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Two-Beam Femtosecond Rotational CARS for One-Dimensional Thermometry in a Turbulent, Sooting Jet Flame

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Single-laser-shot femtosecond rotational coherent anti-Stokes Raman scattering (fs-RCARS) temperature measurements are performed across a 6-mm line in a turbulent, sooting ethylene jet flame to characterize temperature gradients. A 60-fs pulse is used to excite many rotational Raman transitions in N_2, and a 160-ps pulse is used to probe the Raman coherence. The spatial resolution of the measurements is 500 µm in the direction of beam propagation and 50 µm in the transverse directions. Measurements have been performed at multiple locations in the jet flame, and the measured temperature are similar to previously recorded point measurements. Future work will include performing simultaneous laser-induced incandescence (LII) measurements to measure soot volume fraction to perform joint statistical analysis of the sooting turbulent flame.

I. Introduction

Soot is an important aspect in many combustion applications. Particularly, soot plays a major role in radiation, which can impact engine hardware and combustion performance in boilers, furnaces, and other combustion devices. Additionally, soot had an adverse effect on the environment and human health. To better understand the role of soot, one-dimensional temperature measurements are performed in a canonical, turbulent, sooting ethylene jet flame that has been previously characterized using laser-induced incandescence (LII)[1–2] and point temperature measurements.

Coherent anti-Stokes Raman scattering (CARS) has been used for temperature, pressure, and species-concentration measurements in gas-phase reacting and nonreacting flows for many decades[3],[4] and more recently with ultrafact laser systems[5,]. Two distinct advantages of ultrashort-pulse CARS are the collision-free nature of the measurement due to the ultrafast time scales of the laser–matter interactions and the high peak-energy of the femtosecond (fs) and picosecond

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(ps) pulses. Several variations and improvements to ulstrashort-pulse CARS techniques have been presented in the combustion diagnostics literature including the use of hybrid fs/ps CARS for pure rotational[6,7] and rovibrational[8] measurements, chirped-probe pulse measurements[9,10], the use of second harmonic bandwidth compression to achieve high-energy ps-duration probe pulses[11], pressure measurements[12], and new methods for obtaining high spatial resolution for one-dimensional CARS spectra[13]. One-dimensional measurements have been demonstrated using a two-beam phase-matching approach for rotational CARS[14,15].

II. Experimental Setup

For the one-dimensional temperature measurements presented in this work, a fs laser (800 nm, 60 fs, 1 kHz, 7 mJ, Astrella from Coherent, Inc.) provided the pump/Stokes beam and a ps laser (532 nm, 200 ps, 10 Hz, 90 mJ, Positive Light) provided the probe pulse. Each laser system had an 80 MHz oscillator which seeded a regenerative amplifier. The two oscillator systems were locked and the temporal jitter was estimated to be less than 1 ps. The regenerative amplifiers were triggered from a down converted 80 MHz signal from the oscillators. The pulse energies at the probe volume were 5.9 mJ for the pump/Stokes pulse, and 58 mJ for the probe pulse. Half-wave plates and thin-film polarizers were used to control the pulse energies. The polarization of each beam at the probe volume was vertical. The probe beam was expanded using a lens–telescope system to match the diameter of the pump/Stokes beam. The spatial overlap of the beams was accomplished using a beam-profiling camera at the probe volume. The beams were focused to the probe volume by a single cylindrical lens with a focal length of 300-mm. The beam crossing angle was 6°. A 400-mm cylindrical lens was used after the probe volume to collimate the CARS signal. An angle-tunable ultrasteep short-pass filter (SP01-561RU, Semrock) was used to reject the probe beam and transmit the CARS signal. A 1-m spectrometer with a 1200 g/mm grating was used to disperse the CARS signal onto a back-illuminated CCD (ProEM, Princeton Instruments). A diagram of the optical system is shown in Fig. 1.

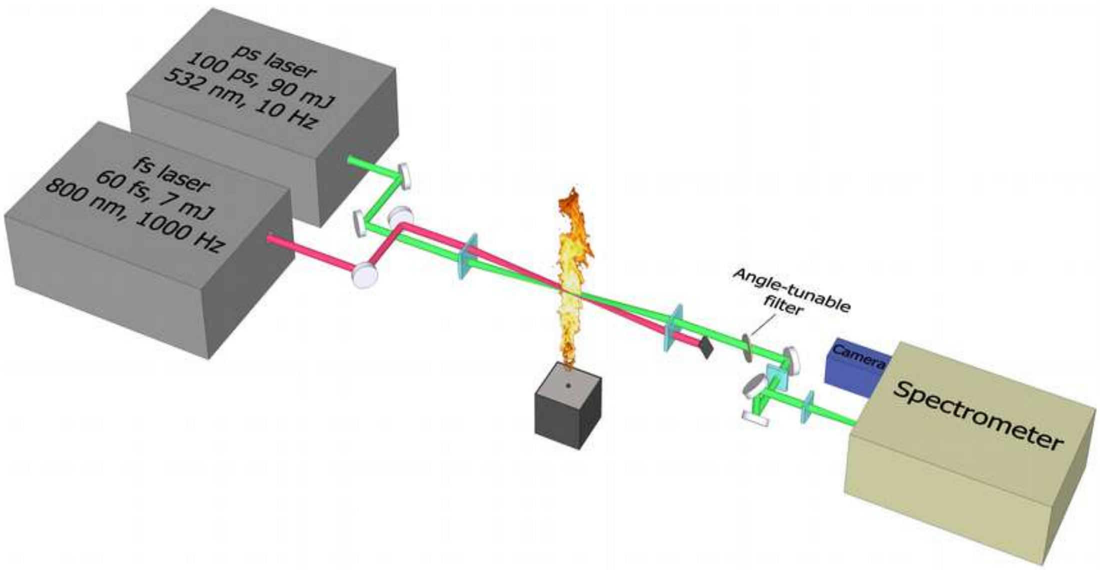

Figure 1. Diagram of the laser system used to perform one-dimensional fs/ps rotational CARS thermometry measurements.

The spatial extent of the probe volume was measured by translating a glass slide along the direction of beam propagation and integrating the nonresonant signal generated in the glass slide. The probe volume length was found to be 600 μm as determined by the the distance between the points where the nonresonant signal rose to 10% of the maximum value. A cylindrical lens was used to image the probe volume onto the entrance slit of the spectrometer and the spatial resolution of the detection system was measured by translating a sharp edge across the probe volume in a direction perpendicular to the beam propagation direction. The spatial resolution of the detection system was 10.6 μm per pixel. The point spread function was approximately 40 μm as determined by an image recorded with a sharp line in the object plane. During data collection, the images were binned by 4 pixels in the direction of spatial resolution to have a final spatial resolution of 42 μm and by 2 pixels in the direction of spectral resolution for a final spectral resolution of 0.4 cm^{-1}. The extent of the other transverse direction of the probe volume was estimated by imaging the beams a the focus using a beam profiling camera and it was estimated to be 50 μm.

Temperature measurements were performed in a piloted, turbulent ethylene jet flame with Reynolds number Re = 20,000. The piloted burner design is described in detail by Zhang et al.[1]. The fuel jet had a diameter of 3.2 mm and was centered in a 15.2-mm tube which contains the premixed gases for the lean pilot flame. These tubes were centered in a 152-mm square coflow of conditioned air. The ethylene in the premixed pilot flame contained about 2% of the total fuel flow. The flow rate of the ethylene in the main fuel jet was 26.2 standard liters per minute (SLPM). Previous studies have been conducted on this burner to measure the soot volume fraction[2] and temperature using point CARS measurements[16].

III. Results

Prelimenary one-dimensional measurements have been performed at multiple flame locations. Example raw spectograms recorded at an axial heights of 35 and 160 diameters downstream of the jet exit are shown in Figs. 2 and 3 respectively.

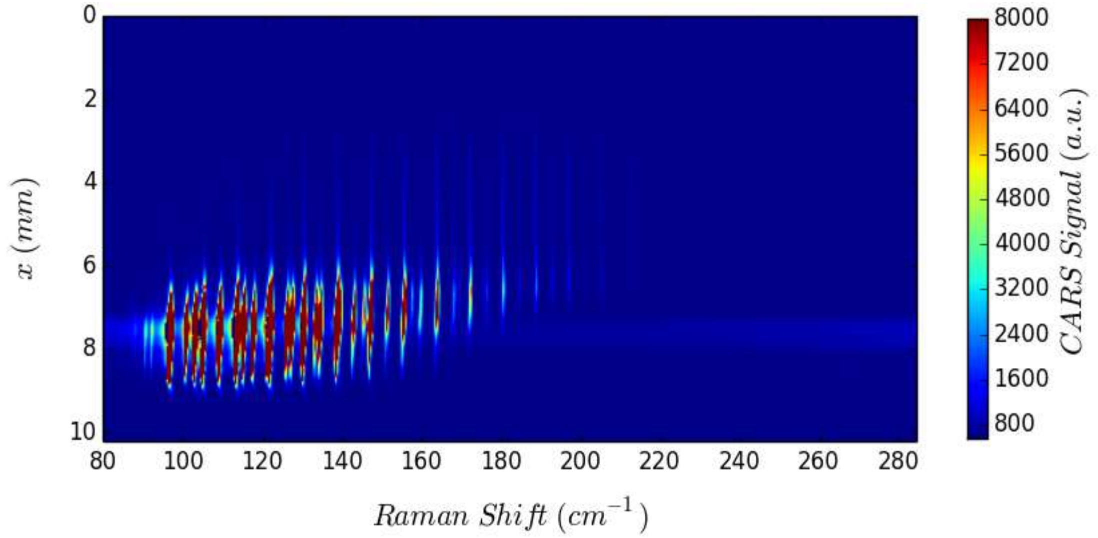

Figure 2. Example spectrogram at an axial location of z/d = 35.

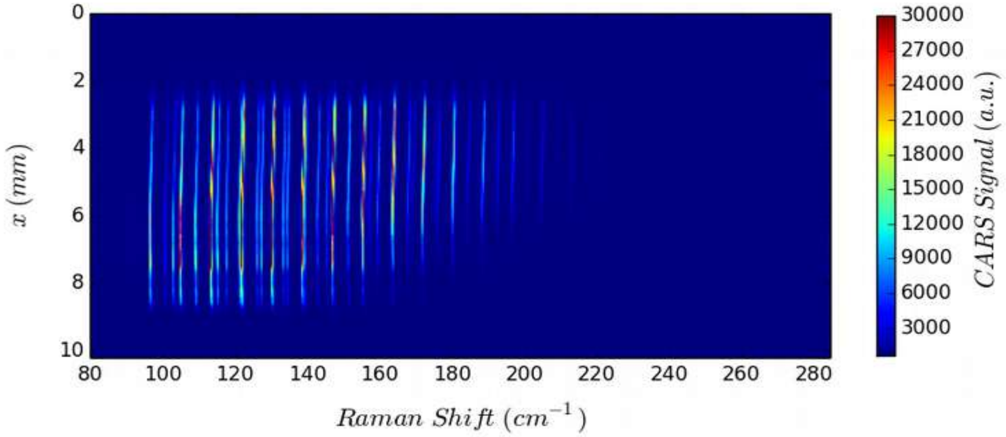

Figure 3. Example spectrogram at an axial location of z/d = 160.

CARS spectra from each row was fit to determine spatially resolved, one-dimensional temperature profiles in the flame. A scatter plot of spatially related, best-fit temperatures is shown in Fig. 4, and a histogram of best-fit temperature values from all spatial locations is shown in Fig. 5.

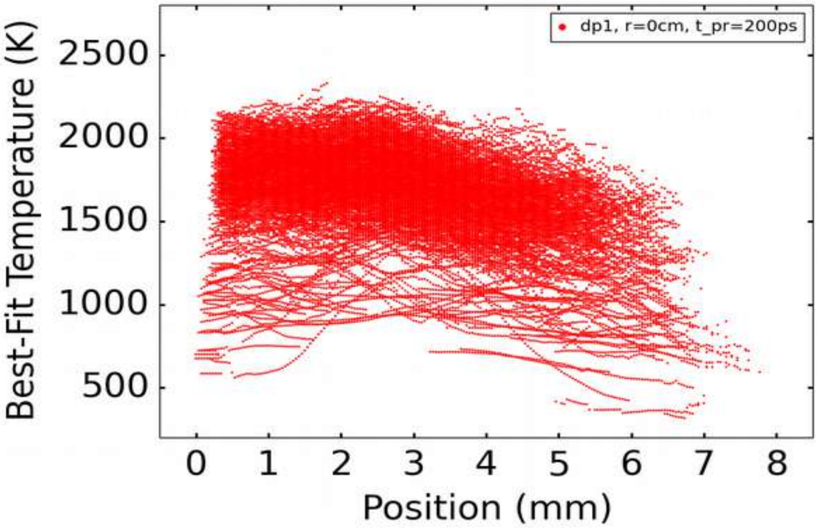

Figure 4. Best fit temperatures from 500 single-laser-shot spectrograms at an axial location of z/d = 160.

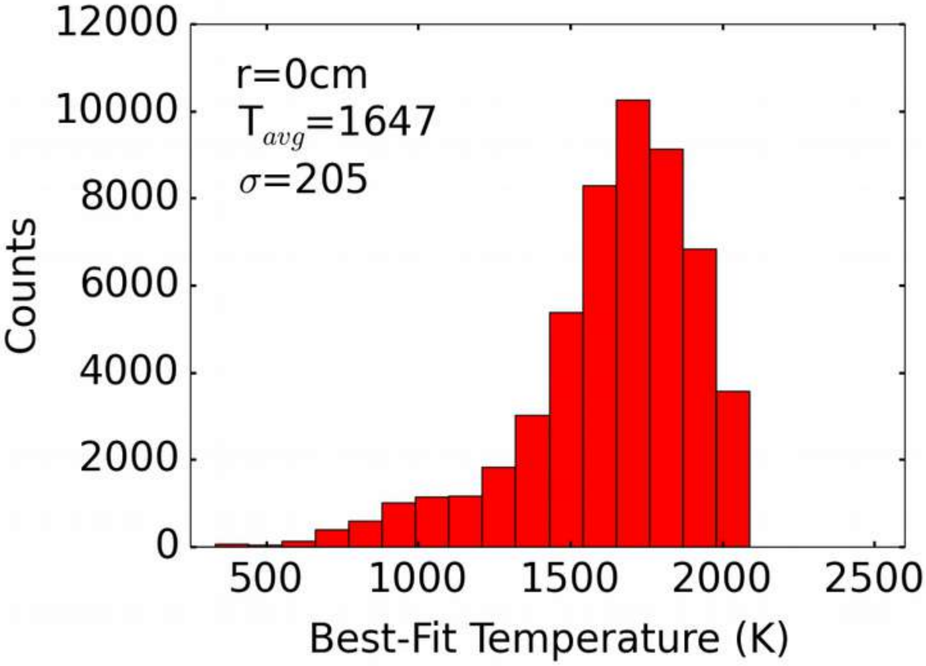

Figure 5. Histogram of best fit temperatures from 500 single-laser-shot spectrograms at an axial location of z/d = 160. All temperatures have been accumulated into a single histogram.

IV. Conclusions

One-dimensional rotational CARS thermometry has been performed in a turbulent, sooting ethylene jet flame. In future efforts, data recorded at multiple flame locations will be analyzed to extract temperature gradient information along the measurement line. Statistics of the temperature gradients will be analyzed to characterized the turbulent flame fluctuations.

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References

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1 Zhang, J., Shaddix, C.R., and Schefer, R.W., “Design of “model-friendly” turbulent non-premixed jet burners for C_{2+} hydrocarbon fuels,” Rev. Sci. Instrum. Vol. 82, 2011, pp. 074101.

2 Shaddix, C.R., Zhang, J., Schefer, R.W., Doom, J., Oefelein, J.C., Kook, S., Pickett, L.M., and Wang, H., “Understanding and predicting soot generation in turbulent non-premixed jet flames,” Sandia Report, SAND2010-7178, 2010.

3 Eckbreth, A.C., *Laser Diagnostics for Combustion Temperature and Species*, Gordon & Breach, London, 1996.

4 Roy, S., Gord, J.R., and Patnaik, A.K., “Recent advances in coherent anti-Stokes Raman scattering spectroscopy: Fundamental developments and applications in reacting flows,” *Prog. Energ. Combust. Sci.* Vol. 36, No. 2, 2010, pp. 280–306.

5 Gord, J.R., Meyer, T.R., and Roy, S., “Applications of Ultrafast Lasers for Optical Measurements in Combusting Flows,” *Annu. Rev. Anal. Chem.* Vol. 1, 2008, pp. 663-687.

6 Miller, J.D., Roy, S., Slipchenko, M.N. Gord, J.R., and Meyer, T.R., “Single-Shot Gas-Phase Thermometry using Pure-Rotational Hybrid Femtosceond/Picosecond Coherent Anti-Stokes Raman Scattering,” *Optics Express*, Vol. 19, No. 16, 2011, pp. 15627-15640.

7 Stauffer, H.U., Miller, J.D., Slipchenko, M.N., Meyer, T.R., Prince, B.D., Roy, S., and Gord, J.R., “Time-and Frequency-Dependent Model of Time-Resolved Conherent Anti-Stokes Raman Scattering (CARS) with a Picosecond-Duration Probe Pulse,” *J. Chem. Phys.*, Vol 140, No. 2, 2014, pp. 024316.

8 Miller, J.D., Slipchenko, M.N., and Meyer, T.R., “Probe-pulse optimization for nonresonant suppression in hybrid fs/ps coherent anti-Stokes Raman scattering at high temperature,” *Optics Express* Vol. 19, No. 14, 2011, pp. 13326-13333.

9 Richardson, D.R., Lucht, R.P., Kulatilaka, W.D., Roy, S., and Gord, J.R., “Theoretical modeling of single-laser-shot, chirped-probe-pulse femtosecond coherent anti-Stokes Raman scattering thermometry,” *Appl. Phys. B*, Vol. 104, No. 3, 2011, pp . 699-714.

10 Dennis, C.N., Slabaugh, C.D., Boxx, I.G., Meier, W., and Lucht, R.P., “Chirped Probe Pulse Femtosecond Coherent Anti-Stokes Raman Scattering Thermometry at 5 kHz in a Gas Turbine Model Combustor,” *Proc. Combust. Inst.*, Vol. 35, No. 3, 2015, pp. 3731-3738.

11 Kearney, S.P., and Scoglietti, D.J., “Hybrid femtosecond/picosecond rotational coherent anti-Stokes Raman scattering at flame temperatures using a second-harmonic bandwidth-compressed probe,” *Opt. Lett.* Vol. 38, No. 6, 2013, pp. 833-835.

12 Kearney, S.P., and Danehy, P.M, “Pressure Monitoring using Hybrid fs/ps Rotational CARS,” *53rd AIAA Aerospace Sciences Meeting*, AIAA 2015-1696, January 5-9, 2015, Kissimmee, Florida, USA.

13 Miller, J.D., Dedic, C.E., and Meyer, T.R., “Vibrational femtosecond/picosecond coherent anti-stokes Raman scattering with enhanced temperature sensitivity for flame thermometry from 300 to 2400 K,” *J. Raman Spectrosc.* Vol. 46, No. 8, 2015, pp. 702-707.

14 Kliewer, C.J., “High-spatial-resolution one-dimensional rotational coherent anti-Stokes Raman spectroscopy imaging using counter-propagating beams,” *Opt. Lett.*, Vol. 37, No. 2, 2012, pp. 229-231.

15 Bohlin, A. Mann, M., Patterson, B.D., Dreizler, A. and Kliewer, C., “Development of Two-Beam Femtosecond/Picosecond One-Dimensional Rotational Coherent Anti-Stokes Raman Spectroscopy: Time-Resolved Probing of Flame Wall Interactions,” *Proc. Combust. Inst.,* Vol. 35, No. 3, 2015, pp. 3723-3730.

16 Kearney, S.P., Hoffmeister, K.N.G., Guildenbecher, D.R., Winters, C., Grasser, T.W., and Hewson, J.C., “Hybrid fs/ps rotational CARS temperature and oxygen measurements and soot LII measurements in a turbulent C2H4-fueled jet flame,” AIAA SciTech 2016, 54th Aerospace Sciences Meeting, AIAA2016-0281.