinery positive-displacement flowmeter with ±0.5% full-scale accuracy. The air-flow system consists of three Sierra 5600-standard-liters-per-minute mass-flow controllers with ±1% full-scale accuracy. The inlet air is heated to 450 K with a constant flow rate of 0.028 kg/s. The air pressure drop across the combustor dome is ~4.8–5.2% of the main supply. Most of the airflow enters the combustor through the swirl-cup injector, but a small

Fig. 1. (a) Swirl injector geometry used in the current study, and (b) photograph of near-field flame structure. Flow is left to right. Regions A–C depict the fuel evaporation and preheat zone, the turbulent flame brush, and the recirculation region, respectively.

Fig. 2. Experimental setup for simultaneous planar LII, OH PLIF, and droplet Mie scattering in an atmospheric pressure, swirl-stabilized, liquid-fueled, model gas-turbine combustor. FCU, frequency-conversion unit.
percentage enters through aspiration holes along the aft wall. No liner air jets are used in the secondary zone; therefore the fuel–air ratio depends almost entirely on the flow rates through the injector cup.

The combustor is optically accessible through 75-mm-wide quartz windows along the top and sides for in situ laser-based diagnostics. In addition, a sampling probe used to measure particle number density (counts per cubic centimeter) with a condensation nuclei counter is located at the exit of the combustor.

B. Hydroxyl Radical Planar Laser-Induced Fluorescence System

A review of PLIF fundamentals can be found in Eckbreth.26 As shown in the optical setup in Fig. 2, 50% of the laser energy from a frequency-doubled, Q-switched Nd:YAG laser (Spectra-Physics Pro290) is used to pump a dye laser (Sirah Precision Scan), the output of which is frequency doubled to obtain wavelengths in the (1,0) band of the OH A–X system. The dye laser is tuned to the Q(9) transition at 283.922 nm (in air), which has less than ±2.5% variation in the ground-level Boltzmann fraction from 1600 to 2400 K. As shown in Fig. 3, this range of temperatures coincides with the equilibrium conditions expected for JP-8 fuel at equivalence ratios used in this study (ϕ = 0.5–1.15).27 Considering the full range of temperatures from 1100 to 2400 K, which are within typical lean and rich flammability limits,7 the Boltzmann fraction for this transition varies by up to ±12.5%.

The maximum laser energy available for OH PLIF is 24 mJ. A 1.5-m focal-length spherical plano-convex lens and a −75-mm focal-length plano-concave lens are used to form a laser sheet that enters the combustor through the top window. The laser-sheet thickness is 330 μm at a full thickness at half-maximum that we measured by translating a knife edge across the beam. We obtained a 7-cm, top-hat-like sheet-width profile that transitions to zero laser energy within approximately 1 mm by clipping the wings of the laser sheet at the last turning mirror above the combustor. The sheet slowly expands with a 3° full-angle divergence.

We collected the fluorescence from approximately 306 to 320 nm through the (1,1) and (0,0) bands of OH using an intensified charge-coupled-device (ICCD) camera (Princeton Instruments PI-MAX SB) oriented slightly off normal to the sheet. Two 1-mm WG295 Schott Glass filters are used in front of the camera lens to reduce scattering from droplets at 283.922 nm. A UG11 filter nearly eliminates flame emission, scattering from the LII laser at 532 nm, and fluorescence from polycyclic aromatic hydrocarbons (PAHs). A 105-mm focal-length f/4.5 UV lens is used to collect the OH fluorescence. An intensifier gate width of 20 ns is used to capture the OH signal. Images are typically collected with 2 × 2 binning (512 × 512) to obtain adequate resolution and framing rate. The pixel viewing area in each 2 × 2 superpixel is 200 μm × 200 μm.

On the basis of the dimensions of the OH PLIF laser sheet and total available laser energy of 24 mJ, it is estimated that the maximum laser irradiance of 1.36 × 107 W/cm2 is 2–3 orders of magnitude lower than that required to achieve 90–95% saturation.22,23 Therefore the OH PLIF signal is linearly related to laser energy variations. OH PLIF signal corrections (typically ±15%) in the axial direction are performed in postprocessing, based on measurements of the laser-sheet profile after each run. Signal variation (typically ±3%) due to the 3° laser-sheet expansion in the cross-stream direction is also corrected in postprocessing. Corrections are not made for laser energy attenuation due to OH absorption and droplet scattering as this leads to signal uncertainties of ±10% in the lower region of each image. The effect of this error is substantially reduced in the upper half of the combustor, where most of the data in this study are extracted. Shot-to-shot fluctuations in laser energy add an estimated ±5% uncertainty, as determined from data collected in a laminar diffusion flame with the same OH PLIF system.

For measurements with low laser irradiance, the effect of collisional quenching on fluorescence efficiency must also be considered. For a given imaging system and laser irradiance, the OH PLIF signal S_{OH} from each pixel volume is proportional to the OH number density N_{OH} and the fluorescence efficiency η,28 as shown in approximation (1):

\[
S_{OH} = N_{OH} \eta = N_{OH} \frac{A_{OH}}{A_{OH} + Q_{OH}}.
\]  

The fluorescence efficiency is proportional to the rate of spontaneous emission, A_{OH}, from molecules in the excited state and inversely proportional to the rate at which excited molecules are depleted by spontaneous emission and collisional quenching, Q_{OH}. Collisional quenching is a function of the temperature- and pressure-dependent quenching coefficient as well as the number densities of the quenching species.28 As a result of offsetting effects in the equilibrium combus-
tion products of JP-8, the collisional quenching rate is found to be fairly constant for equivalence ratios less than unity, as shown in Fig. 3. Under rich conditions the conversion of CO to CO\(_2\) decreases substantially, leading to an increase in collisional quenching and a decrease in fluorescence efficiency. In regions where equilibrium assumptions are valid, the LIF signal can be used along with approximation (1) and the Boltzmann distribution to determine the relative OH number density; this is discussed further in Section 3.

In the liquid-spray region where lean and rich pockets coexist, qualitative signal interpretation is problematic since fluorescence efficiency can vary by more than \(\pm 30\%\), according to Fig. 3.

C. Mie-Scattering System

Mie scattering is obtained with the same optical setup as that for the OH PLIF system. It is found that use of up to six optical filters can reduce but not altogether eliminate scattering from large droplets. Because of induced birefringence in the turning mirrors, the combustor windows, and the spray flame itself, use of parallel polarization in the detection scheme further reduces but does not altogether eliminate droplet scattering. It is found that two WG295 color glass filters (CVI Laser) and parallel-polarization detection provide optimal OH PLIF sensitivity and minimizes the likelihood of damaging the ICCD due to intense levels of droplet scattering. When the laser is tuned off the OH absorption line, as shown in Fig. 4, the intense, highly localized droplet scatter can be distinguished from the large, more uniformly distributed OH layers. Large droplet clusters appear primarily near the injector exit, and single droplets with trailing flames are often observed traveling into the recirculation region. The trailing flames of these droplets do not appear in the off-line images and therefore are not attributable to scattering from fuel vapor or fluorescence from broadband sources such as PAH compounds. Large droplet clusters appear primarily near the injector exit, and single droplets with trailing flames are often observed traveling into the recirculation region. The trailing flames of these droplets do not appear in the off-line images and therefore are not attributable to scattering from fuel vapor or fluorescence from broadband sources such as PAH compounds.

D. Laser-Induced Incandescence System

Some of the first two-dimensional visualizations of soot volume fraction with LII were performed by Quay and co-workers\(^{15}\) and by Vander Wal and Weiland.\(^{16}\) The effects of various parameters such as laser fluence, laser-sheet profile, detection wavelength, camera gate width, and camera gate delay have been explored in a number of follow-up investigations.\(^{29-31}\) A list of reviews on the subject is provided by Urban and Faeth.\(^{32}\)

The LII optical layout employed in the current study is shown schematically in Fig. 2, where 50% of the energy from a frequency-doubled Nd:YAG is formed into a sheet by use of a 2-m plano-convex spherical lens and a \(-50\)-mm plano-concave cylindrical lens. The full thickness at half-maximum of the laser sheet is approximately 700 \(\mu\)m within the measurement volume, which we measured by traversing a knife edge across the sheet. As is the case for the OH PLIF laser sheet, the long 2-m focal-length lens is used to minimize variations in laser-sheet thickness within the measured region. The sheet width is \(-14\) cm, with wings that are clipped prior to the last turning mirror to generate a top-hat-like profile that transitions to zero laser energy within approximately 2 mm. The sheet has a full angle divergence of 6° within the test section. An overall tilt of 5° is used to overlap the LII and PLIF laser sheets. The laser fluence distribution varies by \(\pm 15\%\) over the first 7 cm of the sheet, corresponding to the region where PLIF and Mie scattering are measured. Over the remaining 7 cm of the sheet, the laser fluence decreases more quickly from a peak of 460 mJ/cm\(^2\) to a minimum of 180 mJ/cm\(^2\). To reduce systematic errors due to laser-sheet-width intensity variations in the downstream half of the laser sheet and due to laser extinction in the measurement volume, the LII system is operated in the saturated regime. A saturation fluence near 200 mJ/cm\(^2\), shown in Fig. 5, agrees with previous measurements in the literature.\(^{29,31}\) Figure 5 indicates that the uncertainty in the relative soot-
volume-fraction measurements is within \( \pm 10\% \) over the full width of the laser sheet.

The LII signal is detected with a \( 1024 \times 1024 \) ICCD camera (Princeton Instruments PI-MAX SB-MG) and an \( f/1.2 \), 58-mm focal-length glass lens. After \( 4 \times 4 \) pixel binning, the measurement resolution is approximately \( 575 \times 575 \) \( \mu \)m. A 500-nm short-pass filter (CVI Laser) is used for detection from 415 to 500 nm, which reduces contributions from nascent soot particles, \( \text{OH} \) fluorescence and chemiluminescence, redshifted fluorescence from PAH compounds, and \( \text{C}_2 \) Swan-band fluorescence and chemiluminescence. Chemiluminescent flame emission is further reduced by use of a 50- or 200-ns ICCD intensifier gate width; light leakage from flame luminosity while the ICCD intensifier is gated off is minimized by use of a 25-ms gate UNIBLITZ shutter. The relatively short-lived PAH and \( \text{C}_2 \) Swan-band fluorescence are also minimized by use of a time-delayed detection scheme. Scattering from the 532-nm laser source is eliminated by use of a 532-nm zero-degree reflective mirror with the 500-nm short-pass filter and delayed detection. During postprocessing the residual background signal from flame luminosity is subtracted from each image. A color scale is chosen with a minimum value of 5\% above the background and a maximum value at a 100\% signal.

To optimize the timing of LII detection, data are collected in the swirl-stabilized flame for a number of camera intensifier gate delays and widths. A camera delay of 20 ns after the laser pulse is found to reduce laser scatter to nearly the background level and maintain LII signal-to-noise ratios greater than 20:1. The LII signal decays quickly within the first 200 ns after the laser pulse, as shown in Fig. 5. The long decay in the signal after 200 ns is dominated by larger, slow-cooling particles. With an intensifier gate width of 50 ns, errors due to particle-size effects are estimated to be of the order of 5–10\%.

E. Combined Laser–Induced Fluorescence and Laser-Induced Incandescence System

The OH PLIF and LII cameras are synchronized with an external delay generator (Stanford Research Systems DG535) driven by the advanced \( Q \)-switch TTL output of the Nd:YAG laser. The laser pulses are separated by a few nanoseconds to avoid fluid movement during LIF and LII detection. The precise camera delay required to capture each image is imposed with a timing generator in each ICCD controller. Because of spatial constraints within the test cell, both cameras are positioned on the same side of the combustor at slight 3.5° angles to overlap the two imaged regions. We minimized this angle by placing the LIF image to the far right of the camera viewing area and using a relatively large LII viewing area. Thus the PLIF image area overlaps the left half of the LII image nearest the injector cup. After camera alignment, registration images are collected prior to each run for use in postprocessing. At higher equivalence ratios (>0.7), thermal loading from flame radiation is significant, and heat shielding is employed to reduce misalignment of the LII–PLIF optics. During each run the OH PLIF and LII sheets are checked periodically with burn paper and adjusted to ensure that the laser intensity distributions and positions have not changed.

3. Results

A. Instantaneous Flame Structure

The average OH distribution at \( \phi = 0.5 \) is shown in Fig. 7(a). All images used for averaging are background subtracted and corrected for laser-sheet intensity variations and laser-sheet divergence. A slight asymmetry is apparent in the upper and lower halves, with the effects of laser attenuation being evident in the lower half of the image. For this reason, data are collected primarily in the upper (laser entrance) half of the combustor. As discussed in Subsection 3.C, the occurrence of soot is highly intermittent and is not expected to significantly alter the OH PLIF data.

The intermittency and spatial inhomogeneity of the instantaneous flame structure is shown by the OH PLIF images in Figs. 7(b) and 7(c). These images indicate that the fuel-preheat and reactant-mixing layers are highly turbulent. The instantaneous thickness of the OH layer varies significantly because of
fluid entrainment from large-scale vortex structures. These structures are shed from the shear layer that is anchored on the lip of the outer air swirler; they enhance the mixing process, bring fresh reactants into the outer conical flame, and can reach across the flame layer and be a source of local flame extinction and intermittency. The latter is more prominent in Fig. 7(c), which shows an instantaneous OH PLIF image at \( \phi = 0.9 \) with no contiguous flame in the viewing area. The size of the structures in Figs. 7(b) and 7(c) that are generated during the turbulent cascade from large to small scales ranges from approximately 0.5 mm to the entire width of the flame layer. Since the airflow rate is held constant, much of this intermittency can be attributed to the behavior of the liquid spray as it impinges on and sheds off the lip of the outer air swirler. This indicates that experiments and computations based on gaseous-fuel injection would not capture the significant changes in large-scale structure dynamics induced by increased liquid-fuel injection.

To quantify the intermittency of the primary flame layer, probability density functions (PDFs) of OH PLIF signals are computed and plotted in Fig. 8 for locations A and B shown in Fig. 7(a). Bin sizes of 200 counts are used along with 200 images. Normalization is performed only for data in the range of \( 0-6000 \) counts, which is below the range typically observed from droplet Mie scattering. Location A is within the mixing layer dominated by large-scale turbulent structures, whereas location B is within the central region of the outer conical flame. The PDFs at both locations show bimodal distributions but with opposite peaks. At location A high levels of intermittency lead to a primary peak with low signal counts and a secondary peak with 3000–3500 counts. At location B low signal counts have decreased in probability and high signal counts have increased in probability, indicating that large-scale structures seldom bring fresh reactants to this point in the flame at \( \phi = 0.5 \).

B. Determination of Local Equivalence Ratio
Figures 7(b) and 7(c) also show the distribution of droplets marked by Mie scattering. This signal, which scales as the droplet diameter squared, is biased toward larger droplets and cannot be used to interpret the true size distribution. However, it can be used as a qualitative marker for those large droplets that escape the initial preheat zone. Interestingly, the droplets in Fig. 7(b) have trailing flames, which indicates that evaporation and mixing with available oxygen is occurring in their wakes. Figure 7(c), however, shows droplets entering the recirculation zone without trailing flames. Since the temperature, evaporation, and reaction rates are expected to be higher in this region for the higher equivalence
ratio of Fig. 7(c), the absence of trailing flames indicates a lack of sufficient oxygen for combustion.

In fact, it can be shown that the local equivalence ratio for the case of Fig. 7(c) is higher than the overall value of 0.9. Using a region in the recirculation zone that is free of droplet scatter [see Fig. 7(c)], we performed an equilibrium calculation for JP-8 fuel at overall equivalence ratios varying from 0.5 to 1.15. The validity of equilibrium assumptions in this region is not known a priori but has been proposed in previous investigations of can-type gas-turbine combustors. The temperatures and species concentrations from this equilibrium calculation are then used to account for the effects of LIF efficiency and Boltzmann fraction with $\phi$ (see Fig. 3). Confidence intervals include LIF uncertainty and flame fluctuation.

C. Soot Formation Mechanisms

Figure 10 shows two instantaneous LII contour plots at $\phi = 1.0$ overlayed with OH PLIF images that are collected simultaneously. It should be noted that these LII images are typical for approximately 5% of the data set. More commonly, the spatial extent of the LII signal from highly concentrated soot pockets encompasses less than 1% of the primary flame zone. Images such as those in Fig. 10 therefore account for the turbulent flame brush noted in Fig. 1(b) that may be responsible for most of the soot production in liquid-spray flames. The flow patterns noted in Fig. 10 are derived by observations from high-speed digital images collected in the same combustor. Soot is generated along the inner cone of the flame in regions of low OH PLIF intensity. A portion of the soot is advected along the outer path of the recirculation zone, whereas a portion appears to enter immediately into the recirculation zone.

Most of the LII signal is detected in regions that are
free of droplet Mie scattering (as verified with the OH PLIF camera) and is attributable to the presence of soot. Some of the signal from the LII camera does occur in regions of high Mie scattering (region A in Fig. 10), indicating that some, if not most, of the signal near the injector exit cannot be attributed to the presence of soot. The LII signal is not likely to come from PAH fluorescence, which would appear more consistently and have peak signals near the spray region. Background images collected without the laser sheet show that the contribution from nascent soot incandescence is less than 5%.

Thus it is likely that soot formation is, in fact, initiated along the inner-cone region (B) between the spray flame (A) and the recirculation zone (C). The absence of OH PLIF in region B is quite evident in the lower half of the spray flame (see Fig. 10), regardless of whether LII is detected. This region likely contains a rich mixture of fuel and air that escapes the main primary flame zone and particulate number density from condensation nuclei counter data in exhaust. LII measurements with camera gate of 50 ns are fit with an exponential function. Data with a 200-ns camera gate are used to check for particle-size bias.

D. Averaged Soot-Volume-Fraction Measurements

The combined use of LII, OH PLIF, and Mie scattering has been shown above to provide physical insight into soot formation in the current flame environment. Data described in the discussion that follows demonstrate the utility of LII and OH PLIF for studying the effects of fuel-inlet conditions on soot production. This is illustrated in Fig. 11, where the temporally and spatially averaged relative soot volume fraction is plotted as a function of the overall equivalence ratio for the current spray flame. The LII data show an exponential increase in soot volume fraction with equivalence ratio. The sampling probe condensation nuclei counter data display a threshold effect at approximately $\phi = 1.0$, below which soot in the exhaust is effectively oxidized due to long residence times and greater quantities of $O_2$ and OH. In the primary zone of the combustor, there is less time to oxidize the soot. In addition, the local $\phi$ is higher in the primary zone than in the exhaust.

The LII experiment is also performed at two camera gate widths to assess the sensitivity of the data to particle-size effects. A bias toward higher particle sizes for the longer gate duration of 200 ns would be expected. Because of normalization, this bias appears as a slight decrease in signal at lower equivalence ratios for which particle sizes are expected to be smaller. This effect appears to be minimal in Fig. 11 (to within experimental uncertainty), suggesting that detection with a 50-ns gate is also free of significant particle-size effects.

Since the dependence of soot volume fraction on $\phi$ is exponential, care must be exercised to differentiate the effect of soot-mitigating fuel additives on $\phi$ from potentially more complex chemical or physical mechanisms. An example is shown in Fig. 12 where methyl acetate, a high-oxygen-containing solvent, is added at 20% by volume to JP-8 fuel during a test at an overall $\phi = 1.05$. Note the large decrease in soot volume fraction during the methyl acetate addition, as measured by LII. This corresponds to a large decrease in particle counts at the sampling probe. A simultaneous increase in OH PLIF signal is also evident in Fig. 12 and, according to Fig. 9, corresponds to a decrease in overall $\phi$. A certain ambiguity exists in the $\phi$ dependence of Fig. 9, however, because the final value could lie on either side of the peak OH signal. Noting that the OH signal increases continuously during methyl acetate addition, it is possible to conclude that the overall $\phi$ remains on the rich side of the peak value. Using Figs. 9 and 11 to determine the functional dependencies of the OH PLIF and LII signals, respectively, we found that a decrease from an overall $\phi$ of 1.05–0.93 took place during methyl acetate addition, with agreement between OH PLIF and
LII to within 1%. The value of 0.93 estimated from both techniques is close to the \( \phi \) of 0.92 calculated from mass flow rates. This agreement suggests that a 20% methyl acetate addition to JP-8 in the current study affects soot production mainly through its effect on \( \phi \) rather than on a fundamental change in the oxidation process. Therefore one can envision use of a combined LII PLIF system to track the performance of soot-mitigating additives without uncertainties in the equivalence ratio.

4. Conclusions

A simultaneous planar LII, OH PLIF, and Mie-scattering system is developed, tested, and demonstrated in a JP-8-fueled, liquid-spray, swirl-stabilized combustor. These combined diagnostics allow us to phenomenologically characterize soot formation mechanisms in this highly turbulent environment by mapping the soot volume fraction, instantaneous flame zone, and fuel droplet behavior. It is found that large-scale structures play a key role in flame intermittency and that soot formation is a strong function of spray-flame interactions as well as the local equivalence ratio. Experimental and numerical studies in gaseous-fueled combustors may not capture these dynamics properly. Soot formation in the inner conical flame region correlates with rich premixed regions with low OH PLIF and droplet Mie scattering. A qualitative study of equivalence ratio effects on the OH PLIF signals shows that equilibrium assumptions can be used for OH signal correction in the recirculation zone. LII data indicate an exponential dependence on the equivalence ratio and highlight the importance of the simultaneous tracking of the local equivalence ratio with OH PLIF, especially for the study of soot-mitigating additives.

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