

# ***A NEW CONCEPT FOR TEMPERATURE MEASUREMENTS IN POLYDISPERSE SPRAYS: THREE COLORS LASER-INDUCED FLUORESCENCE***

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## **ABSTRACT**

The characterization of the local temperature of the liquid phase of a polydisperse spray is an important problem in many engineering applications. This paper presents a new technique to measure the liquid phase temperature in polydisperse sprays, even under evaporation. This technique is based on the use of laser-induced fluorescence of a tracer (sulfo-rhodamine B) added to the liquid. The influence of the liquid volume, temperature and multi-scattering phenomena are studied. The fluorescence emission is detected simultaneously on three spectral bands in order to eliminate the dependency of the fluorescence emission on the concentration of the tracer, dimensions of the probe volume, laser intensity and optical layout and also to correct for the multi-scattering effects of the fluorescence emission. Applications to a heated water polydisperse spray are presented.

## **1. INTRODUCTION**

The characterization of the local temperature of the liquid phase of a polydisperse spray is an important problem in numerous engineering applications. Optical methods for the measurement of droplet temperatures can roughly be divided into two groups: one group is based on Mie scattering (e.g. global rainbow thermometry [1]) and the other group consists of techniques that use the fluorescent properties of a molecule added to the liquid. The exciplex fluorescence has been widely used, but remains limited in its application field [2]. The two colors Laser-Induced Fluorescence (LIF) technique has been successfully applied to mean temperature measurements of single droplets in linear stream, in both evaporation and combustion regime [2, 4]. This technique allows removing the dependency of the concentration of the added tracer, probe volume dimensions, laser intensity and optical layout. It requires two spectral bands for which the temperature sensitivity is highly different. The ratio of the fluorescence signal measured on two spectral bands depends only on temperature. The present paper is devoted to the extension of this technique to water polydisperse sprays.

## **2. PRINCIPLES OF THREE COLORS LASER-INDUCED FLUORESCENCE**

### Two colors LIF technique

The liquid is seeded with a low concentration (a few mg/l) of sulfo-rhodamine B before being atomized into droplets. Sulfo-rhodamine B is an organic dye usually used as fluorescent temperature sensor. Furthermore, the fluorescence of sulfo-rhodamine B can be easily induced by the green line ( $\lambda=514.5$  nm) of the argon ion laser and is a suitable candidate to be a temperature tracer. The sulfo-rhodamine B fluorescence spectrum is broadband, and it has been shown that its temperature sensitivity depends strongly on the wavelength [3]. The fluorescence intensity at the wavelength  $\lambda$ , as a function of the different physical and optical parameters can be expressed [3, 5]:

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

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 liquid),  $I_0$  the laser excitation intensity,  $C$  the molecular tracer concentration,  $T$  the absolute temperature, and  $V_c$  the fluorescence photons collection volume. The product  $CV_c$  of the collection volume by the tracer molecular concentration is in fact related to the number of fluorescence photons reaching the photodetector surface. This parameter is strongly related to the droplet size and to the probe volume dimensions. The factor  $\beta(\lambda)$  characterizes the temperature dependence of the fluorescence intensity at the wavelength  $\lambda$ .

To collect a sufficient number of photons, the signal is detected on a spectral band  $[\lambda_{i1} ; \lambda_{i2}]$ ,  $i$  denoting the spectral band:

$$I_{fi} = \int_{\lambda_{i1}}^{\lambda_{i2}} K_{opt,i}(\lambda) K_{spec,i}(\lambda) V_c I_0 C e^{\beta_i(\lambda)/T} d\lambda \approx K_{opt,i} K_{spec,i} V_c I_0 C f_i(T), \quad (2)$$

where  $K_{opt,i}$  and  $K_{spec,i}$  are the optical and spectroscopic constants related to the spectral band  $i$ .

$f_i(T)$  is the function that characterizes the temperature dependence of the fluorescence emitted on the spectral band  $i$  and can be written [5] :

$$f_i(T) = e^{\frac{a_i + b_i}{T}} \quad (3)$$

$a_i$  and  $b_i$  are two coefficients that depend on the spectral properties of the fluorescent tracer in its solvent and characterize the temperature sensitivity of the tracer in its solvent.

In order to measure properly the temperature of a moving and potentially evaporating droplet, the influence of the parameters  $CV_c$  and  $I_0$  must be removed. The collection volume  $V_c$  is constantly changing as the droplet crosses the probe volume. Furthermore, the distribution of the laser intensity within the droplet depends on the relative position of the droplet and the laser beam, which is influenced by the refractive and focusing effects of droplet surface. In order to get rid of these problems, the fluorescence intensity is detected on two spectral bands for which the temperature sensitivity is highly different. The selection of these spectral bands is optimized by an initial study of the influence of the temperature on the fluorescence spectrum [3]. The fluorescence ratio between the fluorescence intensities collected from both optimal spectral bands is given by:

$$R_f = \frac{I_{f1}}{I_{f2}} = \frac{K_{opt1} K_{spec1} f_1(T)}{K_{opt2} K_{spec2} f_2(T)} \quad (4)$$

This ratio is totally independent of the dimensions of probe volume. The influence of the local laser intensity and tracer concentration is also completely eliminated. The use of a single reference measurement at a known temperature allows eliminating the optical and spectroscopic constants.

#### Application to polydisperse sprays

The situation is more complex in polydisperse sprays, since multi-scattering phenomena occur. Two kinds of multi-scattering phenomena can be distinguished:

- the elastic multi-scattering of the incident laser light, which changes the local distribution of the laser energy; however this problem is overcome by using the fluorescence ratio between the two spectral bands of detection.
- the scattering of the fluorescence emission itself is more problematic, since the fluorescence emission is scattered according to a large range of wavelengths. This may change the spectral distribution of the fluorescence intensity in the collection solid angle and subsequently the fluorescence ratio, which is used to infer the temperature. This last phenomenon must be properly addressed in order to measure the temperature in sprays correctly.

Assuming that the fluorescence multi-scattering effects on the fluorescence intensity received on the photodetector from a particular point of the spray can be taken into account by adding or subtracting a component proportional to local fluorescence, this process may be applied to the two spectral bands of detection.

According to Eq. (2), the fluorescence received on the photodetectors associated to the spectral bands 1 and 2 may be written:

$$I_{f1} = (1 + \alpha) K_{opt1} K_{spec1} V_c I_0 C f_1(T) \quad (5)$$

$$I_{f2} = (1 + \delta) K_{opt2} K_{spec2} V_c I_0 C f_2(T) \quad (6)$$

where  $\alpha$  and  $\delta$  are the applied correction factors taking into account the fluorescence multi-scattering effects.

When the ratio between Eqs. (5) and (6) is calculated, there are now three unknown parameters:  $\alpha$ ,  $\delta$  and the temperature  $T$ .

The analysis of the temperature sensitivity curve of sulfo-rhodamine B (very similar to that of rhodamine B [3]) dissolved in water, shows that there is a large spectral area where the temperature sensitivity  $\beta(\lambda)$  is almost constant. The spectral bands 1 and 2 must be selected so that the sensitivity difference is as large as possible. If the fluorescence signal is additionally detected on a third spectral band with the same temperature sensitivity as the second band, the intensity detected on the band 3 can be written as :

$$I_{f3} = (1 + \gamma) K_{opt3} K_{spec3} V_c I_0 C f_2(T) \quad (7)$$

where  $\gamma$  is the contribution of the fluorescence multi-scattering effects for the 3<sup>rd</sup> spectral band.

Using a reference measurement at a known temperature  $T_0$  in order to eliminate the system constants, i.e.  $K_{opt}$  and  $K_{spec}$ , the ratios  $R_{12}$  and  $R_{32}$  between the fluorescence intensity collected on bands 1 and 2 or on bands 3 and 2 respectively can be expressed as :

$$\frac{R_{12}}{R_{120}} = \left( \frac{1 + \alpha}{1 + \gamma} \right) \frac{f_1(T) f_2(T_0)}{f_2(T) f_1(T_0)} \quad (8) \quad \frac{R_{32}}{R_{320}} = \left( \frac{1 + \delta}{1 + \gamma} \right) \quad (9)$$

Measuring the fluorescence ratio  $R_{32}$  provides directly the factor  $(1 + \delta/1 + \gamma)$ . The distortion of the fluorescence spectrum observed by the photodetector is caused by the wavelength dependence of refraction index of the liquid. Thus, it may be assumed, that for a stationary spray, a relationship between the factors  $(1 + \delta/1 + \gamma)$  and  $(1 + \alpha/1 + \gamma)$

exists. This relation  $(1 + \alpha/1 + \gamma) = H(1 + \delta/1 + \gamma)$  is assumed to be universal for a given optical device (i.e. detection spectral bands), and a given liquid. From a practical point of view, this relationship can be determined by changing the spray characteristics (i.e. droplet size distribution and spatial distribution). This operation, called dynamic calibration, can be achieved by varying the spray injection pressure or other injection conditions.

Knowing experimentally the relation  $H$ , the local spray temperature can be inferred by the relation (8). The function  $f_1/f_2(T)$  must be initially calibrated as a function of the temperature.

### 3. EXPERIMENTAL SET-UP AND DATA PROCESSING

#### Optical set-up

A Laser Doppler Velocimetry probe (DANTEC FiberFlow probe) is used to create the probe volume. The fluorescence is detected in back-scatter direction by means of an optical doublet integrated in the emission probe that is connected to an optical fiber acting as a pinhole. The laser light scattered on the droplets is high pass filtered ( $\lambda=514.5$  nm). The remaining fluorescence signal is separated into three spectral bands by means of a set of dichroic and neutral beamsplitters (fig. 1). The optical signal detection on the three spectral bands is performed by means of three photomultiplier tubes equipped with three rapid pre-amplifiers (bandwidth: 10 MHz). The acquisition and sampling of the fluorescence signals is carried out by means a rapid computerized multi-channels acquisition board.

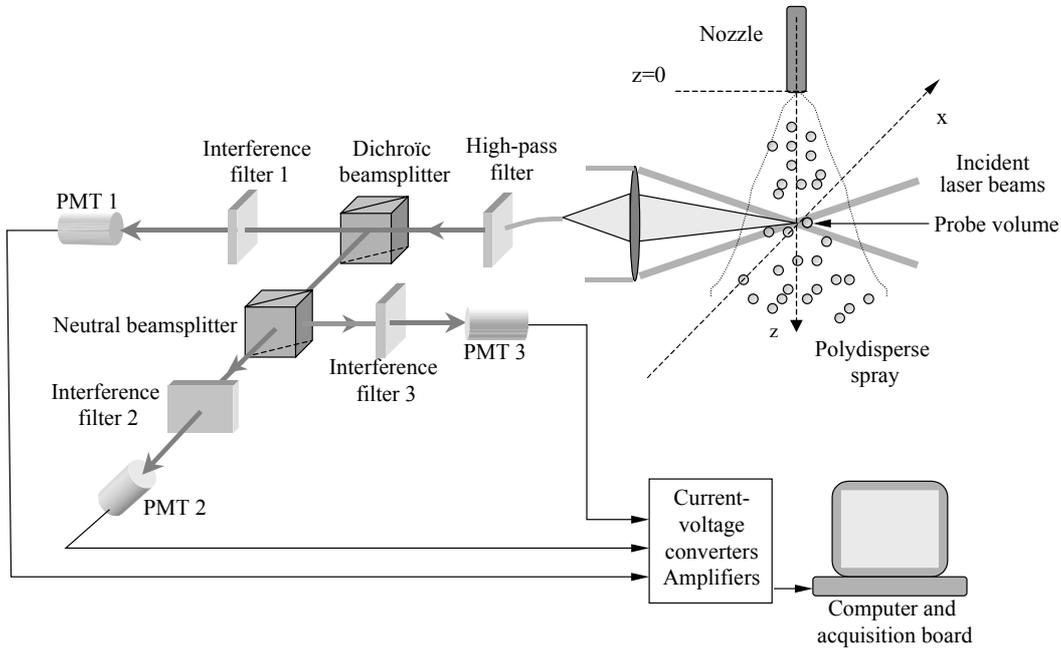


Fig. 1: Block diagram of the experimental set-up.

#### Data processing

A threshold is fixed above the natural noise level of the photomultipliers (thermal noise and ambient light) in order to detect the droplets crossing the probe volume (fig. 2). For each acquired sample higher than the threshold, the fluorescence signal is stored in a buffer and a summation of all samples above the threshold, corresponding to a detected droplet, is realized. For each retained sample on the channel where the threshold is applied, the matching samples are also accumulated in the same way on the second and third channel.

The ratio of the fluorescence collected on two spectral bands  $i$  and  $i'$  is calculated as follows:

$$R_{i'i} = \frac{\sum_{j=1}^N I_{fij}}{\sum_{j=1}^N I_{fi'j}} \quad (10)$$

where  $I_{fij}$  is the fluorescence intensity integrated on a droplet (index  $j$ ) crossing the probe volume, for the spectral band  $i$ , and  $N$  is the total number of acquired droplets. Based on the ratios  $R_{12}$  and  $R_{32}$ , the Eqs. (8) and (9) allow to calculate the temperature  $T$ , which can be interpreted as an average temperature of the liquid crossing the probe volume during the acquisition time. The temperature value converges quickly if the spray is stationary.

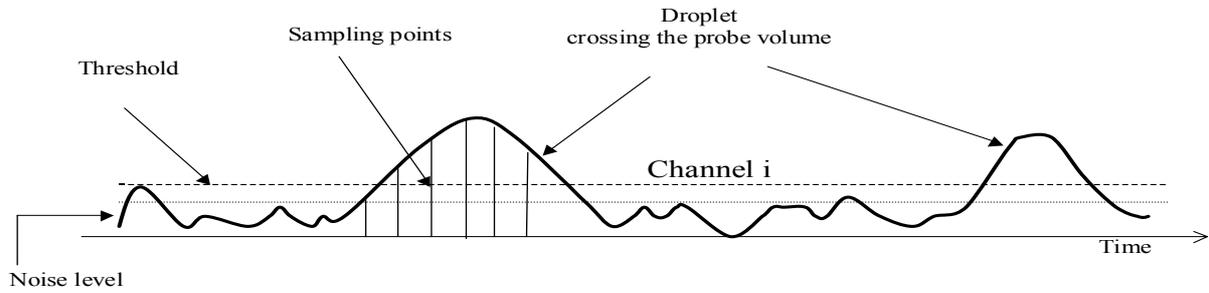


Fig. 2 : Principle of the droplet detection on the 3 spectral bands.

#### 4. CALIBRATION AND EXPERIMENTAL VALIDATION

In a first step, the evolution of the fluorescence ratio  $R_{12}$  as a function of the temperature is measured one time for all in a cell where the temperature can be controlled. The calibration curve, presented in Fig. 3 allows to determine the function  $f_1/f_2(T)$  and subsequently the coefficient sets  $a_i$  and  $b_i$  according to Eq. (3).

In order to validate the assumptions done about the multi-scattering of the fluorescence emission, a spectral study was performed. A first spectrum of the fluorescence emission of sulfo-rhodamine B dissolved in water was realized in a reference cell. Three other spectra were recorded in the spray centreline, for three injection pressures and for similar temperature conditions. The spectra measured in the spray (fig. 4) are clearly shifted from the reference spectrum, which demonstrates that the detected spectrum is affected by the spray environment (i.e. droplet size distribution, spatial distribution and density).

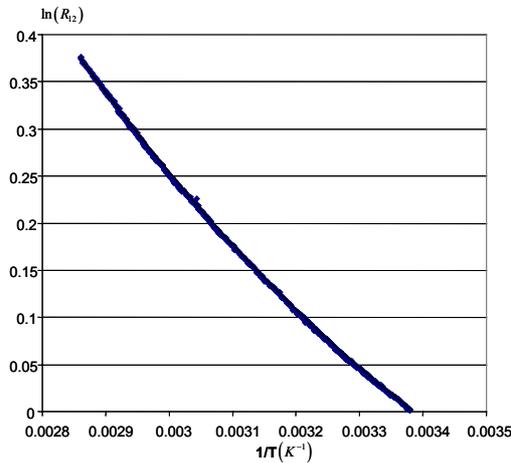


Fig. 3 : Calibration curve of the sulfo-rhodamine B dissolved in water.

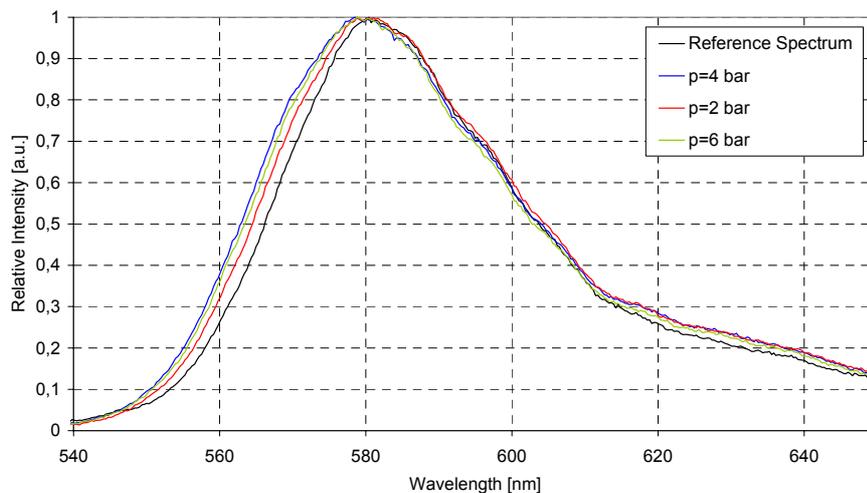


Fig. 4: Fluorescence emission spectra recorded in the spray for different injection pressures. Comparison to a reference spectrum taken in a single-phase environment.

The relationship between the factors  $(1+\delta/1+\gamma)$  and  $(1+\alpha/1+\gamma)$  was tested on several sprayers, in order to validate its universal nature for a given optical and tracer system.

A water spray is created by forcing pressurized water, previously seeded with sulfo-rhodamine B, through a 100  $\mu\text{m}$  orifice, resulting in a 30° or 45° aperture polydisperse spray, depending on the orifice shape. The droplet velocity near the injection is 6.2 m/s and 5.9 m/s, and the droplet mean diameter is 18.3  $\mu\text{m}$  and 20.0  $\mu\text{m}$  for the 30° and 45° sprayer respectively. An additional atomizer - based on the disintegration of a liquid jet by three air jets - was used to produce somewhat higher droplet diameters (mean diameter: 22.8  $\mu\text{m}$ ) together with a higher flow-rate and droplet velocity close to the injection (33.4 m/s).

For each of the sprayers or atomizers, the injection pressure (for the two sprayers) and the air pressure (for the atomizer) was varied over the accessible range. The plot of the factor  $(1+\alpha/1+\gamma)$  as a function of  $(1+\delta/1+\gamma)$  (Fig. 5), called dynamical calibration, shows that all the points follow the same trend. A second order polynomial seems to fit well with the experimental data coming from the three injection devices, which seems to be representative of spray environment effect on the detected fluorescence.

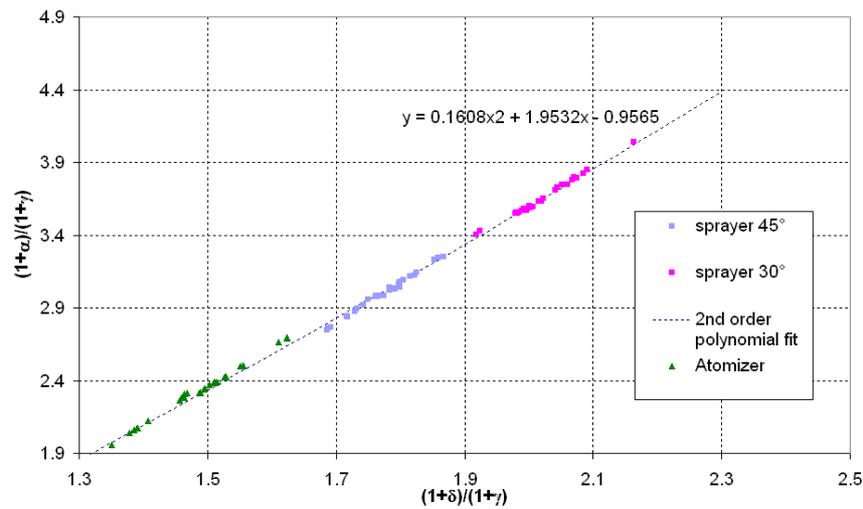


Fig. 5: Calibration curve of the fluorescence multi-scattering in the spray.

## 5. EXPERIMENTAL RESULTS

The technique was tested on a heated water spray (Fig. 6), generated by the mechanical sprayer with a 30° aperture, at a temperature higher than the ambient temperature. The injection velocity is about 6.3 m/s and the injection temperature is about  $T_{inj}=50^{\circ}\text{C}$  (ambient  $T_{amb}=25^{\circ}\text{C}$ ). According to phase Doppler measurements, the droplet size histogram is centred on 18  $\mu\text{m}$ . The fluorescence of the tracer added in the liquid is induced by the laser system of the PDA and is collected in the laser beams intersection volume (fig. 1). The measurements are performed on 1000 detected droplets, and the repeatability of the measured temperature is estimated at about  $\pm 1^{\circ}\text{C}$ . A scan of the droplet temperature in the spray streaming direction ( $z$ ) is presented in fig. 7. A strong cooling of the liquid appears after atomization and the temperature decreases clearly under the ambient temperature due to the effect of the vaporization of the water, enhanced by the moderately high injection temperature. Some liquid temperature profiles are presented in Fig. 8, where lateral expansion of the spray can be observed, although a certain degree of asymmetry can be noticed.

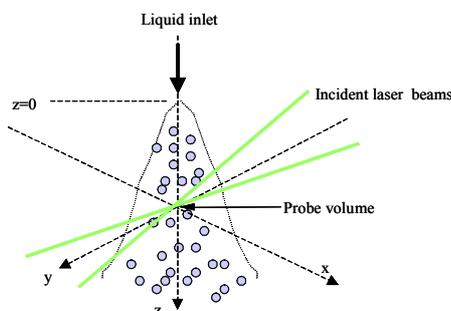


Fig. 6: Spray testing facilities and probe volume position.

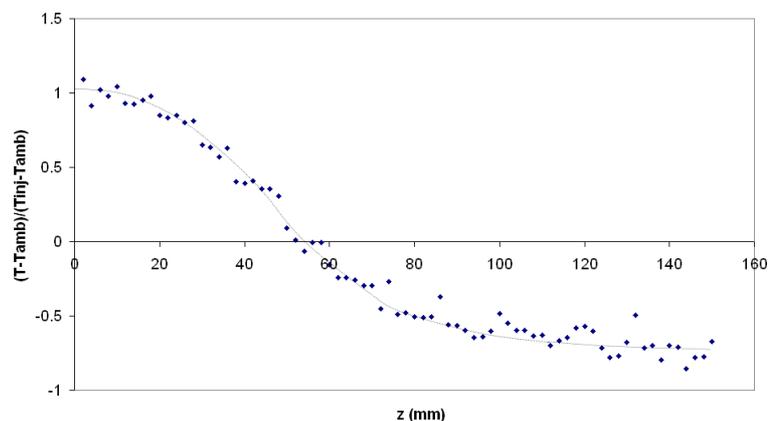


Fig. 7: Downstream liquid temperature measurements in the heated water spray.

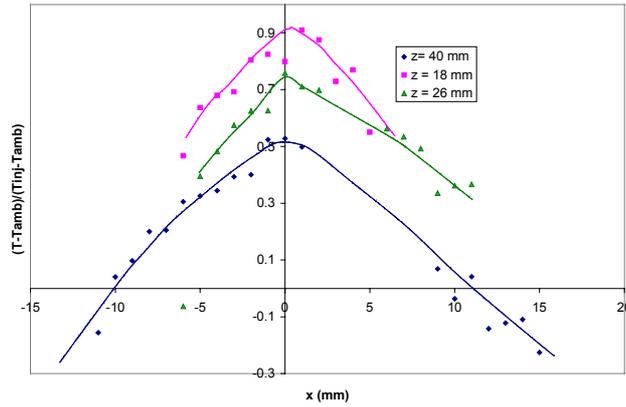


Fig. 8: Temperature profiles at different downstream positions in the heated spray.

## 6. CONCLUSIONS

A new measurement technique based on the detection of the laser-induced fluorescence of a tracer added to the liquid on three spectral bands allows to measure the mean temperature of the liquid phase of a polydisperse, stationary spray. The multi-scattering effects of the fluorescence can be corrected in-situ by using the fluorescence signal ratio on two spectral bands, the temperature being measured by the ratio of the fluorescence on two other spectral bands.

Preliminary results were obtained on a heated water spray, which are compatible with what can be expected in such a situation.

In the next developments, the technique will be extended to other liquids in order to check if a similar correction of the multi-scattering phenomena of the fluorescence can be applied. In parallel, a theoretical computation of the scattering phenomena will be undertaken, to implement a predictive tool for the investigation of these phenomena.

## NOMENCLATURE

### Latin symbols

$a$  : temperature sensitivity coefficient (2<sup>nd</sup> order) ( $K^{-2}$ )

$b$  : temperature sensitivity coefficient (1<sup>st</sup> order) ( $K^{-1}$ )

$f(T)$  : temperature dependence function

$I_f$  : fluorescence intensity ( $W/m^2$ )

$R_f$  : fluorescence ratio (dimensionless)

$T$  : absolute temperature (K)

$T_{amb.}$  : ambient temperature (K)

$T_{inj.}$  : injection temperature (K)

$V_c$  : measurement volume ( $m^3$ )

### Greek Symbols

$\alpha, \delta, \gamma$  : scattered part of the total detected fluorescence intensity

$\beta$  : spectral temperature sensitivity ( $K^{-1}$ )

$\lambda$  : wavelength (nm)

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