Infrared Laser-Induced Fluorescence with a Continuous-Wave Optical Parametric Oscillator

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Abstract: A continuous-wave optical parametric oscillator was used to produce spectrally resolved, infrared laser-induced fluorescence (IR-LIF) signals of CO_2 in a heated jet. Spatially resolved temperature measurements were obtained by spectral fitting to the IR-LIF signals.

1. Introduction

Infrared laser-induced fluorescence (IR-LIF) is a promising tool for imaging gas properties and a variety of molecular species that are important to combustion science. This is because the vast majority of molecular species do not exhibit rovibronic absorption spectra and/or fluorescence quantum yields that are well-suited for traditional visible- or ultraviolet-LIF techniques. Kirby and Hanson [1,2] performed the first IR-LIF measurements of CO and CO_2 in flames and jets using high-power, pulsed lasers. Zetterburg et al. [3,4] utilized a pulsed laser to image CO_2 in reaction zones surrounding hot catalysts. Goldenstein et al. [5] utilized an external-cavity quantum-cascade laser (EC-QCL) to perform the first IR-LIF measurements of CO_2 and gas properties using a continuous-wave (CW) light source. Most recently, Mathews and Goldenstein [6] developed wavelength-modulated LIF (WM-LIF) to provide background-free IR-LIF measurements of CO in a flame using a quantum-cascade laser (QCL). To the best of our knowledge, this work presents the first spectrally resolved IR-LIF measurements performed using a CW optical parametric oscillator (CW-OPO). Using a CW-OPO as the excitation source provides two primary benefits compared to prior work performed with QCLs. (1) the CW-OPO can produce wavelengths from 1.5 to 4 μm, thereby enabling measurements of multiple species with a single light source. (2) The CW-OPO produces $\approx$ 50$\times$ more output power than narrow linewidth QCLs which ultimately enables larger LIF signals to be produced.

2. Experiment

A schematic of the experimental setup used to perform IR-LIF measurements of temperature in a heated jet is shown in Fig. 1. A fiber-coupled, distributed feedback (DFB) seed laser was amplified with a fiber amplifier to provide a 10 W CW pump beam for the OPO. The injection-current of the DFB seed laser was scanned with a 10 Hz sine wave to scan the intensity and wavelength of the OPO idler beam across several CO_2 absorption transitions near 3703.3 cm^{-1}. The 0.5 W OPO idler beam was focused to a 1/e^2 diameter of $\approx$ 0.1 mm using a 40 mm focal-length lens and then passed through a heated jet of 5% CO_2 in argon at a location 1.5 mm above the jet exit. The flow rate of the jet was 1.0 scfh and it was heated to approximately 560 K by wrapping heating tape around the jet body. LIF signals from CO_2's ν_3 fundamental vibration band were imaged orthogonal to the laser beam using a high-speed, IR camera with a frame rate of 8.5 kHz and an exposure time of 30 μs. A spectral bandpass filter centered at 2335 cm^{-1} with a full-width at half-maximum of 37 cm^{-1} was installed in the camera to

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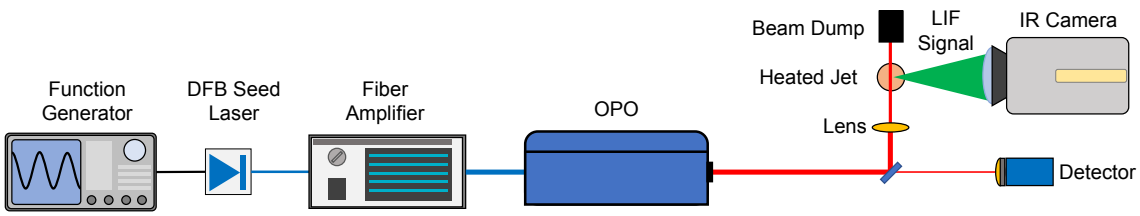

Fig. 1. Experimental setup used to acquire IR-LIF measurements of temperature in a heated jet.

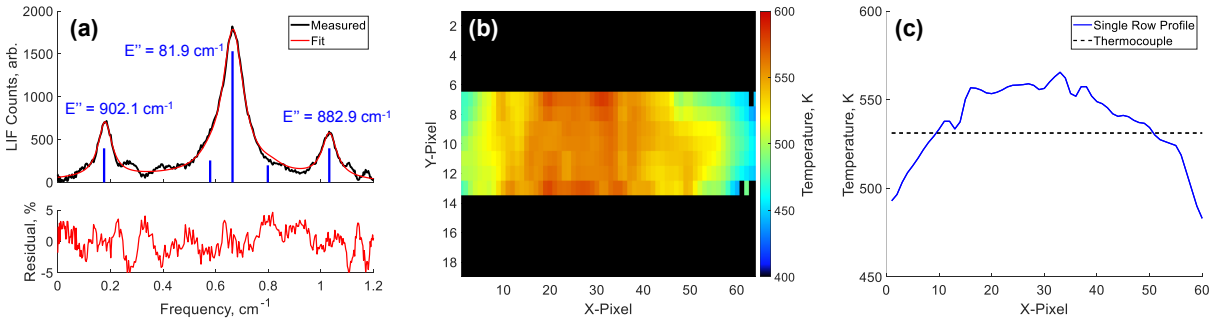

Fig. 2. Background-subtracted CO_2 LIF signal and corresponding best-fit spectrum (a), single-scan temperature image (b), and single-row temperature profile corresponding to row Y = 10 (c)

post-processing, a 2x2 pixel average was applied to each frame of the raw camera data, and each pixel's time history (after background subtraction) was divided by the intensity time history of the idler beam to correct for the influence of the time-varying excitation power on the LIF signal.

For steady state excitation in the weak excitation limit, the intensity of the broadband LIF signal traces the local absorbance spectrum. As a result, the LIF signal recorded by each pixel was fed to a spectral-fitting routine to determine the gas temperature. The spectroscopic model consisted of five absorption lines, and the integrated area, linecenter frequency, and collisional broadening width of the three strongest transitions were treated as free parameters (see Fig. 2a). The lineshapes were modeled as a Voigt profile. The measured ratio of the integrated areas of the transitions with E" = 882.9 cm^{-1} and E" = 81.9 cm^{-1} was used to calculated the gas temperature using conventional two-color thermometry. The parameters describing the weakest two transitions were fixed based on the measured temperature and the linecenter and collisional width of the strongest transition.

3. Results

Fig. 2a shows a background-subtracted LIF signal (initially acquired as a time history) and resulting best-fit spectrum plotted as a function of the idler beam frequency. The LIF signal has a peak magnitude of $\approx$ 1800 counts and its variation with idler frequency illustrates the underlying absorption transitions of CO_2. For the spectrum shown, the best-fit spectrum corresponds to a temperature of 561.5 K. Fig. 2b, shows an image of temperature determined from a single scan across the CO_2 absorption lines for each pixel with an adequate signal-to-noise ratio. The temperature image illustrates the structure expected in a heated, laminar jet: a high-temperature core surrounded by a low temperature boundary layer. Fig. 2c shows a comparison between a single-row temperature profile and the bulk temperature recorded by a thermocouple. The measured temperature profile corresponds to pixels along the row Y = 10 shown in Fig. 2b, and the temperature agrees relatively well with the thermocouple value which supports the accuracy of the IR-LIF diagnostic.

Acknowledgements

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References

1. B. J. Kirby and R. K. Hanson, "Planar laser-induced fluorescence imaging of carbon monoxide using vibrational (infrared) transitions," Appl. Phys. B **69**, 505–507 (1999).
2. B. J. Kirby and R. K. Hanson, "Linear excitation schemes for IR planar-induced fluorescence imaging of CO and CO_2," Appl. Opt. **41**, 1190–1201 (2002).
3. J. Zetterberg, S. Blomberg, J. Gustafson, Z. W. Sun, Z. Li, E. Lundgren, and M. Aldén, "An in situ set up for the detection of CO_2 from catalytic CO oxidation by using planar laser-induced fluorescence." The Rev. Sci. Instruments **83**, 053104 (2012).
4. J. Zetterberg, S. Blomberg, J. Gustafson, J. Evertsson, J. Zhou, E. C. Adams, P.-A. Carlsson, M. Aldén, and E. Lundgren, "Spatially and temporally resolved gas distributions around heterogeneous catalysts using infrared planar laser-induced fluorescence," Nat. Commun. **6**, 1–8 (2015).
5. C. S. Goldenstein, V. A. Miller, and R. K. Hanson, "Infrared planar laser-induced fluorescence with a CW quantum-cascade laser for spatially resolved CO_2 and gas properties," Appl. Phys. B **120**, 185–199 (2015).
6. G. C. Mathews and C. S. Goldenstein, "Wavelength-modulated planar laser-induced fluorescence for imaging gases," Opt. Lett. **42**, 5278–5281 (2017).