

# Simultaneous measurements of mean and surface temperature of evaporating moving droplets using combined two colors Laser-Induced Fluorescence and Infrared Thermometry. Extension to the measurement of the temperature distribution within the droplets.

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In order to understand and to quantify the physical processes encountered when fuel is injected into a combustion chamber, two non intrusive droplet temperature measurement methods have been implemented, for the first time, on the same test bench. The droplet surface temperature is investigated by Infrared Thermometry and the mean droplet temperature or the temperature distribution within the droplet by two colors Laser-Induced Fluorescence. The case of ethanol droplets, pre-heated above the ambient temperature and evolving in atmosphere is considered.

## 1. Introduction

The fuel spray is a central problem which merits investigations in the internal combustion engines area. The fuel is injected into the combustion chamber by high pressure atomizers as a liquid spray composed with individual droplets. The main objective in this area is to gain in the understanding of the highly complex aerothermal phenomena, where heat, mass and momentum transfers are intimately linked. Predictive capabilities of the combustion computation codes would benefit from a better understanding of these phenomena and basic experimental studies are necessary to address properly this goal.

Since experiments on full scale combustors are complex and rather hard to interpret because of the complexities of the real spray combustion, simplest and idealized sprays are designed. Experiments on monodisperse droplets lines are suitable for an optimal understanding of the fundamental phenomena, since it allows to obtain the same diameter, the same temperature and the same velocity at the injection point so the effects of the different parameters will be easily separated.

Reliable experimental databases about the energetic budget of the droplet in its gaseous environment can be deduced from measurements of the droplet mean temperature, surface temperature and temperature distribution within the droplet.

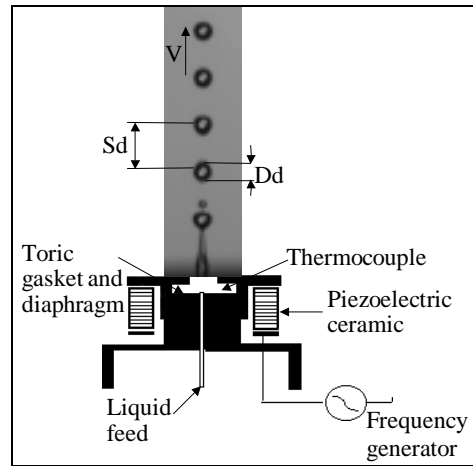
A two colors Laser-Induced Fluorescence (LIF) has been developed in LEMTA (Nancy) in order to measure the mean droplet temperature [1]. A recent extension of this technique enables to determine the space distribution of the temperature within the droplet, if the droplet is scanned by a sufficiently small probe volume. The method allows to determine an image of the temperature distribution in about 50% of the droplet volume but the near surface temperature gradient and the surface temperature cannot be determined.

An Infrared Thermometry technique (IR), based on the measurement of the infrared emission of the droplets in the 8  $\mu\text{m}$ -12  $\mu\text{m}$  range, investigated and developed in ONERA (Toulouse) [2,3] measures the surface temperature. For the first time, the two techniques (LIF and IR) have been

implemented on the same test bench, which consists of a monodisperse injector of ethanol droplets (diameter, about 200  $\mu\text{m}$ ). The fuel is pre-heated in the injector and the droplet cooling process, due to evaporation and forced convection is observed and analyzed.

## 2. The monodisperse droplet stream

A linear monodisperse droplet stream is generated by Rayleigh disintegration of a liquid jet, by means of a mechanical vibration supplied by a piezoceramic, excited by a square wave (figure 1). The applied voltage on the piezoceramic depends on the desired position of the break-up zone and on the fuel physical properties, related to the injection temperature. For a given frequency, the liquid jet breaks up into equally spaced and monosized droplets, at the frequency of the forced mechanical vibration.



**Fig. 1** The monodisperse droplet stream generator

The droplets can range from 100  $\mu\text{m}$  to 200  $\mu\text{m}$  in diameter and their velocity is adjusted from 2  $\text{m.s}^{-1}$  to about 10  $\text{m.s}^{-1}$ . The fuel temperature adjusted in the injector body by means of an external heated water circulation. The temperature of the fuel is measured exactly at the injection point using a K type thermocouple. In such a periodic device, the distance from the injection point is converted into time by measuring the local droplet velocity.

## 3. Two colors Laser Induced Fluorescence : principles and applications

### 3.1. 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 [4]. The fuel, ethanol here, is previously seeded with a low concentration (a few  $\text{mg.l}^{-1}$ ) 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 ( $\lambda=514,5 \text{ nm}$ ) 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 [4]. If beer's absorption phenomena are neglected, the fluorescence emission on a given spectral band, as a function of the different physical and optical parameters, is given by [4], [5] :

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

where  $K_{\text{opt}}$  is an optical constant,  $K_{\text{spec}}$  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  $\beta$  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 combusting 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 both fluorescence intensities collected on both optimal spectral bands is given by :

$$R_f = \frac{I_{f1}}{I_{f2}} = \frac{K_{\text{opt1}}}{K_{\text{opt2}}} \frac{K_{\text{spec1}}}{K_{\text{spec2}}} e^{\frac{\beta_1 - \beta_2}{T}} \quad (3)$$

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. The resulting temperature sensitivity is about 2%/ °C.

### 3.2. Measurement principles and droplet temperature mapping

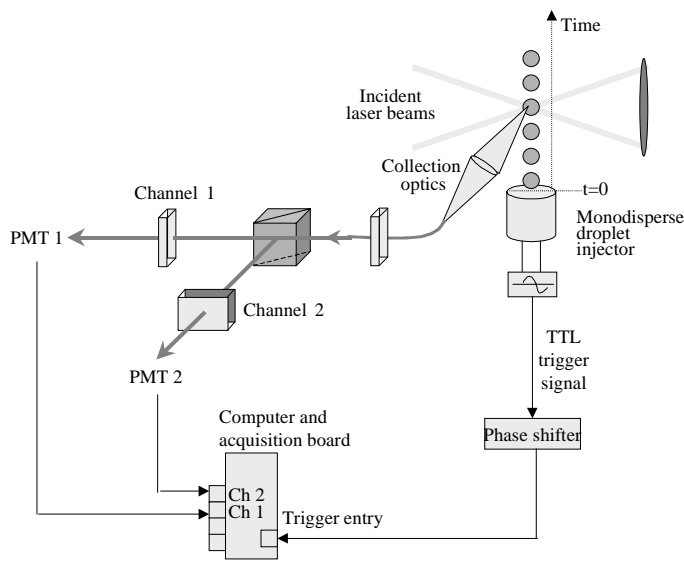
A LDV optical device, providing two intersecting laser beams issuing from the same laser source has been used in order to create the probe volume. On one hand, a mean droplet temperature is measured by using a probe volume diameter comparable to the droplet diameter itself and by averaging the fluorescence signal on the overall crossing time of the probe volume by the droplet. The other advantage to use a LDV device is to obtain a simultaneous droplet velocity measurement.

On the other hand, mapping the temperature field within a 200  $\mu\text{m}$  diameter droplet requires the use of a particularly small probe volume. The probe volume effective size is given by the combination of laser excitation area and the receiving optics resolution. The combination of a beam expander and a short focal front lens for the LDV system provides an ellipsoid shaped laser excitation volume, with the dimensions (20x20x90  $\mu\text{m}^3$ ).

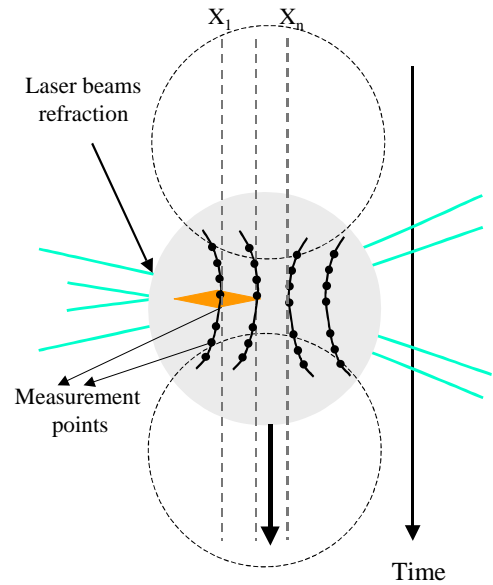
The fluorescence signal is collected at right angle by means of an achromatic doublet connected to an optical fiber, acting as a pinhole. According to the selected focal length for the fluorescence signal receiver, the collection volume corresponds to a 68  $\mu\text{m}$  diameter cylinder, assuming that the depth of field is on the order of the laser beam diameter. 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 [1] (figure 2).

As a droplet crosses the laser excitation area in the stream direction, if the probe volume is sufficiently small compared to the droplet size, different zones of the droplet are successively illuminated by the laser and the fluorescence is detected on the two spectral bands. By shifting the probe volume in a perpendicular axis of the stream direction, it is possible to scan different lines  $X_i$  in the droplet (figure 3).

Due to random process of the photons arrival on the photocathode of both PM tubes, a noticeable noise appears in the space distribution of the fluorescence signal. The periodicity and the repeatability of the droplet trajectories allow to process phase-locked averaged on a suitable number of droplets transits in the probe volume (about 1000). The synchronization is realized by a trigger issuing from the piezoceramic controller of the injector. The same work is performed on both acquisition channels, corresponding on the acquisition on both color bands. The 3D refraction laws are used in order to determine accurately the deviation of the laser beams axis at the droplet interface and to position their intersecting point, and subsequently the real location of the measurement point within the droplet (figure 3). The simple 3D refraction law applied at the spherical interface do not enable to position all the measurement points within the droplet volume, the points located near the droplet surface being in a total reflection situation. Consequently, only a part of the droplet volume can be mapped. Finally, a linear interpolation of the temperature values between the different points positioned in the equatorial plane is calculated in order to get a continuous temperature map.



**Fig. 2** LIF experimental arrangement



**Fig. 3** Principle of droplets scanning

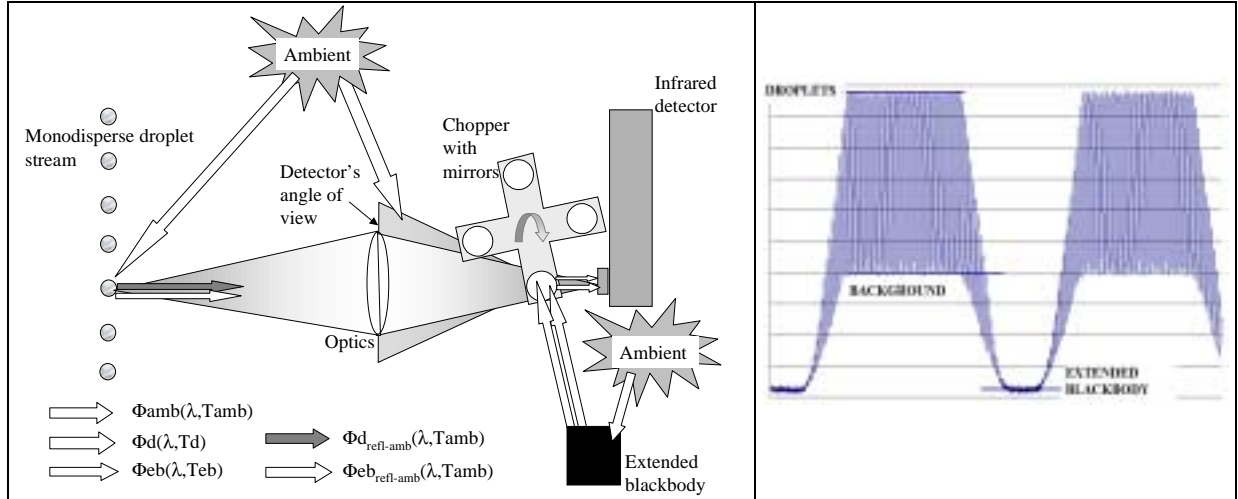
#### 4. Droplet surface temperature measurements using Infrared thermometry :

The Infrared thermometry method is based on the measurement of the infrared emission of the droplets by an IR photodetector in the  $8\text{ }\mu\text{m}$ – $12\text{ }\mu\text{m}$ , in comparison to that of a reference blackbody. A new device was introduced in 2001 which needed a set of initial calibrations to take the respective parts of the contributions of the droplet and background emissions into account, as a function of the probe volume and droplet sizes [6].

The different parts of the measurement system are represented on the figure 4. The flux emitted by droplets ( $\Phi_d$ ) is collected by an Infrared lens that focuses all the flux on the detector. This lens has a magnification of 4.1 so the theoretical object seen by the detector is a  $25\text{ }\mu\text{m}$  diameter disk. In that configuration an alternative signal is coming out the detector where the two levels correspond first when the droplet is in the probe volume with the flux coming from the droplet and secondly when there is no droplet at the focal point, the detector receives the background flux ( $\Phi_{\text{atm}}$ ). To quantify the droplets surface temperature, a reference flux is necessary. This is done by the use of an extended blackbody which temperature is fixed at  $60^\circ\text{C}$ ; its flux ( $\Phi_{\text{eb,ref}}$ ) is sent into the detector by means of mirrors on a rotating chopper. So the detector gets alternatively the flux coming from the main scene and the flux coming from the blackbody. An

analysis of the complete signal given by the detector (figure 4) allows to estimate the flux coming from the droplets.

A radiative budget which must take of parameters such as the droplet emissivity  $\epsilon_d$ , the optics reflections  $\rho_{\text{optics}}$ , the spectral detector response  $S(\lambda)$ , the sensitive detector area  $A_d$ , the detector's angle of view  $\Omega_d$  and the atmosphere transmission  $\tau_{\text{atm}}$ , has to be established in order to calculate droplet surface temperature ( $T_d$ ) (cf. figure 4). The different fluxes depend on the temperature ( $T$ ) and on the wavelength ( $\lambda$ ).



**Fig. 4** Radiative flux sources present in the experimental configuration. Signal coming out the detector and visualized on a oscilloscope screen

Chopper position 1: the flux from the main scene (droplet and background) reaches the detector:

Flux collected when a droplet is at the focal point:

$$\Phi_{d_{\text{all}}}(\lambda, T_d) = \Phi_d(\lambda, T_d) + \Phi_{\text{amb}}(\lambda, T_{\text{amb}}) + \Phi_{d_{\text{refl-amb}}}(\lambda, T_{\text{amb}}) + \Phi_{\text{atm}}(\lambda, T_{\text{atm}})$$

Flux collected between two droplets:

$$\Phi_{\text{atm}_{\text{all}}}(\lambda, T_{\text{atm}}) = \Phi_{\text{atm}}(\lambda, T_{\text{atm}}) + \Phi_{\text{amb}}(\lambda, T_{\text{amb}})$$

Chopper position 2: flux from the main scene is hidden, and the mirror is reflecting the extended blackbody's flux :

Extended blackbody's flux :

$$\Phi_{\text{eb}_{\text{all}}}(\lambda, T_{\text{eb}}) = \Phi_{\text{eb}}(\lambda, T_{\text{eb}}) + \Phi_{\text{amb}}(\lambda, T_{\text{amb}}) + \Phi_{\text{eb}_{\text{refl-amb}}}(\lambda, T_{\text{amb}}) + \Phi_{\text{atm}}(\lambda, T_{\text{atm}})$$

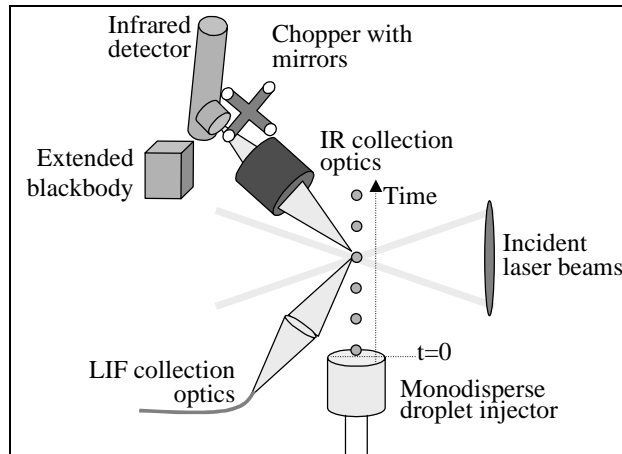
We record the amplitude signal which represents the difference between the flux emitted by the droplet and the flux emitted by the extended blackbody. The pre-calibration gives the temperature of the equivalent extended blackbody placed instead of the droplet. The droplet temperature is then calculated considering the equation below :

$$\boxed{\Phi_d(\lambda, T_d)} = \boxed{\Phi_{\text{eb}}(\lambda, T_{\text{eb}})} + \boxed{\Phi_{\text{eb}_{\text{refl-amb}}}(\lambda, T_{\text{amb}}) \text{ during the calibration experience}} - \Phi_{\text{eb}_{\text{ref}}}(\lambda, 333\text{K}) - \Phi_{\text{eb}_{(\text{ref})\text{refl-amb}}}(\lambda, T_{\text{amb}}) \text{ during the calibration experience} - \boxed{\Phi'_{d_{\text{refl-amb}}}(\lambda, T_{\text{amb}})} + \Phi'_{\text{eb}_{\text{ref}}}(\lambda, 333\text{K}) + \Phi'_{\text{eb}_{(\text{ref})\text{refl-amb}}}(\lambda, T_{\text{amb}}) = A_d \cdot \Omega \cdot \int_{\Delta\lambda} \epsilon_d(\lambda) \cdot \tau_{\text{atm}}(\lambda) \cdot \rho_{\text{optics}}(\lambda) \cdot S(\lambda) \cdot L_{\text{eb}}(\lambda, T_d) \cdot d\lambda$$

The framed elements correspond to the fluxes which are transmitted to the detector by the Infrared device, the other fluxes are reflected by the mirrors on the chopper.

As specified previously, the two techniques (LIF and IR) have been implemented for the first time on the same test bench. The two non intrusive droplet temperature measurement methods are focusing the same point of the monodisperse stream (cf. figure 5). The optical detectors are

fixed and the monodisperse stream is moved in order to explore different positions, corresponding to the temperature time evolution.

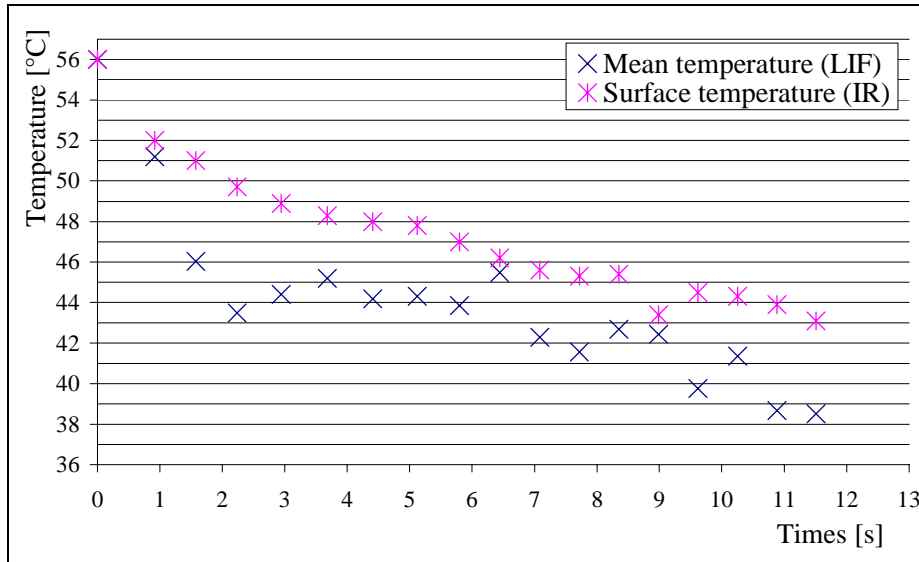


**Fig. 5** Sketch a of implementation of combined IR thermometry and LIF techniques

## 5. Experimental results

Monodisperse ethanol droplets are injected above the ambient temperature and the downstream droplet cooling is observed. The droplet diameter is  $202\ \mu\text{m}$ , the injection temperature is  $56^\circ\text{C}$  and the injection velocity is approximately  $8\ \text{m.s}^{-1}$ .

The evolution of the droplet surface temperature measured by IR and of the mean droplet temperature measured by LIF are reported in figure 6. Both mean and surface temperature decrease as the distance from the injection point is increased.



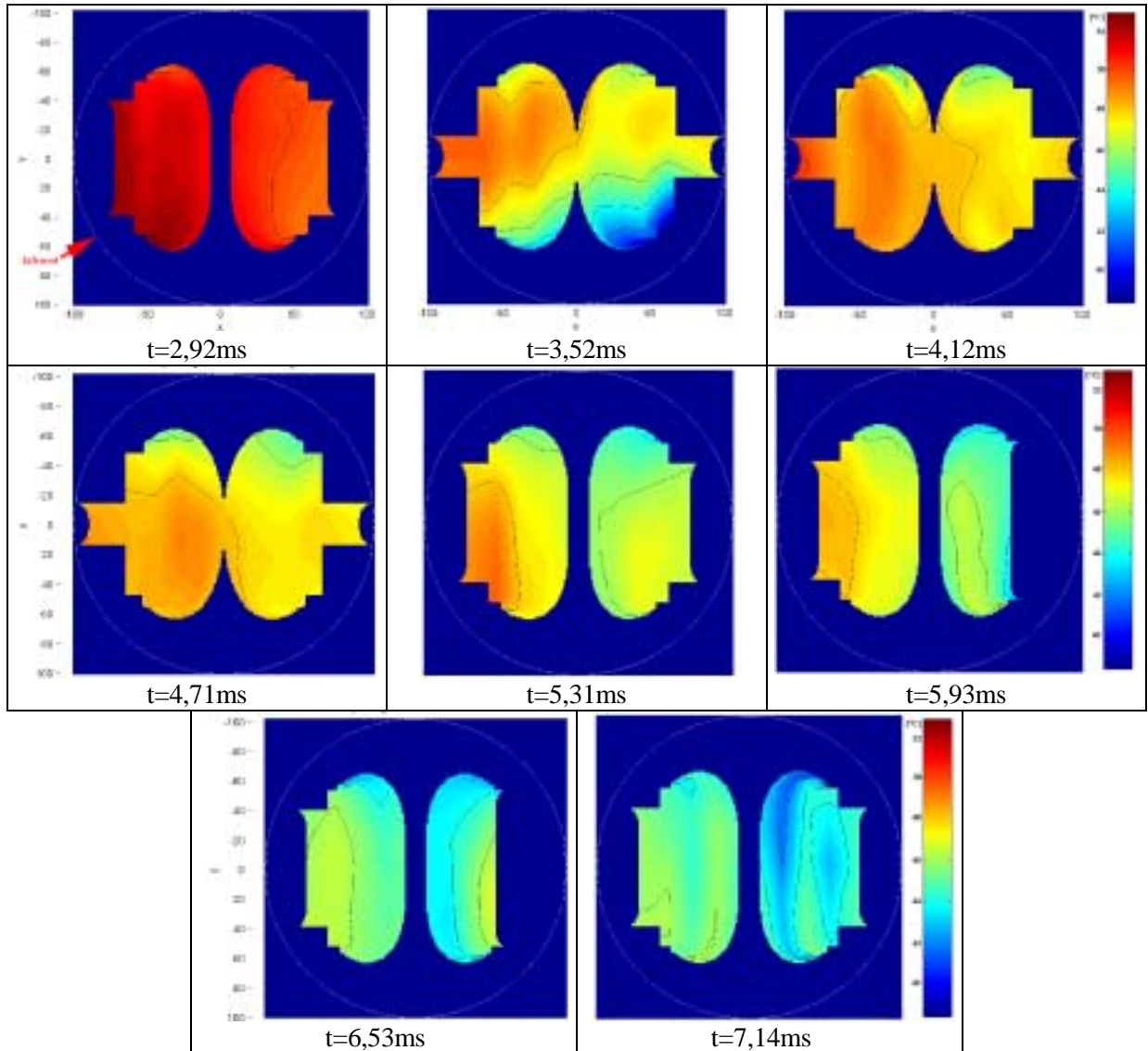
**Fig. 6** Spatio-temporal evolution of surface and mean ethanol droplet temperature

The surface temperature remains ever above the mean temperature. It can be explained by different facts:

- the droplet cooling is mainly due to evaporation at the droplet surface
- the convective heat transfer contributes also to the global cooling, but its effects are limited as the droplet stream entrains a hot air layer
- for aerodynamical reasons, the vapor concentration is quickly depleted in the droplet head, which tends to enhance the local evaporation, and the subsequent cooling of this area is more important.

- for such a droplet size, the heat transfer from the droplet surface to the droplet inner layers is mainly due to convective motion (Hill Vortex models, [7]). The cold area of the droplet head is advected to the droplet center : the cooling of the droplet inner layers occurs in first and the surface is affected after. The IR detector focuses on the droplets side surface as the fluorescence detector averages the temperature on the colder droplet inner layers. This may explain why the mean temperature measured by LIF is lower than the surface temperature measured by IR.

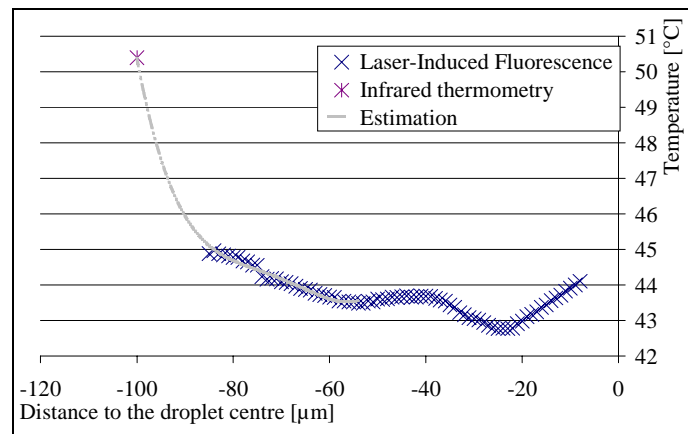
This point of view is confirmed by the 8 successive temperature maps of the droplet equatorial plan (figure 7) recorded from  $t=2,92$  ms to  $t=7,14$  ms ( $t=0$  being the injection temperature). The propagation of the cold area is clearly visible, while the near surface temperatures remain higher.



**Fig. 7** Ethanol droplet temperature mapping (diameter  $202\text{ }\mu\text{m}$ , injection temperature  $56^{\circ}\text{C}$ )  
( $t$ : time elapsed since the injection)

An interesting point is to visualize the temperature gradient inside the droplet : the temperature profile on the droplet diameter, measured by LIF (between  $8$  and  $85\text{ }\mu\text{m}$ ) and the surface temperature measured by IR have been reported on the same plot (figure 8).





**Fig. 8** Radial droplet temperature evolution (left part)

A cold area between 8 and 45  $\mu\text{m}$  is clearly visible, and a strong temperature gradient in the vicinity of the droplet surface is highlighted. A 5°C temperature increase is observed in a 10  $\mu\text{m}$  thick layer.

## 6. Conclusions

The combination of the two colors Laser-Induced Fluorescence and Infrared thermometry offers new perspectives to characterize experimentally the heat transfer from the surface to the interior of a moving evaporating droplet. Such experimental data would be helpful to validate the initial and boundary conditions for convection/conduction models in droplets which is a point of interest in the understanding of in the field of spray combustion.

## Acknowledgment

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