Simultaneous measurements of droplet temperature and size histograms using combined two colors laser-induced fluorescence and PDA.

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This paper presents the possibility to combine two diagnostics on heated and evaporating droplets, one for completing the mean droplet temperature measurements, the other the droplet size. The two colors laser-induced fluorescence technique, applied to the mean droplet temperature measurement and the PDA have been combined in order to determine a temperature averaged on a droplet size class. The main principles of the technique and the data processing strategy are described. An application on a polydisperse line of heated ethanol droplets is presented.

1. Introduction

The droplet size and temperature are two parameters of considerable interest in heated or evaporating polydisperse sprays, situation commonly encountered in engine fuel spray problems.
The PDA (Particle Dynamics Analyzer) is now routinely used in order to measure droplet size distributions in a spray and commercial instruments are widely available.
The measurement of droplet temperatures in comparable situations is another matter, and only a few techniques are available. The main are :

- the global rainbow refractometry, providing a value of the spray temperature, averaged on the droplets crossing an extended measurement volume [1],
- the exciplex fluorescence technique, which remains limited by the oxygen quenching phenomena [2]
- the recently appeared two-colors laser induced fluorescence [3]

The two-colors laser induced fluorescence will be considered in the present paper. The technique has already shown its ability to provide space averaged temperature of evaporating and combusting droplets [4]. The goal is to combine the PDA and the two colors laser-induced fluorescence measurements in order to get a liquid temperature averaged on a droplet size class. The technique has been applied to the characterization of a polydisperse line of evaporating ethanol droplets.

2. Two colors Laser Induced Fluorescence : principles and applications

2.1. General principles

The main outline of the two colors Laser-Induced Fluorescence technique are detailed in this section. A previous paper presents further technical details [3]. The fuel, ethanol here, is previously seeded with a low concentration (a few mg.l^{-1}) of rhodamine B. Rhodamine B is an organic dye usually used as a fluorescent temperature sensor. Furthermore, the fluorescence of rhodamine B is easily induced by the green line (λ=514,5 nm) of the argon ion laser. The rhodamine B fluorescence spectrum is broadband, and it has been shown that its temperature sensitivity was strongly depending on the wavelength [3]. If beer's absorption phenomena are neglected, the fluorescence emission expression on a given spectral band, as a function of the different physical and optical parameters, is given by ([3], [5]) :

$$I_f = K_{opt} K_{spec} V_c I_0 C e^{\beta/T} \quad (1)$$

where K_{opt} is an optical constant, K_{spec} is a constant depending solely on the spectroscopic properties of the fluorescent tracer in its environment (i.e., the fuel), I_0 the laser excitation intensity, C the molecular tracer concentration, T the absolute temperature, V_c is the fluorescence photons collection volume. The product $C.V_c$ of the collection volume by the tracer molecular concentration is in fact related to the number of fluorescence photons emitted by the rhodamine B molecules excited by the laser radiation and reaching the photodetector surface. This parameter is strongly related to the droplet size and to the probe volume dimensions. The factor β characterizes the temperature dependence of the fluorescence intensity and depends strongly on the fluorescence emission wavelength.

In order to measure properly the temperature of a moving and evaporating droplet, the influence of the parameters $C.V_c$ and I_0 must be removed. In evaporation situations, the dye concentration is likely to vary and the collection volume is constantly changing as the droplet crosses the probe volume. In order to get rid up these problems, the fluorescence intensity is detected on two spectral bands for which the temperature sensitivity is highly different. The fluorescence ratio between the fluorescence intensities collected on both spectral bands is given by :

$$R_f = \frac{I_{f1}}{I_{f2}} = \frac{K_{opt1}}{K_{opt2}} \frac{K_{spec1}}{K_{spec2}} e^{\frac{\beta_1 - \beta_2}{T}} \quad (2)$$

This ratio is totally independent on the dimensions of the intersection between the droplet, the laser excitation volume and the photon collection volume. The influence of the local laser excitation intensity and tracer concentration are also eliminated. The use of a single reference point where the temperature is known allows to eliminate the optical and spectroscopic constants. An initial calibration, performed under static conditions in a heated vessel, allows to determine the parameter (β_1-β_2). The resulting temperature sensitivity is about 2%/ °C.

2. Experimental set-up

2.1. Droplets generation

The polydisperse droplet line is created by a pressurized injector equipped with a 100 µm diameter output hole. The resulting droplet size distribution ranges between 180 µm and 220 µm. The injected liquid is ethanol, seeded with rhodamine B, previously heated at 48°C in the injector body.

2.2. Optical set-up

The same excitation volume and excitation wavelength (λ=514.5 nm issuing from the argon ion laser) are used for both PDA and LIF systems. The PDA (DANTEC), equipped with a classic receiver, has been used in refraction mode with a diffusion angle of 19° (figure 1). The maximum measured particle diameter is then 267 µm with these parameters. The fluorescence signal is collected at right angle by means of an achromatic doublet connected to an optical fiber, acting as a pinhole. The fluorescence signal is transmitted by the optical fiber to a set of beamsplitters and optical filters, which enables to divide the fluorescence signal into the two specified spectral bands, as indicated in the previous paper [3] (figure 2).

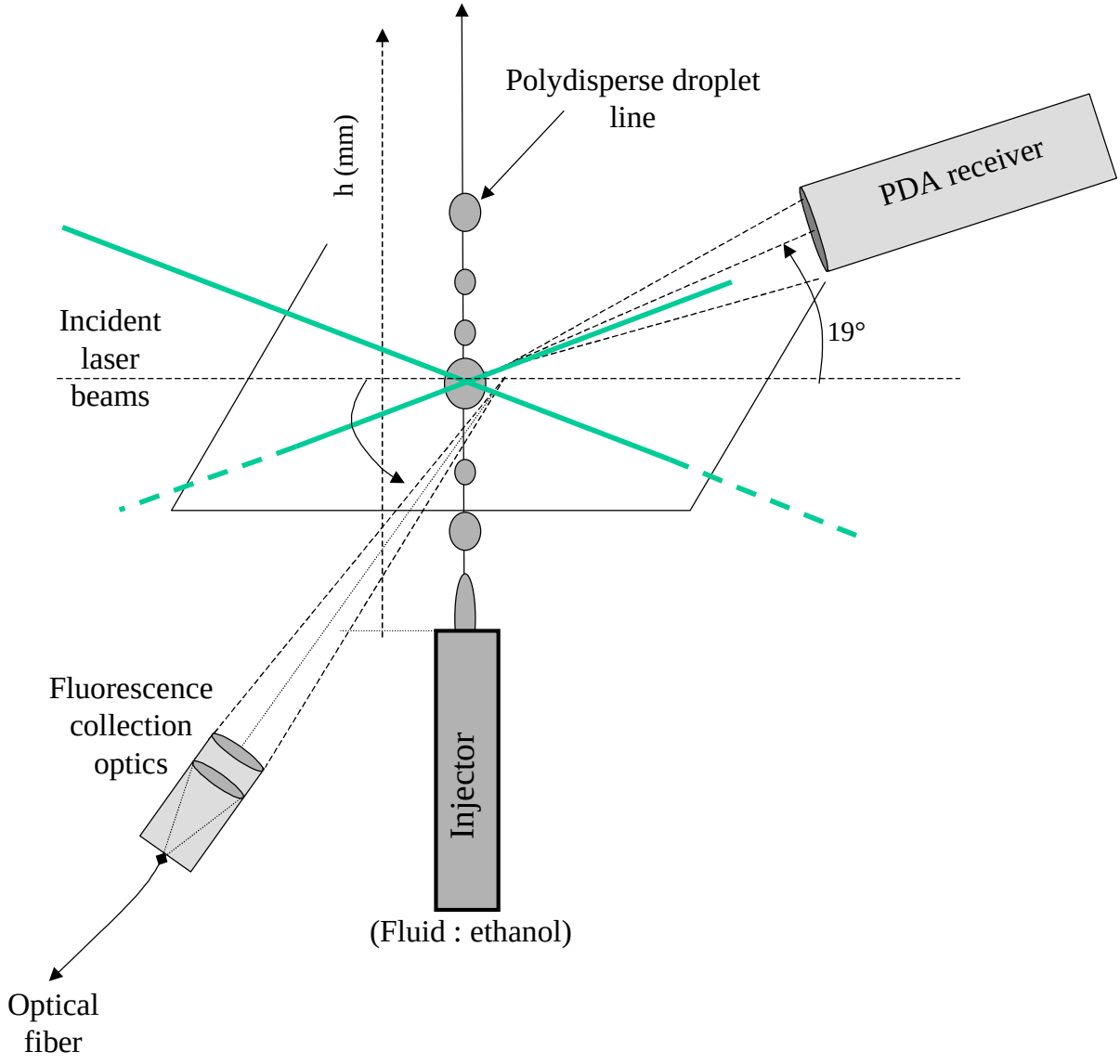

Fig. 1 Experimental set-up for simultaneous droplet temperature and size measurements on a polydisperse droplet line.

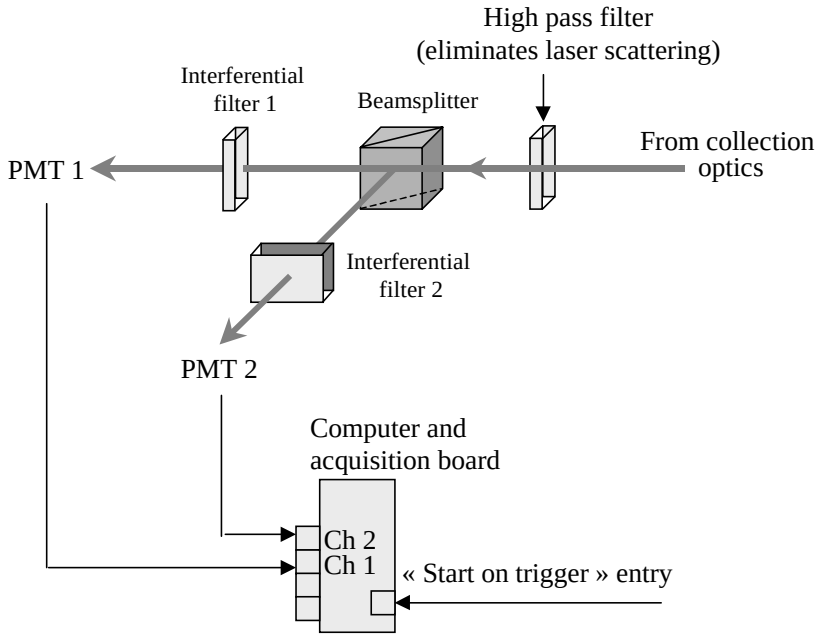

Fig. 2 LIF experimental arrangement

3. Data acquisition and processing

The goal is to combine the data provided by the PDA (size distribution) and the droplet temperatures provided by LIF. The synchronization of the two apparatuses could allow to provide a temperature for the droplets belonging to a given size class only (provided by the PDA measurements). The retained solution is to get two acquisition files, one for the PDA and the other for the fluorescence. A post processing of the two files enables to determine a droplet temperature averaged on a size class.

3.1. Droplet fluorescence processing and temperature determination

An acquisition board enables to sample the fluorescence signal simultaneously on two channels at 5 MHz with a 12 bits resolution for the A/D conversion.
A threshold level is fixed over the natural noise level of the PMT's (thermal noise and ambient light) in order to detect the droplets crossing the probe volume (figure 3). For each acquired sample higher than the threshold level, the fluorescence signal is stored in a buffer and a summation of each samples over the threshold, corresponding to a detected droplet, is realized. For each retained samples on the channel where the threshold is applied, the matching samples are also accumulated in the same way on the second channel.

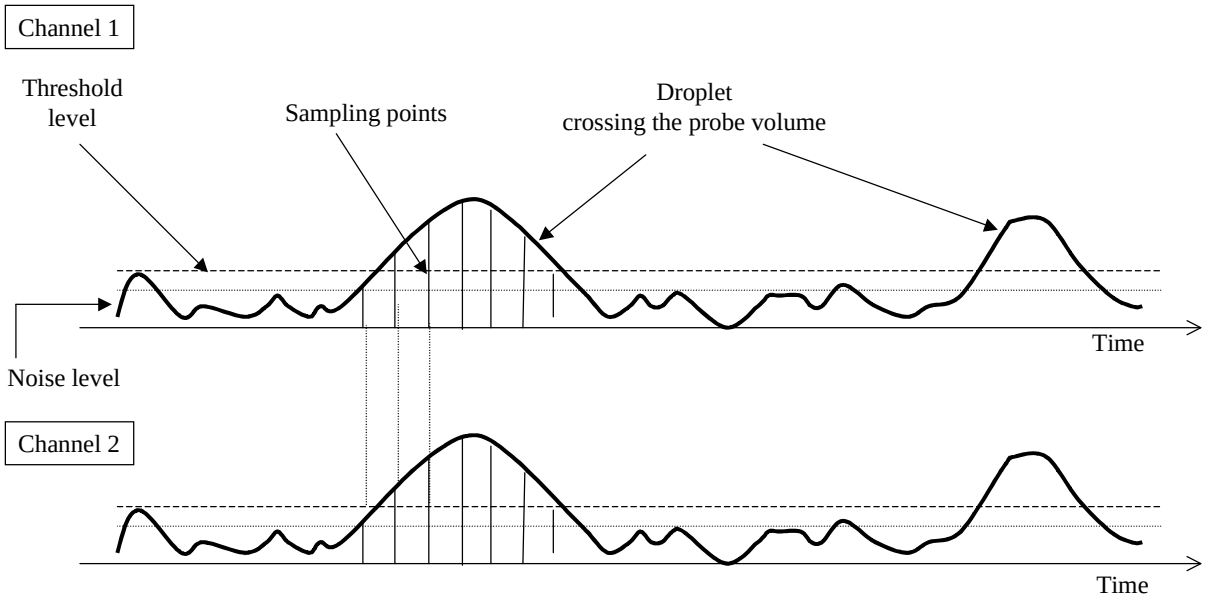

Fig. 3 Principle of droplets detection.

The fluorescence intensity on the two colors bands, integrated on a droplet (index i) crossing the probe volume, can be written as :

$$I_{f1i} = K_{opt1} K_{spec1} C I_0 V_{ci} e^{\frac{\beta_1}{T_i}} \tag{3}$$

$$I_{f2i} = K_{opt2} K_{spec2} C I_0 V_{ci} e^{\frac{\beta_2}{T_i}} \tag{4}$$

The fluorescence ratio is used to calculate the averaged temperature T_{avj} on N_j droplets crossing the probe volume, belonging to the given j^{th} size class :

$$R_{fj} = \frac{\sum_{i=1}^{N_j} I_{f1i}}{\sum_{i=1}^{N_j} I_{f2i}} = \frac{K_{opt1} K_{spec1} C I_0 \sum_{i}^{N_j} V_{c_i} e^{\frac{\beta_1}{T_i}}}{K_{opt2} K_{spec2} C I_0 \sum_{i}^{N_j} V_{c_i} e^{\frac{\beta_2}{T_i}}} \sim \frac{K_{opt1} K_{spec1}}{K_{opt2} K_{spec2}} e^{\frac{\beta_1 - \beta_2}{T_{avj}}} \tag{5}$$

T_{avj} can be interpreted as an average temperature of the liquid volume crossing the probe volume during the acquisition, for the given j^{th} droplet size class (figure 4). A simple temperature reference point, where the temperature is known, allows to remove the system constants, i.e. $\frac{K_{opt1} K_{spec1}}{K_{opt2} K_{spec2}}$, and the fluorescence ratio is used to yield the temperature T_{avj}.

3.2. Combined LIF and PDA measurements

The main problem is to match the droplets detected by the two instruments; two main difficulties have been solved to complete such a coupling :

- both acquisitions are not piloted by the same clock, the PDA being driven by its own processor clock and the fluorescence acquisition board being driven by its own clock. Practically, for an acquisition of a few seconds, the two clocks can present a shift ranging from 5 to 10 µs.
- the detection range is different for the two instruments : it means that some droplets could be rejected (or not detected) by one instrument, and detected by the other.

The main issues to be addressed in order to combine both instruments are :

- to have a common time index for the events detected by the PDA and by the LIF system. The two instruments are started simultaneously by using the “start on trigger” function of the acquisition board for the fluorescence and of the PDA, by sending a common trigger pulse simultaneously on the two apparatuses.
- The two files (PDA and LIF)are analyzed in a post-processing session in order to match the events detected by the two systems.

3.3. PDA and LIF data post-processing

A time function, taking into account the droplet arrival time and transit time in the probe volume is created for the PDA and LIF acquisition files (figure 5).

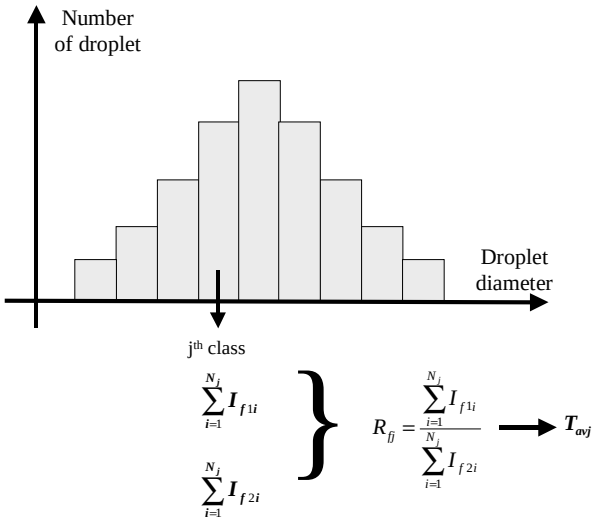

Fig. 4 Principle of fluorescence signal averaging on each droplet size class.

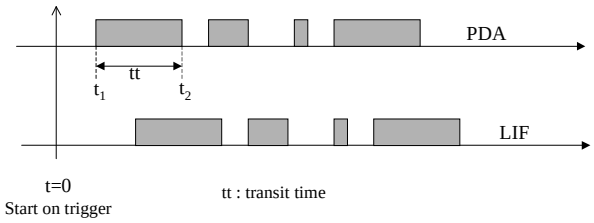

Fig. 5 Principle of simultaneous LIF and PDA data acquisition.

The cross-correlation on the two time functions (PDA and LIF) is calculated in order to yield the shift between the two acquisition files and to determine the droplets commonly detected by the PDA and the LIF system. In the next step, only the commonly detected droplets will be processed. These droplets are sorted by diameter classes, and the fluorescence is averaged on each detection color band as previously described (equations (3) and (4)), on each diameter classes (figure 4).

4. Validation of the process on a polydisperse line of heated ethanol droplets

All the measurements have been performed on an acquisition of 10^5 droplets, resulting in about 50000 common droplets detected by the PDA and LIF systems. Several results are presented in figures 6 to 8. The figure 6 presents the evolution of the mean droplet diameter and velocity as a function of the distance from the injection point : the mean diameter is increased from about 185 µm to 222 µm, due to the occurrence of droplets coalescences. The mean droplet velocity tends to decrease slowly due to the drag force effect.
The droplet size histogram evolution, measured by the PDA, as a function of the distance from the injection point is presented in figure 7. The peak diameter tends to shift to higher diameter region, and the size range seems to depend highly on the distance from injection.

The more interesting point is the comparison between the mean droplet temperature evolution for different droplet size classes : the most separated size classes are [170-180 µm] and [240-250 µm] (figure 8). Initially, the mean droplet temperature corresponding to the two size classes is quite the same, but a differentiated evolution appears quickly, the smallest droplets remaining at a higher temperature than the bigger. The class of highest droplet concentration can also be defined : it corresponds to the class of the peak of the size histogram. According to figure 7, this class is progressively shifted from the smallest droplet diameters to the bigger. In a first time, the mean temperature of the class of highest droplet concentration corresponds to the class of the smallest droplets, and for larger distances from injection, it corresponds to the biggest droplets. Between these two extremes, the mean temperature of the class of highest droplet concentration is located in an intermediate position between the smallest and biggest droplets temperature. This evolution matches well with the drop size population evolution given in figures 6 and 7 (figure 6 for the mean diameter evolution and figure 7 for the size histograms evolution).

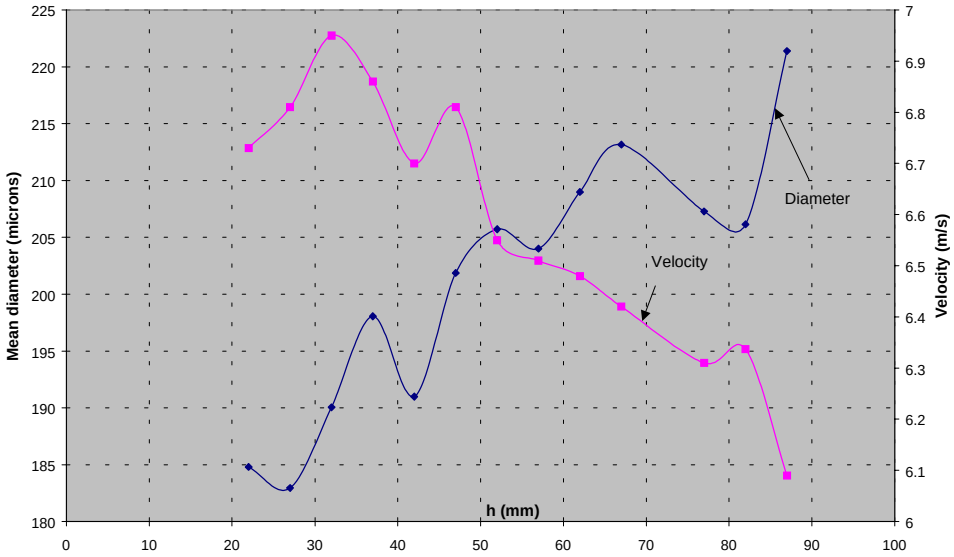

Fig. 6 Evolution of the droplet mean diameter and velocity as a function of the distance from injection.

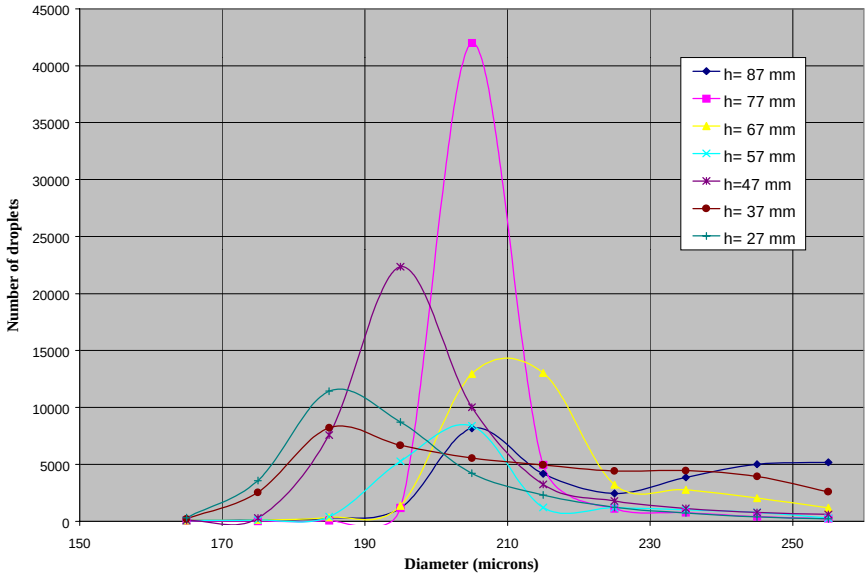

Fig. 7 Evolution of the droplet size histogram as a function of the distance from injection.

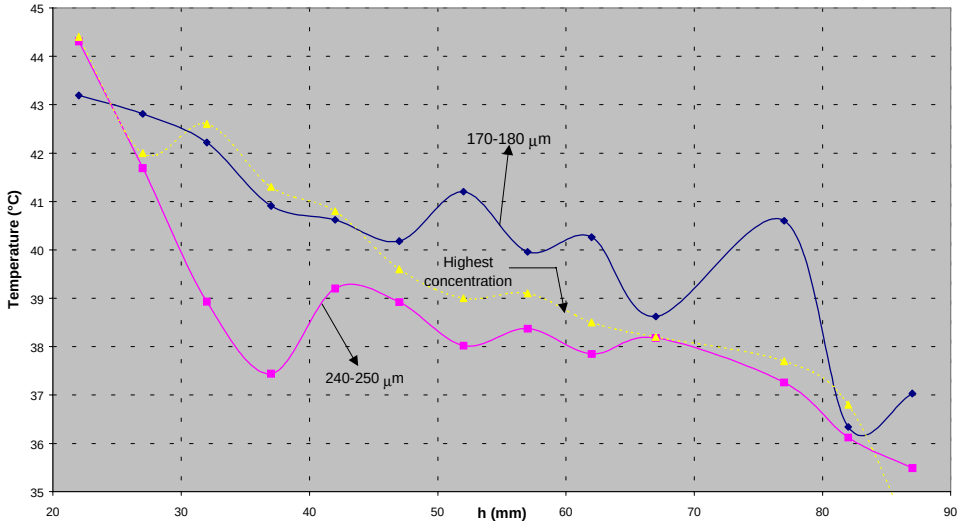

Fig. 8 Comparison of the evolution of the temperature of the two extreme droplet size classes and temperature of the class of highest droplets concentration, as a function of the distance from the injection.

5. Concluding remarks

The two colors laser-induced is a powerful technique which is able to provide mean temperature of flying heated and potentially evaporating droplets. The absolute accuracy of the technique, according to the uncertainties linked to the calibration process and to the linearity of the detection chain, is estimated to 1°C, but the resolution can be estimated at less than 0.3°C.
Combining this technique with the PDA enables to obtain a mean droplet temperature for a given size class. The present study has shown this possibility by using a post-processing of the PDA and LIF data. One improvement of the technique will be to develop two processors operating in parallel, one for the LIF measurements, the other for the PDA, driven by the same clock. The next step will be also to extend the technique to polydisperse sprays.

References

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