Novel strategies for imaging temperature distribution using Toluene LIF

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Abstract. The distinct temperature dependence of toluene fluorescence has enabled the application of toluene laser-induced fluorescence (LIF) for quantitative imaging of temperature. Two novel thermometry techniques based on toluene LIF are introduced and demonstrated: a single-color detection method, which can be applied for temperature measurements in homogeneously seeded flows and a two-color detection technique (i.e. the simultaneous detection of two different wavelength regions of the fluorescence spectrum) that can be applied in inhomogeneously seeded systems.

1. Introduction
Advanced understanding of the temperature and excitation-wavelength dependencies of toluene LIF [1,2] has supported the development of quantitative temperature diagnostics. Two different strategies will be presented in this paper. A single-color-detection technique provides temperature images in homogeneously seeded flows (e.g. a seeded gas flow over a heated surface when investigating heat transfer phenomena in non-reacting non-mixing flows). This approach requires a one-laser one-camera setup. In the case of inhomogeneous tracer distribution (e.g. mixing studies) the toluene-LIF signal depends on both temperature and local tracer number density. Here, one can take advantage of the red shift of the emission spectrum with increasing temperature. A two-color-detection technique will then provide temperature information. In this case, the ratio of two different wavelength regions after single-laser excitation is calculated. Thus, the local tracer concentration cancels and the signal ratio depends solely on temperature. This detection strategy requires two cameras but only a single laser in contrast to temperature measurements using a two-color excitation of acetone or 3-pentanone [3,4] where two laser sources are needed. Results are discussed for nitrogen and air as bath gas.

2. Experimental
For the demonstration of the temperature sensitivity of our techniques we choose a heated turbulent free jet with an unheated slow coflow. The setup is depicted in figure 1. The jet was electrically heated in a Sylvania heater (model 014683) and injected into quiescent gases through a conical nozzle with a 1.7 mm orifice. The flow exit velocity was about 30 m/s. Toluene was seeded to the gas flow (air or nitrogen) through a Bronkhorst CEM (controlled evaporation and mixing). The toluene concentration (0.5-2%) was controlled by a Bronkhorst liquid flow controller. The coflow was seeded with toluene by percolating air or nitrogen through a bubbling system in order to obtain fluorescence signal.
throughout the entire observed area. Exit velocity of the coflow was about 0.9 m/s and can thus be regarded quiescent in comparison to the exit velocity of the jet. Flow and seeding rates could by varied in order to obtain either homogeneous (i.e. the same toluene concentration in the jet as in the coflow) or inhomogeneous seeding (i.e. different concentrations of toluene in jet and coflow). Varying the applied heating voltage allowed to investigate different exit temperatures of the flow. With the heated jet and the room-temperature coflow mixing, an inhomogeneous temperature field was provided. Laser light from a Lambda Physik EMG 150 KrF* excimer laser (248 nm) was formed to a light sheet. Each sheet consists about 95 mJ/cm² laser energy density. Signal detection was realized by two intensified CCD cameras (FS2, LaVision) with $f = 105$ mm, $f_\# = 4.5$ lenses (Nikkor UV). The data were processed with the DAVIS software from LaVision. Appropriate filters (Schott, WG 280 as well as WG 320) in front of the camera enabled the two-color detection.

Figure 1. Experimental setup of the two-camera experiment.

3. Results
3.1 Single-color detection
The toluene-LIF signal $S_{fl}$ at each point $(x,y)$ is proportional to the product of the number density $n_{vis}$, the absorption cross-section $\sigma_{abs}$, and the fluorescence quantum yield $\phi_{fl}$ of the fluorescing species:

$$S_{fl}(T, x, y) \sim n_{vis}(T, x, y)\sigma_{abs}(T)\phi_{fl}(T)$$

where $T$ may be a function of the spatial coordinates $(x,y)$. In homogeneously seeded, constant pressure systems, $n_{vis}$ depends on $1/T$ only. The LIF signal is then a function of temperature only, with $\sigma_{abs}(T)$ and $\phi(T)$ known from cell-measurements [1,2]. One region or condition of known temperature is then sufficient for calibration in order to obtain absolute temperatures. Calibration curves for 1-bar air and nitrogen flows are shown in figure 2. The fits (equations 2 and 3) allow the fluorescence image to be converted to temperature. The resulting images give absolute temperature.
Figure 2. Calibration curves for the determination of temperature from the toluene-LIF signal in a homogeneously seeded nitrogen gas (left) or air (right) flow.

Nitrogen:

\[ T = -57.895 \ln S_\beta + 289.08 \quad T \text{ in K} \]  

Air:

\[ T = -21.944 x^2 + 194.94 x + 298.96 \quad \text{with} \quad x = \ln(1/S_\beta(248 \text{ nm})) \quad \text{and} \quad T \text{ in K} \]  

In comparison to the signal in nitrogen, temperature sensitivity is significantly reduced in air. Total signal decreases only by one order of magnitude in 300-750 K temperature range, while in nitrogen it is more than three orders of magnitude. The reason for this is that oxygen quenching reduces the influence of temperature. In general, when oxygen quenching is the dominant de-excitation process, temperature effects on the fluorescence quantum yield can be neglected. Exemplary results for measurements in air for high voltages (e.g. exit flow temperatures) are shown in figure 3. The figure shows a 7 x 18 mm\(^2\) area of the jet above the nozzle. The highest temperatures are directly above the nozzle. Stream upwards, the jet mixes and cools down. Compared to the left image (0 V, no heating) the coflow heats noticeably up. At 0 V a homogeneous image is obtained.

Figure 3. Single shot single-color temperature imaging for various voltages (i.e. exit flow temperatures, cf. figure 7).
3.2 Two-color detection

In the case of inhomogeneously seeded systems, one can take advantage of the temperature-dependent red-shift of the fluorescence spectrum to measure temperature (figure 4). The idea is to measure fluorescence simultaneously in two different wavelength regions with two cameras and appropriate filters after excitation at a single wavelength. Evaluating the ratio of the signals, number density and laser intensity will cancel at each point and the result depends solely on the local temperature $T(x,y)$:

$$\frac{S^1_{\text{blue}}(x,y,T)}{S^2_{\text{red}}(x,y,T)} = \frac{\eta^1 E_{\text{laser}}(x,y)n_{\text{red}}(x,y)\sigma_{\text{abs}}(T(x,y))\phi^1_{\text{blue}}(T(x,y))}{\eta^2 E_{\text{laser}}(x,y)n_{\text{red}}(x,y)\sigma_{\text{abs}}(T(x,y))\phi^2_{\text{red}}(T(x,y))} = \frac{\phi^1_{\text{blue}}(T(x,y))}{\phi^2_{\text{red}}(T(x,y))} = f(T(x,y)) \quad (4)$$

where $\eta$ denotes the detection efficiency. The temperature-sensitivity depends on the chosen combination of filters and on the bath gas.

Figure 4. Red shift of the emissions spectrum with increasing temperature.

Figure 5. Plots of the fluorescence signal ratio as a function of temperature for various filter combinations in nitrogen (left) or in air (right).

Figure 5 shows the signal ratio of different parts of the emission spectrum calculated from the cell measurements [1] for different combination of filters. The WG 280, 305, 320 and 335 filters are common, relatively cheap, commercially available (Schott), long-pass absorption filter. BP 280 denotes an interference band-pass for the detection of the peak fluorescence of 280 ± 5 nm. This filter
can be custom made but was not available at the time of this experiment. For this experiment we chose to employ a WG 280 with the transmitted signal dominated by the peak fluorescence ("blue" detection) in combination with another long-pass filter. The longer the wavelength region transmitted by this second filter, the better the temperature sensitivity of the signal ratio. However, signal intensity is decreasing at the same time. For this reason we decided to use a WG 320 as the other filter ("red" detection).

A fit of the data for the filter combination used in this experiment (WG 320 and WG 280) in nitrogen yields:

\[
\frac{S_{T}^{\text{WG320}}}{S_{T}^{\text{WG280}}} = 8 \times 10^{-6} T^2 - 0.0013 T + 0.6677, \quad T \text{ in K} \tag{5}
\]

Exemplary results of the demonstration experiment in nitrogen for an inhomogeneously seeded flow are shown in figure 6. The top row displays instantaneous images of temperature and the bottom row displays average images of 50 single shots. The average temperature images show a spreading angle. At 0 V a homogeneous image is obtained. This is a sign for successful mapping of the LIF-images.

| Temperature fields (inhomogeneously seeded system, toluene/N\textsubscript{2}) |
|-----------------|----------------|----------------|----------------|----------------|----------------|
|                 | 0 V           | 10 V           | 15 V           | 20 V           | 25 V           | 30 V           |
| Single shot     | Single shot   | Single shot   | Single shot   | Single shot   | Single shot   | Single shot   |
| Average         | Average       | Average       | Average       | Average       | Average       | Average       |

**Figure 6.** Two-color temperature imaging in an inhomogeneously seeded flow. Top row: single shot, bottom row: average. Exit temperature increases from left to right.

The two-color technique can be applied also in air. However, temperature sensitivity will be reduced compared the case of a nitrogen flow. Figure 5 displays the temperature sensitivity for the same filters in nitrogen as well as in air. In general, for applications in a rough environment as in an engine, a good band-pass for the detection of the peak fluorescence will be needed in order to achieve a distinct temperature-dependence of the signal ratio. The temperature sensitivity is then similar to the two-line ketone thermometry.
Figure 7. Single shot images of a homogeneously seeded flow, analyzed with a single-color technique (top row), and also with a two-color technique (bottom row). Exit temperature increases from left to right.

For a comparison of one-color and two-color technique, we evaluated the homogeneously seeded flows with both techniques. Thus, a comparison on a single-shot basis is possible.

Directly above the nozzle, where the temperature field is relatively homogeneous, temperatures have been measured with a thermocouple and compared to the results from figure 3, 6 and 7 at the same position (figure 8). Results are in satisfactory agreement.

Figure 8. Comparison of the presented techniques with the experimental data of a thermocouple, measured directly above the nozzle.

4. Conclusions
New temperature imaging strategies based on toluene-LIF have been demonstrated for both homogeneously and inhomogeneously seeded flows. The single-color detection technique yields high-
resolution temperature fields, especially in nitrogen flows, but is restricted to systems with a homogeneous tracer distribution. The two-color detection technique has a reduced temperature resolution in comparison but can be applied to flow systems with inhomogeneous tracer concentration.

References

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