

# Optical tomography in reacting flows based on Stokes Raman scattering

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**Abstract** This paper reports on development of an optical system for tomographic imaging in reacting flows. The measurement principle is based on registration of Stokes Raman scattering (rovibrational transitions for molecular nitrogen), when a transparent object is illuminated by a laser sheet. The method allows to retrieve local gas density and concentration.

## 1. Introduction

State-of-the-art optoelectronic devices provide detection of weak emission signals. It allows for non-intrusive measurements in reacting flows with high spatial and temporal resolution. Powerful lasers, efficient photocathodes with photo-multiplying tubes, and new optical filters can be combined into an optical system for registration of 2D images of Raman scattering, characterized by weak signal. The present paper reports on development of such system for local density and concentration measurements in flames based on detection of Stokes Raman scattering from molecular nitrogen.

## 2. Experimental setup

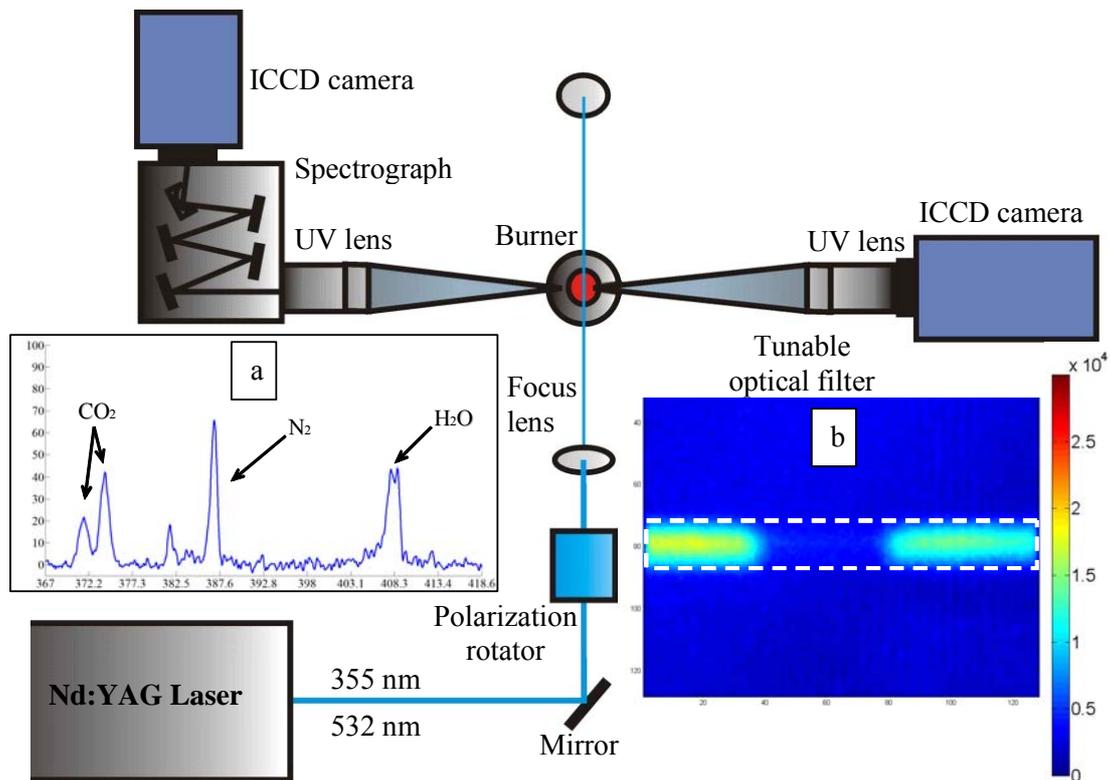
Sketch of the experimental setup for 1D and 2D measurements is shown in figure 1. The third (355 nm) or the second (532 nm) harmonic of a pulsed Nd:YAG laser (QUANTEL BrilliantB) was used for the illumination of sampling volume. The third harmonic of the laser was used only in 1D Raman system. The second harmonic of a pulsed Nd:YAG laser (Quanta-Ray) was used for 2D Raman system with combination of collimation optics. The energy of 6 ns laser pulses was monitored by an energy meter (Coherent LabMax-TOP). On average, the energy was 120 and 690 mJ for 355 and 532 nm, respectively, with 5% RMS fluctuations. Figure 1b shows the 2D image when a flame was illuminated by a non-focused laser beam. Orientation of linearly polarized laser light was controlled by half-wave plates. This was necessary to record signal for two perpendicular polarizations of the incident laser light. The images for the horizontal polarization were subtracted from those for the vertical polarization in order to minimize influence of the dark-current, reflections, and possible fluorescence (for UV).

## 3. 1D Raman system

1D system captured spectrum of the scattered light along the laser beam by using a Czerny-Turner spectrograph (Newport MS127i 1/8 m) equipped with a UV lens. The spectrometer alignment ensured the parallel orientation of the entrance slit and the laser beam. Grating with 1 200 lines/mm was used to provided spectral resolution of 1 nm. The spectra along the beam were registered by a 12-bit ICCD

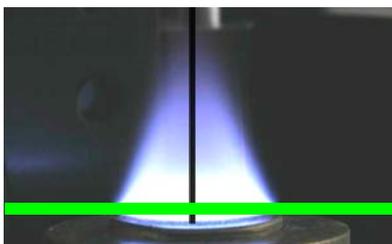


camera (PCO DICAM Pro, GEN II photocathode type with quantum efficiency 20% in UV spectral region) mounted at the output of the spectrograph. To reduce noise, the scattered light from 100 laser pulses was collected during acquisition of each image. The collection time during each shot was 30 ns. For each measurement point, 10 frames were captured and averaged in order to reduce contribution of read-out noise. The image size of 1280×800 pixels corresponded to 108 nm on 105 mm. The full width at half maximum of the registered Stokes peaks was 7 pixels.



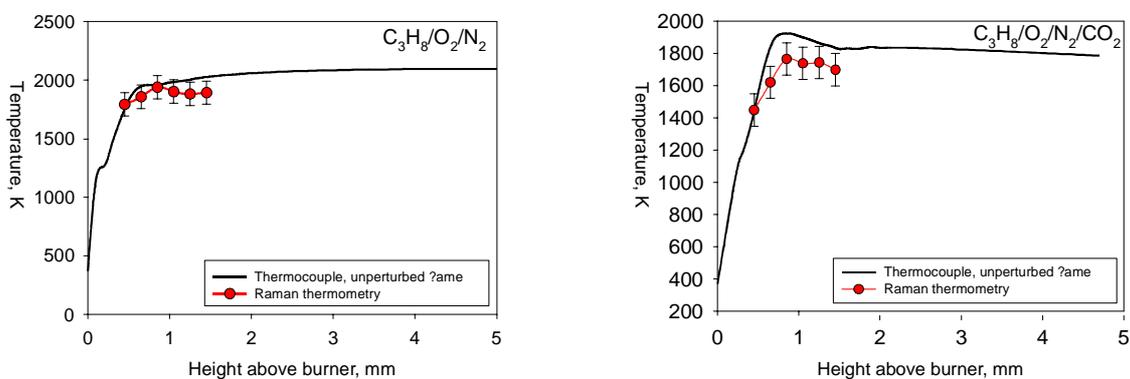
**Figure 1.** Scheme of the experimental setup for Raman thermometry and data example (a- Stokes band of Raman spectrum, b- 2D distribution of Raman signal for N<sub>2</sub> vibronic transition) in flame.

The used temperature evaluation approach is based on the paper of Rabenstein and Leipertz [1]. The beam passed through the ambient air and the flame simultaneously; thus, the Raman spectrum was imaged for both regions (see the example Fig. 1b). The air was considered as the control volume (its temperature was monitored). Following Egermann et al. [2], the Raman spectra were recorded for two perpendicular polarizations of the laser light (vertical and horizontal). The images for the horizontal polarization were subtracted from those for the vertical polarization in order to minimize influence of the dark-current, reflections, and fluorescence. Unfortunately, the light scattered at 355 nm was not removed by a special filter, Rayleigh signal was present on the images, that limited dynamic range. The photo of the studied flame is shown in figure 2.



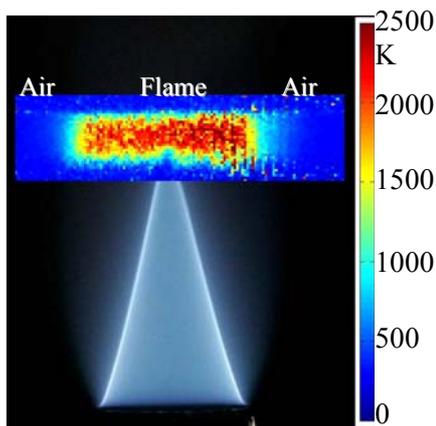
**Figure 2.** Photo of the studied flame. The black line indicates the area of study, the green line indicates the direction of the laser beam.

Intensity of Stokes lines depends on the temperature and volume fraction of the molecules. The line for molecular nitrogen was used to evaluate ratio between the flame and ambient air temperatures. The spectra in both regions was averaged over 60 pixels (i.e., for 8 mm along the beam). The background from the Rayleigh signal was approximated by an analytical fit function and was removed. According to [1], the dependence of the effective Raman scattering cross-section on temperature should be taken into account. This was done from calculations of the Raman spectra by using RAMSES code [3]. The fraction of nitrogen in the flames was evaluated from the numerical simulations. In addition, the approach was tested for the flows when the mixture was issuing from the burner, but the flame was not ignited. The results are compared with the temperature measured by the thermocouple are shown in figure 3.

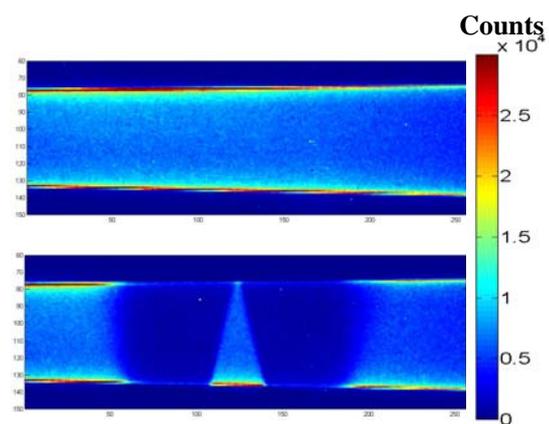


**Figure 3.** Temperature profiles in fuel-rich  $C_3H_8/O_2/N_2$  and  $C_3H_8/O_2/N_2/CO_2$  flame measured by thermocouple (solid black line) and by Raman thermometry technique (solid red line and circles) [4].

#### 4. 2D Raman system



**Figure 4.** Temperature distribution in laminar Bunsen flame cone measured by 2D Raman technique with cylindrical laser beam and photo of Bunsen cone.



**Figure 5.** Example of Raman signal distribution in air and in the laminar Bunsen flame cone.

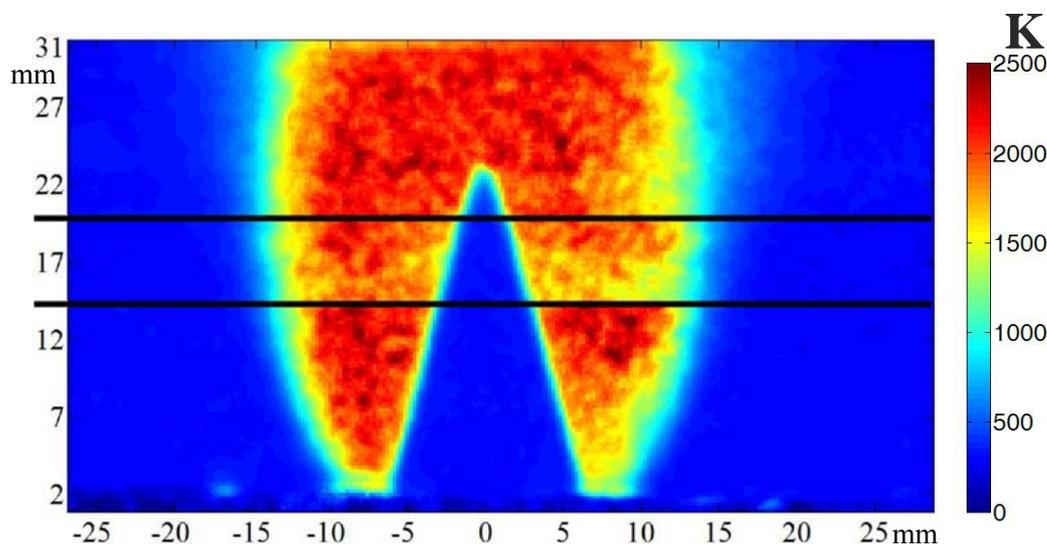
##### 4.1. 2D Raman system (cylindrical laser beam)

For registration of the Raman signal, a 16-bit ICCD camera (Princeton instruments PI-MAX-4) equipped with a tunable optical filter (VariSpec LC), based on liquid crystals, was used to collect the

emission for the desired wavelength, corresponding to the vibronic transition of nitrogen (607.3 nm when excited at 532 nm). A multi-notch holographic filter was also used to block the emission from Rayleigh scattering, which is about 104 times greater than the Raman scattering and was not blocked completely by the liquid-crystal filter. The scattered light from 200 laser pulses was collected during acquisition of each image with 8x8 pixels binning. The collection time was 200 ns. Figure 4 shows the temperature distribution in laminar Bunsen flame cone measured by 2D Raman technique with cylindrical laser beam.

#### 4.2. 2D Raman system (collimated laser sheet)

To increase the spatial resolution and reduce an error was used a more powerful laser (Quanta-Ray). To provide a measurement in plane the cylindrical laser beam was transformed into the laser sheet by using collimating optics. Examples of Raman signal intensity distribution in air and the flame is shown in figure 5. Figure 6 demonstrates temperature distribution in a laminar Bunsen flame cone. Black line shows the borders between three temperature fields measured at different heights above the burner.



**Figure 6.** Temperature distribution in laminar Bunsen flame cone measured by 2D Raman technique with collimated laser sheet.

## 5. Conclusion

Comparison of 1D Raman temperature measurements with results of thermocouple (type R) measurements shows acceptable accuracy of the optical system for temperatures below 1800 K. The characteristic temperature of the propane flame, as can be seen from Figure 3, is about 2100 K. For temperatures above 1800 K the accuracy of the temperature measurements was reduced by, a limited dynamic range of the ICCD sensor. In case of 2D Raman system more sensitive 16-bit ICCD camera (Princeton instruments PI-MAX-4) was used to provide precision temperature measurements. Figure 5 shows that the results of temperature measurements slightly higher than expected, which is associated with low signal intensity. This work demonstrates the possibility of measuring the spatial temperature distribution in the reacting flow by method based on Raman scattering. The increase in signal-to-noise ratio for further studies by using more precisely selected conditions of the experiment will reduce the error in determining the temperature.

## Acknowledgments

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**References**

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