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Gas-phase temperature imaging in spray systems using multi-line NO-LIF thermometry

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ABSTRACT Two-dimensional gas-phase temperature fields were measured in spray flames and evaporating spray systems using laser-induced fluorescence (LIF) of nitric oxide (NO). The recently developed multi-line technique yields absolute temperature without calibration. It is successfully applied to temperature measurements in the presence of droplets. The method is based on the temperature dependence of the NO-LIF signal. Measurements have been carried out in heated nitrogen flows at room temperature to validate the accuracy ($< \pm 1\%$) and precision (1%) of the technique by comparing results to thermocouple readings. Temperature measurements in a dilute evaporating acetone spray at room temperature showed cooling of the entrained air of 15 ± 6 K. Temperature imaging in an ethanol spray flame at various conditions yields the entire temperature range from the coflow temperature at 300 ± 4 K (1%) to the flame temperature at 1900 ± 40 K (2%).

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1 Introduction

Temperature is a crucial parameter for understanding and modeling spray combustion. In this paper we present measurements of two-dimensional gas-temperature fields in non-reactive and reactive spray systems using multi-line thermometry based on laser-induced fluorescence (LIF) of nitric oxide (NO). This method has been previously demonstrated in stationary stoichiometric and sooting atmospheric-pressure flames [1] as well as in high-pressure flames up to 40 bar [2, 3].

Laser-based imaging techniques have the capability to provide multi-dimensional temperature information without perturbing the investigated system. Temperature information can be gained from various techniques as described in [1]. Two-dimensional fields can be obtained by LIF techniques as well as Rayleigh [4] and filtered Rayleigh thermometry [5]. Vibrational and rotational Raman techniques [6] are often limited to line measurements and coherent anti-Stokes Raman spectroscopy (CARS) [7] only yields point measurements. Infrared absorption techniques [8, 9] yield line-integrated information.

2 Multi-line NO-LIF thermometry

LIF thermometry is based on temperature-dependent changes of the populations of rotational and vibrational energy levels of a molecule. In contrast to two-color LIF thermometry [10, 11], the multi-line technique yields absolute temperatures without calibration [12]. The laser is tuned over a part of the absorption spectrum of the respective molecule while individual images are taken with an intensified CCD camera for each excitation wavelength. From the resulting stack of images (each with the laser tuned to the next wavelength) LIF excitation spectra can be extracted for every single pixel. Simulated spectra are then fitted to the experimental data with absolute temperature, broadband background, and signal intensity as free parameters. Therefore, the technique can be applied even in systems with strong scattering and fluorescence background and is independent of local variations in laser intensity [13]. Because the complete shape of the spectra (including several absorption features and line broadening) is included in the data evaluation, the technique is more precise than two-color thermometry. NO is present in flames and can be seeded (100–1000 ppm) to the fresh gases to provide information from both the burned and the unburned regions. This is a clear advantage compared to OH-LIF thermometry that is restricted to the area of natural occurrence of this intermediate species. NO-LIF excitation spectra are simulated using the software LIFSim [14].

For a high temperature precision the shape of the observed spectra should exhibit a strong temperature dependence. This is achieved by selecting a part of the excitation spectrum where neighboring peaks assess transitions with a large variation in ground-state energies. We determined the optimum scan regions for room-temperature and flame-temperature ranges by a numerical analysis based on LIFSim [14] with a method described in [1]. Within the spectral scan range accessible with our laser system (Raman-shifted KrF excimer laser) the best range for spectra acquisition was found to be 44 412–44 422 cm^{-1} (225.18–225.11 nm) at

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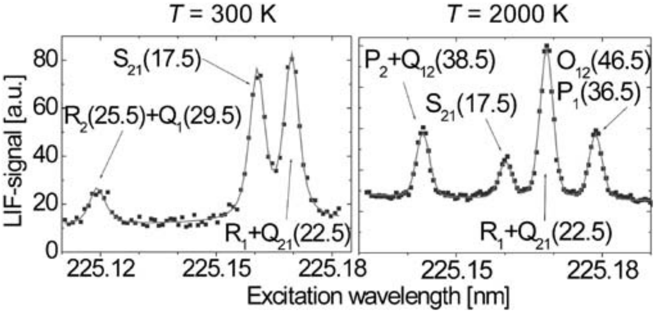

FIGURE 1 Optimum scan range for 300 K (44 412–44 422 cm^{-1}; 225.18–225.11 nm; *left*) and 2000 K (44 407–44 417 cm^{-1}; 225.19–225.13 nm; *right*). *Symbols* are experimental data and *lines* show the fitted spectra. The *labels* show the respective rotational transitions in the NO A-X (0,0) band

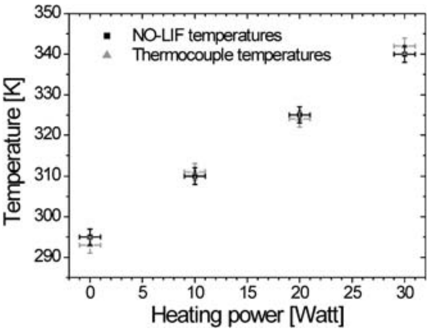

FIGURE 2 Validation of the accuracy of the multi-line NO-LIF thermometry technique by comparison to conventional thermocouple measurements at different heating powers for a heated nitrogen flow

300 K and 44 407–44 417 cm^{-1} (225.19–225.13 nm) at 2000 K. Respective NO-LIF excitation spectra are shown in Fig. 1. Both ranges are coincidentally almost identical, which results in optimum temperature sensitivity in the entire range from 300 K to 2000 K at least. Within these 10 cm^{-1} scan ranges we find transitions originating from ground state rotational quantum numbers $J'' = 17.5$ to $J'' = 46.5$ in the NO A-X (0,0) band.

2.1 *Experimental setup*

A tunable, narrow-band KrF excimer laser (248 nm, $\Delta\nu \sim 0.5\,\mathrm{cm}^{-1}$, Lambda Physik EMG 150 TMSC) is frequency shifted to 225 nm in a Raman cell filled with 8 bar hydrogen [15], enabling NO excitation in the A-X (0,0) band. The laser beam is expanded in the vertical direction and focused with a cylindrical $f = 1000$ mm lens to a light sheet of approximately $40 \times 0.5\,\mathrm{mm}^2$. The LIF signal is recorded with an intensified CCD camera (LaVision). Elastically scattered light is suppressed by Schott UG5 filters and an additional reflection band-pass filter (transmission 230–255 nm, Laser Optik). The general setup, as well as the data-evaluation procedure, is identical to the one shown in [1].

3 Results and discussion

3.1 *Non-reactive heated flows*

A heated nitrogen flow was seeded with 1000-ppm NO and was enclosed by a quartz cylinder. The flow was heated by a heating wire operated at 0, 10, 20, and 30 ± 1 W thermal power, yielding temperatures of up to 350 K. Gas-phase temperatures were measured with the multi-line NO-LIF technique. Excitation spectra were taken at 44 412–44 422 cm^{-1}. Temperature fields of the nitrogen flow show a precision of ± 2 K. We use the term ‘precision’ in this paper as the root mean square (RMS) of neighboring pixels in homogeneous areas. Repeated scans were performed to ensure reproducibility. Averaged temperatures for a homogeneous 3×3 mm region containing 49 pixels in the middle of the images are compared to thermocouple readings in Fig. 2. Both methods yield similar temperatures with a deviation of only $\pm 2\,\mathrm{K} (< \pm 1\%)$.

The multi-line NO-LIF thermometry was further used to measure evaporative cooling in a dilute acetone spray at room temperature with the same setup. The investigated cone-shaped spray was created by a droplet generator (Pallas) used in the spray mode with a liquid flow rate of 7 ml/min. NO-seeding and heating conditions were identical with the heated nitrogen flow described above. The experiments were performed in nitrogen to prevent ignition. Absorption of laser light by acetone was negligible, which was proved by NO-LIF raw images that showed the same LIF intensity on both sides of the spray. Acetone fluorescence was rejected by the band-pass filter mentioned in Sect. 2.1. Temperature fields of the spray show a precision of ± 6 K and were compared to measurements without liquid phase. Temperatures in the spray were 15 ± 6 K lower than for the pure nitrogen flow at identical heating power due to evaporative cooling.

3.2 *Ethanol spray flame*

Gas-temperature fields were measured in a 11-kW ethanol spray burner (Fig. 3). The nozzle (Delavan no. 67700-5) produces a hollow-cone spray with a spray angle of 45°. It is surrounded by a homogenous air coflow seeded with 1000-ppm NO. A stable flame was obtained by pre-heating the

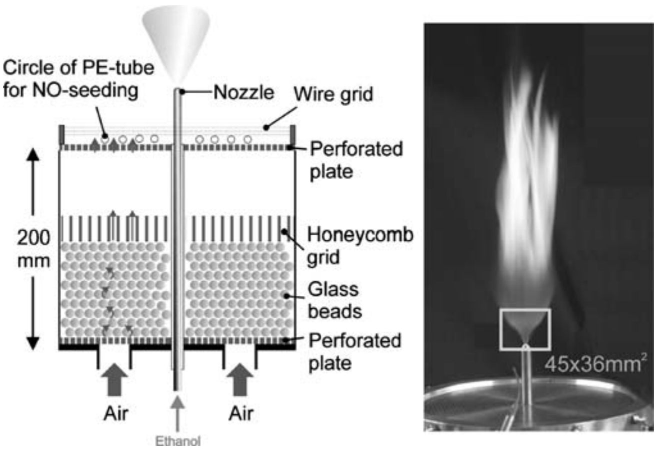

FIGURE 3 Schematic of the spray burner with nozzle and coflow generation

ethanol to 45 °C at the nozzle exit. The resulting flame has two flame zones. The inner flame is located directly above the nozzle exit while the outer flame position depends on the fuel pressure and the coflow speed. It is located 15–20 mm above the nozzle and is further away for higher injection pressures. Figure 4 shows a flame photograph as well as the temperature distribution in a $45 \times 36\,\text{mm}^2$ area of the flame above the nozzle. The nozzle exit is visible in the middle of the lower part of the frame. The post-processing routine simultaneously yields images of the scattering background (which is the baseline strength of each spectra) and the relative NO-LIF signal strength (which is the intensity of the spectra for each pixel). The spatial resolution is $0.45 \times 0.45\,\text{mm}^2$.

Measurements for fuel pressures of 1.4, 2.0, and 2.4 bar injection pressure with liquid flow rates of 30, 35, and 40 ml/min and air coflow velocities of 0.32 and 0.64 m/s were performed. The resulting temperature fields and horizontal temperature profiles at 10, 20, and 30 mm height above the nozzle exit are presented in Fig. 5. Temperatures in the coflow are 300 ± 4 K (1%).

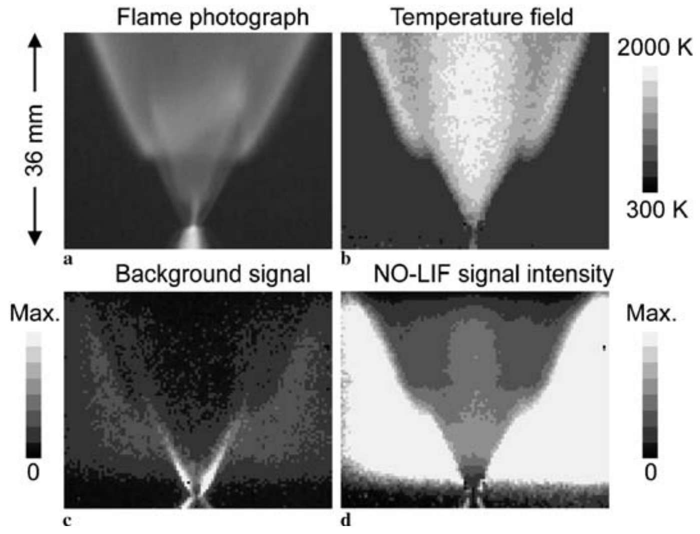

FIGURE 4 (**a**) Flame photograph. The post-processing routine calculates (**b**) temperature distribution, (**c**) scattering background in the ethanol spray flame that indicates the position of the spray close to the nozzle exit, and (**d**) NO-LIF signal strength

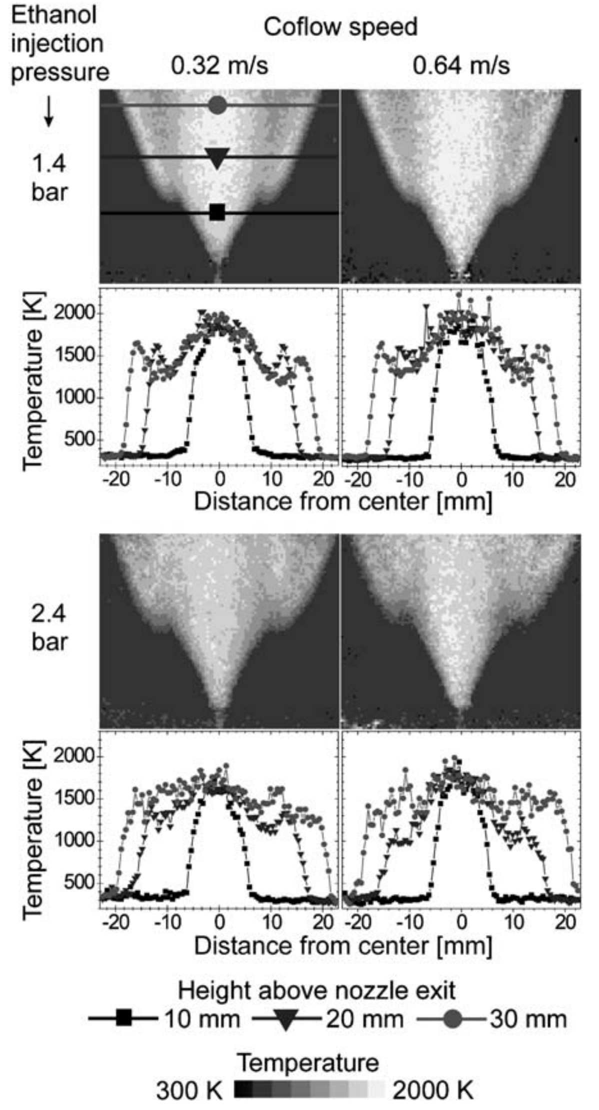

FIGURE 5 Images show the temperature distribution (45 × 36 mm) of the ethanol spray flame at different fuel injection pressures (*upper*/*lower*) and air coflow speeds (*left*/*right*). The *graphs* show horizontal temperature profiles at 10, 20, and 30 mm above the nozzle exit

In the following discussion, we compare temperature values at 20 mm above the nozzle exit in a homogeneous 2 × 2 mm rectangle in the center of the inner flame for the different conditions. For the 1.4 bar, 0.32 m/s case, we find 1900 ± 40 K (2%) in the inner flame. Excitation spectra were acquired using a total of 5000 laser shots (cf. Sect. 3.3). The maximum temperature does not change when doubling the coflow velocity to 0.64 m/s. One realizes, however, that the outer flame zone is compressed and ignites further downstream. When increasing the ethanol injection pressure to 2.0 bar, the droplet velocity increases and the ignition of the outer flame zone takes place a few millimeters further downstream. Temperature at 20-mm height above the nozzle in the inner flame is now decreased to 1775 ± 75 K (4%). Here, we used 500 laser shots only for spectra acquisition, resulting in reduced precision. At 2.4 bar injection pressure the outer flame is shifted even more downstream. The temperature at 20 mm for the 2.4 bar, 0.32 m/s case is 1645 ± 65 K (4%). When doubling the coflow velocity we find an increase in temperature to 1740 ± 85 K (5%). In summary, we find that temperatures at 20-mm height above the nozzle in the inner flame decrease some 100 K when increasing the injection pressure. The inner flame is only slightly affected by a variation in coflow velocity. The outer flame ignites further downstream when increasing both injection pressure and coflow velocity.

3.3 *Temperature precision and accuracy*

The precision of the temperature measurements using the multi-line NO-LIF method depends on the signal-to-noise ratio of the experimental excitation spectra. Using a total of 500 laser shots (50 LIF images between 44 407 and 44 417 cm^{-1} with a spectral resolution of 0.2 cm^{-1}, each averaged over 10 single shots) one achieves a temperature precision of 4% at flame temperatures. With a total of 5000 laser shots (50 images each averaged over 100 laser shots) the temperature precision is 2% in the flame under same conditions. The spectra-acquisition system (laser and camera) was optimized to a repetition rate of 25 Hz. It takes one and five minutes for 500 and 5000 shots, respectively. During that time conditions in the system must be held constant. The accuracy of the multi-line NO-LIF technique was proven by comparisons with thermocouple readings at low temperatures. For a flame temperature of 2000 K, CARS was used in [1] to validate the temperature results in stabilized Bunsen flames.

4 Conclusions

Multi-line NO-LIF thermometry is a non-intrusive, laser-based technique that yields absolute temperatures without calibration. The method can be applied to systems with strong scattering and fluorescence background because temperature information is gained from the entire shape of the excitation spectra. The optimum scan ranges for the excitation spectra are determined by a numerical analysis using the LIFSim program. The spectra-acquisition time is in the range of a few minutes with our laser system. Therefore, only laminar or repetitive systems can be characterized by this method. Temperatures in a heated nitrogen flow were measured with an accuracy and a precision of $< \pm 1\%$ compared to thermocouple readings. The cooling effect of a dilute acetone spray added to the heated nitrogen flow was quantified to 15 ± 6 K. In an ethanol spray flame, maximum temperatures were determined to be 1900 ± 40 K (2%). Temperatures in the air coflow were 300 ± 4 K (1%). This shows the broad applicability of this technique as a characterization tool for various combustion systems.

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