Temperature measurements of evaporating micro-droplets

J. Palmer, R. Kneer, Institute of Heat and Mass Transfer, RWTH Aachen University, Germany (May 2015)

Application Note

Introduction

Biofuels are one possible solution to face diminishing fossil fuels and global warming. Their utilization in engines, however, has a strong influence on the engine's performance and combustion efficiency. Physical fuel properties change the spray breakup, mixture formation and combustion process entirely. The evaporation behaviour of biofuels plays an important role in the mixture formation process. Until today, not all mechanisms of evaporation are totally understood. Due to the many degrees of freedom of an engine, fuel evaporation needs to be investigated apart the engine. Single fuel droplets (D < 100 µm) can be studied under engine-like conditions that are generated by constant-pressure flow vessels. Evaporation is quantified by means of time dependent droplet size, droplet velocity and the droplet's surface temperature. While size and velocity are measured using conventional imaging techniques, temperature measurements are more difficult to perform. One way to measure micro-droplet temperature is 2-color-Laser-Induced-Fluorescence (2c-LIF) [1].

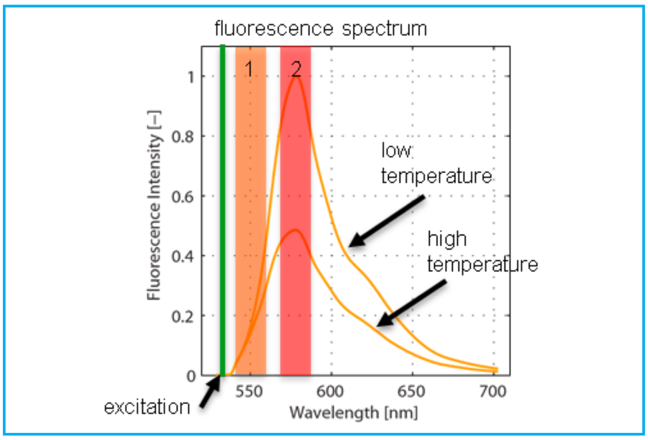

Figure 1: Fluorescence spectra of a dye for different temperatures. The diagram includes two wavelength bands for the 2c-LIF measurement technique.

The 2c-LIF technique requires a temperature sensitive fluorophore that is dissolved in the biofuel of interest and excited with a laser. The complexity of the fluorescence process requires a radiometric measurement procedure that cancels out unknown or fluctuating influences, e.g. fluorophore concentration or laser energy. Therefore, fluorescence needs to be measured in two wavelength bands (I_1, I_2), the first being insensitive to temperature the second being sensitive to temperature (fig. 1).

Thus, the resulting problem is only depending on temperature (T) and two calibration constants (K, β):

$$\frac{I_1}{I_2} = \frac{I_0 \cdot C \cdot K_{opt,1} \cdot K_{spec,1} \cdot V_c \cdot e^{\frac{\beta_1}{T}}}{I_0 \cdot C \cdot K_{opt,2} \cdot K_{spec,2} \cdot V_c \cdot e^{\frac{\beta_2}{T}}} = \frac{K_{opt,1} \cdot K_{spec,1} \cdot e^{\frac{\beta_1}{T}}}{K_{opt,2} \cdot K_{spec,2} \cdot e^{\frac{\beta_2}{T}}} = K \cdot e^{\beta/T}$$

EMCCDs can be used for the detection of even weakest fluorescence intensities. In addition, fluorescence imaging with cameras allows to measure droplet size simultaneously.

Experimental setup

Figure 2 shows an experimental setup that is used for the calibration of the 2c-LIF technique on a droplet chain. The light source of the experimental setup is a pulsed laser emitting light at 532 nm with energies in the magnitude of 10 µJ. The laser power must be kept small to avoid morphology depended resonances within the droplet [3], but needs to be high enough for sufficient fluorescence intensity. The laser beam is formed into a light sheet that is used for fluorescence activation. Micro-droplets of the biofuel are produced by a droplet generator and contain the fluorescent dye. The droplet generator contains a heating cartridge that provides defined droplet temperature for the calibration.

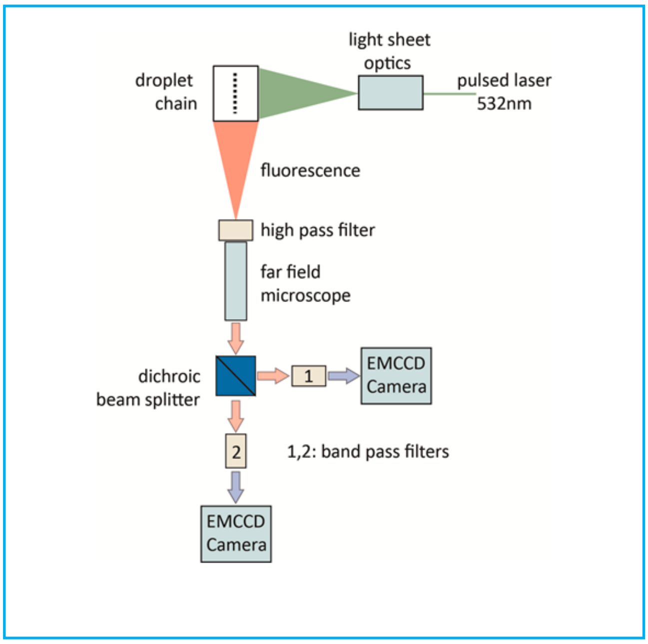

Figure 2: Experimental setup of the 2c-LIF temperature measurement technique [2].

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Fluorescence of the droplet is detected via a long-distance microscope by EMCCDs. A high pass filter suppresses Mie-scattering light of the laser and a dichroic beam splitter separates the light by wavelength to two Andor iXon3 EMCCD cameras (DU888 DC-UVB and DU888 EC-UVB). Additional band pass filters in front of each camera select the desired wavelength band of the fluorescence spectrum.

Results

Images of the droplets are taken for several different temperatures, fig. 3 (left). In a first step, images of both cameras need to be matched pixel by pixel and are then divided pixel-wise. The new images already contain information about the droplet temperature. Figure 3 (right) shows the calibration curve that can be deduced from the image-ratio. The curve shows the average measured fluorescence ration within the droplets for a series of different droplet temperatures.

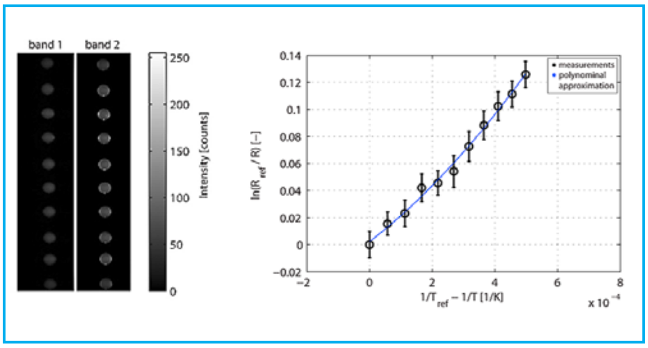

Figure 3: Fluorescence images (left) and the 2c-LIF calibration curve for different droplet temperatures (right).

Measurement results can be improved by a study of the two EMCCDs. A sensitivity analysis of the camera response shows the influence of the electron multiplication gain. Figure 4 displays the relative standard deviation of a fluorescence signal as a function of the mean fluorescence intensity for different electron multiplication gains. Different mean fluorescence intensities are achieved by variation of the laser power. The diagram helps to choose the necessary gain level of a sufficiently low measurement error.

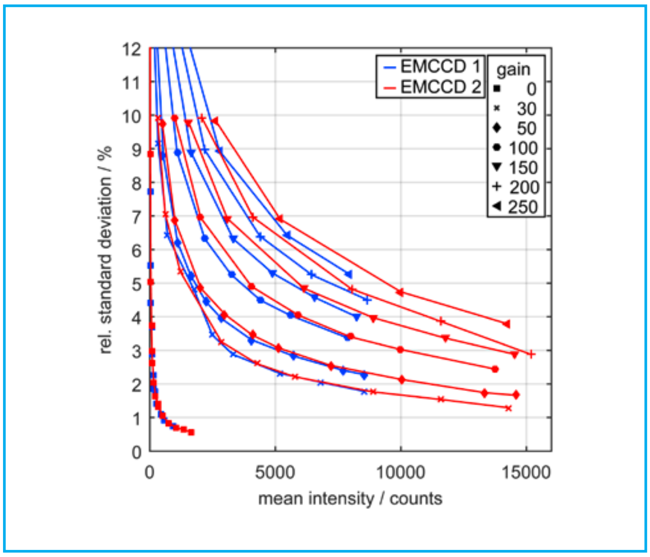

Figure 4: EMCCD response for different electron multiplication gains and laser powers. Measurements are performed in a cuvette filled a fuel/tracer mixture.

References

[1] Lemoine, F., Antoine, Y., Wolff, M., Lebouche, M., Simultaneous temperature and 2D velocity measurements in a turbulent heated jet using combined laser-induced fluorescence and LDA, Experiments in Fluids 26, pp. 315-323, 1999.

[2] Palmer, J., Mathieu, F., Kneer, R. Temperature measurements of evaporating biofuel droplets, ILASS Europe 2014, 26th Annual Conference on Liquid Atomization and Spray Systems, Bremen, Germany, 8-10 Sep. 2014.

[3] Perrin, L., Castanet, C., Lemoine, F., Characterization of the evaporation of interaction droplets using combined optical techniques, 17th International Symposium on Applications of Laser Techniques to Fluid Mechanics, Lisbon, Portugal, 7-10 July, 2014.

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