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Brief Communication

A simplified approach to simultaneous multi-scalar imaging in turbulent flames

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ABSTRACT

This communication describes and demonstrates an approach to making simultaneous multi-scalar measurements with reduced equipment requirements. Specifically, this letter describes and demonstrates the ability to simultaneously acquire high-quality planar laser-induced fluorescence (PLIF) images of CH_2O and either CH, OH, or a combination of CH and OH using a single Nd:YAG-pumped dye-laser system and two intensified cameras. Acquiring these images with common diagnostic equipment was facilitated by exciting strong transitions in the C–X (0,0) band of CH (near 314 nm) and in the A–X (0,0) and (1,1) bands of OH, which are spectrally adjacent. Additionally, Rayleigh scattering images were acquired simultaneously with these PLIF images using a second Nd:YAG laser and an un-intensified camera. However, it would be possible to conduct these measurements with a single, sufficiently energetic Nd:YAG laser.

Employing laser-based imaging techniques to extract detailed information from flames has become a common practice amongst the experimental combustion community (see Ref. [1] for details). Rayleigh scattering imaging (e.g. Refs. [2–9], to list a few) and planar laser-induced fluorescence (PLIF) imaging (e.g. Refs. [2–6,10–18], to list a few), in particular, have become standard tools for visualizing the spatial distributions of temperature and various combustion intermediate species, respectively. Utilizing these techniques together is particularly advantageous and is popular amongst well-established combustion research facilities. However, the high cost of pulsed lasers and cameras generally renders such experimentation infeasible for many research laboratories. Furthermore, to the best of the authors' knowledge, heretofore, there has only been a few investigations in which two-dimensional (2-D) PLIF images of *multiple* combustion intermediates were acquired simultaneously with 2-D Rayleigh scattering images [2–6]. It is noteworthy that in the more recent of those studies [5], a pulsed alexandrite laser, which is not commonly found in combustion research facilities, was employed.

This communication describes a technique that utilizes equipment readily accessible to many combustion research laboratories to acquire Rayleigh scattering images simultaneously with PLIF images of formaldehyde (CH_2O) and either hydroxyl (OH), methylidyne (CH), or a combination of OH and CH. Furthermore, we demonstrate this technique by applying it to extremely turbulent, premixed methane–air flames. The ability to make such multi-scalar measurements with relatively standard diagnostic equipment is made possible by a novel approach to CH-PLIF imaging. Namely, in the past CH-PLIF imaging was primarily conducted via some combination of excitation of and detection from transitions in either the $A^2\Sigma^+$–$X^2\Pi$ ($v'=0$, $v''=0$) or $B^2\Sigma^-$–$X^2\Pi$ (0,0) bands of CH [5,10,12,13]. Here, CH-PLIF imaging was facilitated through the excitation of and detection from transitions in the (0,0) band of the CH $C^2\Sigma^+$–$X^2\Pi$ system (near 314 nm) [15,16].

Owing to the relatively large absorption and emission coefficients of transitions in the CH C–X (0,0) band [19], the primary benefit of this approach to CH-PLIF imaging is that high-quality images can be acquired with low laser fluence (e.g. 1.6×10^{-3} J/cm^2) [15,16]. An additional benefit of this technique, which was first alluded to by Jefferies *et al.* [19] and was recently demonstrated by Carter et al. [15,16], is that with a judicious choice of excitation transitions and filtering schemes, one can obtain CH- and OH-PLIF images simultaneously or separately with a single laser and camera configuration. This can be understood by investigating computed excitation spectra (generated via LIFBASE [20]) for CH and OH, which, alongside PLIF images corresponding to three specific transitions, are displayed in Fig. 1. Note that the OH and CH spectra are scaled arbitrarily such that the maximum intensity of each spectra has a relative emission equaling 100. In actuality, OH-LIF signals are much greater than those for CH, due to the much greater OH concentrations.

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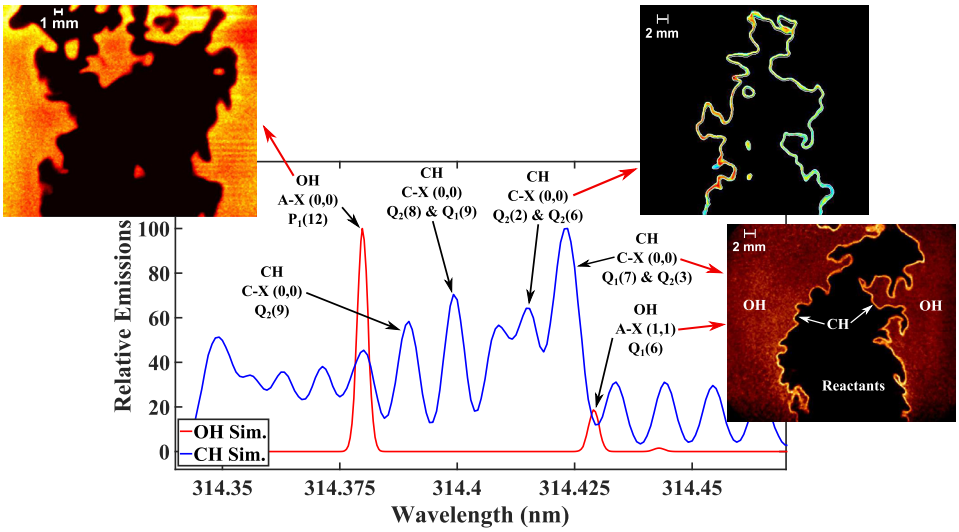

Fig. 1. Computed spectra of the CH C–X and OH A–X systems [20] as well as sample PLIF images.

As shown, two OH lines are located near the Q-branch transitions of the CH C–X (0,0) band. However, as Fig. 1 shows, by tuning to the overlapping $Q_2(2)$ and $Q_2(6)$ transitions in the (0,0) band of the CH C–X system (at 314.415 nm), one can obtain high-quality CH-PLIF images void of OH-LIF signal [15,16]. Additionally, OH-PLIF images, with minimal CH-LIF signal, can be acquired by tuning to the $P_1(12)$ transition in the OH A–X (0,0) band (at 314.380 nm). Finally, by tuning near 314.426 nm, one can excite the CH C–X (0,0) Q-branch band-head (composed of the $Q_1(7)$ and $Q_2(3)$ transitions) and the $Q_1(6)$ transition in the OH A–X (1,1) band; of course, the ground-state for this OH transition is from the $v''=1$ band, and thus its Boltzmann fraction will be relatively temperature sensitive. As the sample image in the lower right corner of Fig. 1 shows, this coincidence of transitions permits the acquisition of images containing both CH- and OH-LIF signal. Notably, though, the technique as described relies on resonant detection of the CH fluorescence, which provides high signal-to-noise ratio (SNR) but no discrimination from background elastic scattering. However, scattering rejection might be obtained by exciting an R-branch transition (say, near 311 nm) and employing a long-wave-pass filter to block background scattering and transmit most of the CH LIF. This approach is in fact described in Ref. [21], but as noted the best SNR is obtained with excitation of a Q-branch transition and resonant fluorescence detection; furthermore, as our intent here was to couple LIF with Rayleigh scattering, minimization of sources of background scattering (from surfaces/particles) was a necessary step.

A further advantage of this technique is that a 314-nm laser beam can be produced with diagnostic equipment common to combustion research facilities. Namely, a straightforward way to produce a 314-nm beam (as was done here) is to frequency double the output from an Nd:YAG-pumped dye-laser system, operating with DCM laser dye, and tuning the dye laser to ~628 nm. Furthermore, because OH- and CH-PLIF imaging via excitation near 314 nm can be achieved with modest laser fluence [15,16], one could conduct CH- and OH-PLIF imaging with a Nd:YAG-pumped dye-laser system even while the majority of the output energy from the pump laser is contained within its frequency-tripled output (near 355 nm) rather than its frequency-doubled output (near 532 nm). Since CH_2O can be excited with the frequency-tripled output from an Nd:YAG laser [22], having a relatively strong 355-nm beam (e.g. >50 mJ/pulse) with the 314-nm beam permits the simultaneous acquisition of PLIF images of CH_2O and either OH, CH, or a combination of OH and CH, with a single laser system and two intensified cameras. Moreover, provided that a sufficiently strong Nd:YAG pump-laser is available (e.g. one that provides ~1 J/pulse at 532 nm), a significant portion of its frequency-doubled output could facilitate Rayleigh scattering imaging, and thus, this diagnostic could be performed simultaneously with PLIF imaging of the aforementioned species using a single Nd:YAG-pumped dye-laser system and three cameras. Such measurements were made in this study, but due to the limited output from the pump laser, a second Nd:YAG laser was used for the Rayleigh measurements.

To demonstrate the technique outlined above, we applied it to premixed methane–air flames produced and stabilized by the Hi-Pilot burner [18]. The primary details of the diagnostic equipment are provided in Table 1, while a more detailed table and a schematic of the diagnostic configuration are provided in the Supplementary material.

Sample PLIF and temperature field images from Cases 1A-0.85, 2B-1.05, and 6A-0.85 of Ref. [18] are provided in Fig. 2. Additionally, the straight gray lines in those images identify the paths along which the plots in Fig. 2 were derived. Figure 2 clearly demonstrates that the laser-based imaging technique described here can provide detailed information about multiple scalar quantities in highly turbulent flames. An interesting observation one can draw from Fig. 2 is that the spatial positioning of these chemical species is like that observed in a laminar flame (see Supplementary material). Specifically, though the CH_2O-LIF signal regions are at times very broad, their highest levels are always located upstream of thin CH-layers and regions where the OH-LIF signals are high. Furthermore, these profiles suggest that the temperature ranges over which the CH_2O-, CH-, and OH-LIF signals exist are similar to that in a laminar flame (see Supplementary material). Of course, building upon this latter observation provides the modeling community with valuable information regarding the distribution of these species in temperature space.

The center panel of the lowest row in Fig. 2 clearly demonstrates that tuning near 314.426 nm provides an image in which the average intensity of the CH-LIF signal is higher than that of the OH-LIF signal. The relative signal levels between these two species can be controlled, to a small extent, by varying the wavelength of the excitation laser sheet: tuning to slightly shorter wavelengths yields higher CH-LIF signals; tuning to slightly longer wavelengths yields higher OH-LIF signals (see Fig. 1). Of course, the relative