A two-color Planar LIF technique to visualize the temperature of droplets impinging onto a heated wall

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Abstract  This study describes the development of a novel measurement technique which is an extension to imagery of the two-color laser-induced fluorescence technique. This technique has already demonstrated its ability to characterize the temperature of droplets in various situations including droplet evaporation in combusting flows and droplet/wall interactions in the case of point wise measurements. This technique is based on the measurement of the relative intensity of two adequate spectral bands of a single fluorescent tracer. It allows absolute temperature measurement when a reference at a known temperature is performed. The imagery system is designed for observing single drop impacts onto a hot wall with a field of view limited to a few millimeter squares. In this study, the focus is placed first on the description of the technique development: the selection of a suitable tracer, its temperature calibration, the correction for the non-linearity of the response of the measurement system and the pixel-by-pixel correspondence of the camera images. After several tests carried out on droplets in temperature controlled conditions, the feasibility of the method is finally demonstrated in the case of droplets impinging on a heated wall for different impact regimes: rebound, splashing, deposition of a boiling liquid film.

1. Introduction

Liquid cooling is widely used in application areas where the required dissipation power is very large. The cooling efficiency is particularly high due to vaporization. While pool boiling and jet impingement techniques have satisfactorily provided high heat dissipation rates, they have generally failed to insure uniform and controlled cooling because of large spatial variations in surface heat flux. Not only the quality of this cooling can be a problem but also its consumption of massive quantities of water and energy. These features are much less of a problem when dealing with sprays. However, the industrial integration of spray cooling remains fairly limited when large power dissipations are required as in steel processing. This is mainly due to poor understanding of the complex flow fields and heat transfer characteristics of spray/wall interactions. In most experimental studies, heat transfers were characterized on the solid side, usually using for example embedded thermocouples. However, these measurements gave limited insights into the phenomena occurring within the liquid phase.

In the present study, the emphasis is placed into the measurement of the liquid variation in temperature when droplets interact with a hot solid surface and different optical techniques have been developed to measure the droplet temperature. The rainbow refractometry consists to observe the angular position of the monochromatic rainbow which depends on the refractive index and hence the liquid temperature (Van Beeck et al. 1995, Walker 1976). The transient cooling of an evaporating water droplet, suspended in a dry-air jet was also determined using thermochromic liquid crystal thermography (Richards et al. 1998). Other methods were based on the Laser Induced Fluorescence (LIF) of dye tracers. Laser Induced Exciplex Fluorescence (LIEF) was used to characterize the transient temperature field within falling droplets (Lu et al. 2000). The ratio of exciplex and monomer in the liquid phase depends on the local temperature. However, an oxygen-free environment is required due to the strong quenching of the exciplex by oxygen. The two-color Laser-Induced Fluorescence (2cLIF) was developed specifically to measure the temperature of droplets in either inert or reactive flows (Lavieille et al. 2001). This method is a two-color one-single dye approach, i.e. the emission from two different spectral bands with different temperature sensitivities are utilized. The ratio of the fluorescence intensity of these two bands allows eliminating the effects of parameters that are unknown or difficult to control such as the variations
in laser intensity, tracer concentration or measurement volume during the acquisitions. Being in principle insensitive to the shape of the liquid volume, the 2cLIF technique is particularly well adapted to handle complex situations with droplet deformations such as droplet/wall interactions. Recently, the 2cLIF thermometry was used to determine the droplet change in temperature during their impingement on a heated solid surface (Castanet et al. 2009). A linear monodispersed droplet stream was impacted onto a nickel plate, the temperature of which can be set above the Leidenfrost point. A series of point-wise measurements were performed near the location of the droplet impact in order to determine the average heating of the droplets during their transit close to the wall. Results reveal a clear correlation between the droplet heating and the incident Weber number based on the normal component of the droplet velocity.

So far, the application of the 2cLIF thermometry was mostly restricted to point-wise measurements which imply a point-by-point scanning of the flows. This paper presents an extension of the 2cLIF technique to planar laser induced fluorescence (PLIF) in order to visualize the temperature of droplets interacting with a heated wall.

2. Description of the experimental set-up

In order to study droplet/wall interactions, an experimental set-up was specifically designed. Regarding the heated plate and the droplet injector, the experimental set-up is very similar to that used in a previous study (Castanet, et al. 2009). A sketch of the experimental set-up is presented in fig.1. The heated plate is a square parallelepiped (2×2×10 cm$^3$) which is made of nickel. An electrical resistance (110Ω) is inserted in its center and the plate is heated by the energy dissipated into the resistance. A power regulator allows adjusting the voltage supplied to the resistance in order to reach a setpoint temperature in the core of the plate where a thermocouple is positioned. Due to the high thermal conductivity of nickel ($\lambda=50$ W.m$^{-1}$·K$^{-1}$), the temperature at the surface of the heated sample is almost homogeneous (Castanet, et al. 2009). The wall temperature can be set to a value much higher than the Leidenfrost temperature for which a vapor film forms almost instantaneously between the liquid water and the wall. Presently, this occurs around 220°C for a water sessile droplet.

Additionally, a linear monodisperse droplet stream is created by the disintegration of a liquid jet. The breakup is driven by a Rayleigh-type instability than can be triggered by mechanical vibrations from a piezoceramic. For some specific frequencies of the vibrations, the liquid jet split into equally spaced and monosized droplets. The size of the injector orifice and the inlet pressure can be changed from an experiment to another which allows to some extents adjusting separately the size, the frequency and the velocity of the droplets. The droplet generator can be rotated to obtain several angles of incidence. The temperature of the injector body is regulated while the liquid temperature is measured by a thermocouple. Knowing the injection frequency, the initial droplet size can be determined very accurately from the measurement of the liquid flowrate.

3. Time-resolved shadow imaging

A high-speed (HS) camera is used to visualize the impact of individual droplet. The HS camera is a Phantom v710 equipped with a 12-bits CMOS sensor that can provide up to 7500 fps at full resolution (1280×800 pixels). It is used with a reduced resolution (512×128 pixels) which enables to perform the image acquisition at a much higher frame rate, typically in the order of 100,000 fps. This is sufficient to resolve in time the droplet/wall interactions in the experimental conditions encountered in this study. For example, a droplet with a 150 µm size in the bouncing regime has a resident time of about 150 µs in the experiments. As presented in fig.1, the droplets are illuminated from behind using a very bright light source (a 400 W HMI lamp with a parabolic reflector). Sharply contrasted images of the droplets are obtained by shadow imaging while the shuttering of the camera is maintained around 1µs to avoid any motion blur. A zoom lens allows observing in
details the droplets deformation and possible splashing. The images are then processed with a home-made tracking program in order to determine the main features of the impact such as the incident angle, the normal and tangential velocities, the residence time, or the spreading diameter of the droplets.

![Diagram](image)

Fig.1: Schematic view of the experimental set-up and the optical layout for shadow imagery.

4. The two-color PLIF technique

PLIF techniques have been used in liquids to characterize temperature fields. Coolen et al. (1999) visualized the temperature in a natural convection flow by means of rhodamine B. Almost the full emission spectrum of rhodamine B is detected by a single camera. In such a single-color/single-dye technique, one of the main difficulties is that any spatial and temporal variations in the local incident laser intensity need to be separately accounted for, a condition that is almost impossible to satisfy if the variations are caused by the flow itself. For example, in the case of droplets, the local incident laser intensity is modified by the shapes, the sizes and the positions of the droplets within the laser sheet. For quantitative measurements, another requirement is that the tracer concentration remains constant. This is not possible when droplets evaporate, since the organic dyes used in the liquids (rhodamine, fluorescein,...) are very weakly volatile.

A common method to eliminate these problems is to use a ratiometric method. One possibility is the two-color two-dye where the flow is seeded with two dyes (Coppeta et al. 1998, Kim et al. 2003, Sakakibara et al. 1999, Sakakibara et al. 2004, Shafii et al. 2010). Coppeta and Rogers (1998) makes a comprehensive description of the technique and demonstrate its feasibility, not only for temperature but also for pH. Sakakibara and Adrian (1999, 2004) applied the technique to perform measurements in thermal convection fields. Kim et al. (2003) have extended the method at the microscopic scale. While most of the measurements at larger scales were carried out using two cameras and a dichroic beam splitter at 45° incident angle, they used a single-camera system and the detection of the fluorescence was done sequentially by alternating two band-pass filters. This avoids the problem of the pixel-by-pixel correspondence of the images of the cameras. To achieve accuracy in the two-color two-dye approach, one of the dyes should be sensitive to temperature and the other should not or only very weakly while the emission spectra of the two dyes should differ enough to permit the separation of the emitted light by optical means. Among the difficulties related to this approach, the concentration ratio of the dyes must be kept constant during the experiments. Moreover, the emission of one dye can be partially absorbed by the second dye: the detected emission intensity is then dependent on the optical path length within the liquid.

Another possible approach is the already-mentioned two-color/single-dye strategy (Lavieille et al. 2001). In its PLIF form, the implementations of this method were relatively limited. A demonstration was made in a single phase liquid flow (Bruchhausen et al. 2005). In regard to droplets and sprays, measurements have been reported by Düwel et al. (2007) in the case of burning ethanol droplets seeded with rhodamine B. In this work, two intensified CCD cameras are
positioned on both sides of a spray burner. Because of the large field of view, about 4 cm, the pixelby-pixel correspondence between the two cameras does not seem to be a problem.

In the following, the emphasis will be placed on the development of a two-color/single-dye PLIF system designed to measure the temperature distribution within a stream of droplets at a small spatial scale limited to a few millimeters.

4.1. Principles of the two-color laser induced fluorescence

The 2cLIF thermometry is based on the measurement of the fluorescence intensity of a dye tracer. In liquids, the fluorescence quantum yield is strongly influenced by the quenching, which depends on the temperature. The temperature dependence of the fluorescence intensity $I(\lambda)$ detected at a given wavelength $\lambda$ can be expressed as (Lemoine et al. 1999):

$$I_f(\lambda) = K_{opt}(\lambda)K_{spec}(\lambda)I_v c V \exp\left(\frac{\beta(\lambda)}{T}\right),$$  

(1)

where $c$ is the concentration of the dye tracer, $I_v$ the intensity of the incident laser beam, $V$ the measurement volume, $T$ the absolute temperature, $\beta(\lambda)$ a function featuring the sensitivity to temperature of the signal. $K_{opt}(\lambda)$ and $K_{spec}(\lambda)$ are two parameters depending on the optical and spectral properties of the detection system (e.g. the solid angle and the spectral sensitivity of the detectors). Therefore, these parameters are constants during the experiments. The fluorescence spectrum of the dye tracer is generally broadband and optical filters are used to select specific spectral bands of the fluorescence emission. For a given spectral band $i$, the fluorescence intensity $I_{f,i}(\lambda)$ is integrated over the wavelength range $[\lambda_{i,1}, \lambda_{i,2}]$ as followed:

$$I_{f,i} = \int_{\lambda_{i,1}}^{\lambda_{i,2}} K_{opt}(\lambda)K_{spec}(\lambda)I_v c V \exp\left(\frac{\beta(\lambda)}{T}\right) d\lambda.$$  

(2)

Lavieille et al. (2004) suggest to approximate this expression as:

$$I_{f,i} \approx K_{opt,i}K_{spec,i}I_v c V \exp\left(\frac{A_i + B_i + C_i}{T^2}\right).$$  

(3)

$A_i$ and $B_i$ are specific to a given combination of dye, solvent, excitation wavelength, and spectral band. In contrast, $C_i$ depends on the exact configuration of the experimental system and can change from one different measurement configuration to another. The ratio $R_f$ of the intensities of two different spectral bands is given by:

$$R_f = \frac{I_{f,3}}{I_{f,2}} = \frac{K_{opt,3}K_{spec,3}}{K_{opt,2}K_{spec,2}} \exp\left(\frac{A_i + B_i + C_i}{T^2}\right),$$  

(4)

$$\text{where } X = X_1 - X_2 \text{ and } X = A_iB_i C_i.$$

When the technique is applied in imagery, only $A$ and $B$ do not depend on the pixel position in the image. All other variables can change from one pixel to the other, especially the parameters $K_{opt,i}$, $K_{spec,i}$ and $C$ that are function of the arrangement of the detection system. Even under isothermal conditions, the fluorescence ratio $R_f$ is not necessarily uniform. To eliminate the influence of the detection system, a reference measurement at a known temperature $T_0$ (with the same optical configuration as for the measurement) is recorded. Denoting $R_0$ the fluorescence ratio obtained in the reference measurement,
When $A$ and $B$ are known from a calibration experiment (see section 4.4), eq. 5 can be used to determine the liquid temperature. It should be noted that this equation is valid if the fluorescence reabsorption can be negligible on the optical path (Bruchhausen, et al. 2005, Lavieille, et al. 2004).

4.2. Selection of the fluorescent tracer and the spectral bands

Rhodamine B or Kiton red were among the most widely used tracer dye because of their high sensitivity to temperature and to their complete solubility in aqueous solutions (Coppeta, et al. 1998). However, none of these tracers has been selected for this study. Instead experiments were performed using fluorescein 27 ($\text{FL27, C}_{20}\text{H}_{10}\text{O}_{5}\text{Cl}$) also called Fluorescein 548. This choice is based on the recent work of Sutton, et al. (2008) who made a comprehensive description of the interesting features of FL27 for temperature measurements in aqueous solutions. They showed that FL27 has a temperature sensitivity significantly higher than traditional tracers including rhodamine B and kiton Red (3.5%/$\degree$C against -1.6%/$\degree$C) for an excitation wavelength of 532 nm, also used in this study. However, these observations refer to the whole fluorescence spectrum, and further investigations were required to determine two bands of detection for the two-color/single-dye approach.

Preliminary measurements using a spectrometer were performed in a temperature-controlled cell. Fig. 2 shows the absorption and emission spectra of FL27 for different temperatures. It can be noticed that the fluorescence signal increases with temperature. This behavior has been interpreted as an effect related to a temperature-dependent shift in the absorption spectrum (Sutton, et al. 2008). A significant portion of the emission spectrum of FL27 is anti-Stokes-shifted with respect to the excitation line, i.e. it is shifted to shorter wavelengths than 532 nm. The absorption cross-section of FL27 is very low at 532 nm compared to other possible excitation wavelengths, this drawback was also pointed out by Sutton, et al. (2008). From fig.2, the evolution of the temperature sensitivity $\beta(\lambda)$ was calculated using eq.(1) and the results are displayed in fig.3. The selected bands for temperature measurements correspond to the ranges [505 nm-515 nm] and [575 nm-605 nm]. This selection has been carried out with regards to the intensity level as well as the sensitivity to the temperature.

4.3. PLIF Measurement system

\[
\ln \left( \frac{R_I}{R_0} \right) = A \left( \frac{1}{T^2} - \frac{1}{T_0^2} \right) + B \left( \frac{1}{T} - \frac{1}{T_0} \right). \tag{5}
\]
The measurement system is illustrated in fig.4. The excitation of FL27 is achieved by means of a CW Nd:YAG laser (Quantum Ventus, $P_{\text{max}} = 1.5 \text{ W}$, 532 nm). An arrangement of spherical and cylindrical lenses provides a laser sheet with a thickness of 220 µm and a height of 16 mm in the measurement zone. This latter is observed by a Questar QM-1 long distance microscope which is positioned at right angle at a working distance of about 84 cm. The microscope field of view is then about $3 \times 3 \text{ mm}^2$. A holographic filter (Notch Plus, Kayser Optical) is used to block the Mie scattering of the laser light by the droplets. The filter has an optical density of $10^{15}$ and a narrow bandwidth ($<700 \text{ cm}^{-1}$). A neutral beamsplitter (R/T 30/70%) allows the separation of the fluorescence signal for its acquisitions by the cameras. Linear glass polarizers and interference filters are mounted in front of the cameras. The linear glass polarizers are used to minimize optical aberrations arising from the light reflections at the surface of the microscope mirrors and the beamsplitter. The interference filters allows selecting the spectral bands depicted in fig.3.

Two electron-multiplying CCD cameras (Hamamatsu EM-CCD camera C9100-02, 14 bits) with a resolution of 1000 x 1000 pixels image the fluorescence field in the measurement zone. To improve the detection statistics, a 4×4 binning of the pixels is applied, even if the spatial resolution is reduced. The acquisition of the two cameras is performed simultaneously by using a common external trigger source.

A particular attention should be paid to the linearity of the measurement system and the signal-to-noise ratio of the image acquisition. Fig.5 shows the relative standard deviation of the camera signal (i.e. the ratio of the standard deviation of the pixel levels to their average value) as a function of the average signal. It is apparent that the relative standard deviation is sharply increased for high gains and low signals. Given that, the measurements were performed with moderate gains (20 and 50 to have balanced signals on both cameras). Several images are acquired successively then averaged in order to improve the accuracy of the measurements. Typically the number of cumulated images is determined so that the average levels of the pixels of interest converge with an uncertainty less than 1%, which corresponds to a moderate uncertainty on the temperature of about 1°C (see section 4.3). As an example, in fig.5, it can be seen that the relative standard deviation is about 3% for a camera gain of 50 and a signal level in the middle range equal to 8000. A set of about 150 images are then required to ensure the statistical convergence of the fluorescence ratio with the previous requirement on accuracy. Another example is given in fig.10 which presents the uncertainty of the convergence of the fluorescence ratio in the case of a droplet stream.

The linearity of the response of the measurement system has been also tested. To that end, the set-
up described in fig.4 has been slightly modified. An enlarged gaussian beam (beam diameter> 5 cm) illuminates a cell containing an aqueous solution of FL27 and the microscope observes the fluorescence field in direct transmission. A wattmeter measures the intensity of the laser beam. Fig.6 shows a typical image obtained by the cameras. A significant variation in the signal level is observed despite the illumination of the measurement volume was perfectly uniform. This may be explained by the non-uniformity of the sensor response, as well as optical aberrations mainly related to the microscope.

Fig.6: Typical image of a uniform scene

Fig.7 presents the evolution of the average signal as a function of the laser power. It is apparent that the system response is not perfectly linear. Only the average signal is represented in fig.7 but each pixel has its own response. Therefore, in the post-processing, a correction should be applied to the pixels depending on their level. This correction is based on the calibration curves representing the pixel level versus the illumination power (identical to fig.7 but for individual pixels). For a given image, the laser power corresponding to the level of a given pixel in the conditions of the calibration is assigned to the pixel. The new image is then corrected at the same time for the effects of non-uniformity and non-linearity of the optical system. In the following, this correction will be applied to all images regardless they were captured on droplets or in a cell. After this correction, the images are subtracted of the background noise that is equal to about 450 gray levels whatever the gain of the cameras.

The linearity of the tracer response is not a problem for laser excitations, which are in the order of 40W/cm² like in this study. However, Sutton, et al. (2008) have determined that the limit of the linear response is approximately 3×10⁵ W/cm² for a pulsed Nd:YAG laser. Considering a repetition rate of 10 Hz and a pulse duration of 10 ns, this limit corresponds to an average intensity as low as 0.03 W/cm². Due to the fact that the EM-CCD cameras are not gated very fast, an increase in the gain of the cameras would be necessary but even so the signal would remain low and quantitative measurements would become difficult due to the signal-to-noise ratio (fig.5). This justifies the choice of a continuous laser excitation in the present study.

4.4. Images correspondence

One of the main difficulties related to the experimental setup in fig.4 is the pixel-by-pixel correspondence of the camera images. In most studies, the correspondence is ensured by imaging a reference object such as a grid plate (Sakakibara, et al. 1999, Sakakibara, et al. 2004, Shafii, et al. 2010, Soloff et al. 1997). Comprehensive descriptions of a procedure for calibrating the image coordinates are given by Sakakibara, et al. (2004) and Soloff, et al. (1997). It allows determining the physical coordinates of each point in the image. In these works, the field of view of the cameras was much larger and an equally spaced grid pattern at a few millimeter intervals can be used. In the
present case, the same method is difficult to adapt in regard to the spatial resolution: 1 pixel correspond to about 10 µm with a $4 \times 4$ binning. For this reason, another procedure has been used for the pixel correspondence. It consists in finding the translation and the rotation to apply to the image of one camera to have the best match with the image of the other camera. Introducing $(x_{1,i}, y_{1,i})$ the row and column position of the $i^{th}$ pixel in the image of the $1^{st}$ camera, the pixel is moved to the position $(x_{2,j}, y_{2,j})$ using the following transformation:

$$\begin{bmatrix} x_{2,i} \\ y_{2,j} \end{bmatrix} = \begin{bmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{bmatrix} \begin{bmatrix} x_{1,i} \\ y_{1,j} \end{bmatrix} + \begin{bmatrix} t_x \\ t_y \end{bmatrix},$$

where $\theta$ is the rotation angle, $t_x$ and $t_y$ the components of the translation. Possible distortions are not taken into account in eq.(6) in contrast to Sakakibara, et al. (2004). The best match is found when minimizing the distance $S(\theta, t_x, t_y)$ between the images defined as:

$$S(\theta, t_x, t_y) = \frac{1}{N} \sqrt{\sum_{i=1}^{N} \left[ I_1(x_{1,i}, y_{1,i})/I_{1,\text{max}} - I_2(x_{2,i}, y_{2,j})/I_{2,\text{max}} \right]^2}.$$ 

In this expression, $I_1$ and $I_2$ denotes the images of the cameras subtracted of their background noise while $I_{1,\text{max}}, I_{2,\text{max}}$ corresponds to their maximum intensities. $N$ is the number of pixels in the images. Since $x_{2,i}$ and $y_{2,j}$ are not integers, $I_2(x_{2,i}, y_{2,j})$ is obtained by a bilinear interpolation. Classical minimization algorithms are used to achieve a sub-pixel convergence of $(x_{2,i}, y_{2,j})$. The convergence error for $(x_{2,i}, y_{2,j})$ is typically in the order of 0.1 pixel, however this may depend on the distribution of the intensity field in the image.

### 4.5. Temperature calibration

The temperature calibration is carried out in a cell filled with an aqueous solution of FL27. The liquid temperature is increased by means of an immersed heater. Isothermal conditions are maintained throughout the experiments by stirring the liquids. The solution has a moderate concentration in FL27 ($c = 5 \times 10^{-7}$ mol/L) and the optical path between the laser sheet and the cell window is limited to less than 1 mm to limit as much as possible the reabsorption of the fluorescence in the first spectral band of detection. The images are firstly subtracted from the background noise, and then they are corrected for the non-linearity of the optical system (see section 4.3). Finally the procedure described in section 4.3 is applied to ensure their correspondence and the fluorescence ratio $R_f$ is calculated. An almost linear trend is observed for

$$\ln(R_f(1/T)) - \ln(R_0(1/T_0))$$

as a function of $1/T$ (fig.8). The slope corresponds to a mean variation of the fluorescence ratio of about 0.8%/°C in the temperature range [20°C-75°C]. From fig.8, the coefficients $A$ and $B$ in eq.(5) can be determined. The standard deviation is also displayed with error bars in fig.8, it corresponds to an uncertainty of about ±0.008 on $R_f$. Therefore, the measurement errors related to the calibration is not expected to exceed ±1°C on the temperature.
5. Validation tests in temperature controlled conditions

5.1. Isothermal droplet streams

The first validation test was to measure the fluorescence ratio of a droplet stream injected at room temperature. Fig. 9 shows the average images of the fluorescence ratio for 4 different positions of the droplet stream. In this figure, the fluorescence ratio is normalized by the ratio measured in a cell at the same temperature. It can be noticed that the fluorescence ratio is almost identical regardless of the position of the droplet stream. However, it should be noted that the measurement ratio on the stream edge may be relatively inaccurate as indicated in Fig. 10 which represents the uncertainty of the convergence of the fluorescence ratio when averaging over 150 images. A reasonable accuracy can be achieved in the center of the droplet streams.

Fig.9: The fluorescence ratio $R_f$ for different positions of the droplets stream. Normalization by the fluorescence ratio measured in a cell at the same temperature $T=19^\circ C$ (average of 150 images).

Fig.10: Image of the uncertainty of the convergence of the fluorescence ratio $R_f$, ($\sigma$: its standard deviation, $\mu$: its average, $n=150$ the number of cumulated images)

Fig.9 reveals that the normalized fluorescence ratio is about 0.9 in the droplet streams while the temperature is the same than in the cell. This could be explained by an effect related to the droplet curvature that has already been described for other tracers. Labergue et al. (2010) showed that the fluorescence ratio can be influenced by the droplet size. This effect was reported for kiton red and pyrromethene 597-8C9 especially for small droplet sizes typically below 80 $\mu m$, but FL27 was not investigated. The study of this phenomenon is beyond the scope of the present article and is not accounted for in section 4.1. In the following, the reference $R_f(T_0)$ in eq.(5) will be measured on droplets near the injector exit but not in a cell so as to minimize the error due to this effect. This can be done since the fluorescence ratio is uniform under isothermal conditions, having corrected the images for the non-uniformity of the optical system (see section 4.3). In addition a relatively high
concentration of tracer \((c=10^{-5} \text{ mol/L})\) to ensure a sufficient level of fluorescence signal.

5.2. Heated droplet streams

The temperature field was also measured at a distance of 4 cm from the injector exit while the temperature of the liquid in the injector is increased from 19°C to 68°C. Fig.11 presents the average temperature in the droplet stream as a function of the liquid temperature in the injector \(T_{\text{inj}}\) measured by a thermocouple. The temperature measured in the droplet stream is slightly lower than those in the injector and the difference increases with \(T_{\text{inj}}\). However, as expected the gap remains limited due to the short distance between the injector exit and the measurement zone, the difference reaches 6°C when \(T_{\text{inj}} = 68\degree\text{C}\).

![Fig.11: Evolution of the average temperature measured in the droplet stream as a function of the liquid temperature in the injector and its standard deviation in the images as error bars.]

6. Application to the study of droplet/wall interactions

The measurement technique was finally used to characterize the heating of droplets impacting onto a heated wall. Depending on the wall temperature and the Weber number of the droplets, several regimes of impact can be observed with the HS camera: a rebound, a splashing or the deposition of a liquid film (fig.12). For each of these regimes, the heat exchange at the wall is modified (Castanet, et al. 2009). For a wall temperature between the boiling point and the Leidenfrost temperature of water, the film boiling regime occurs. The liquid touches the wall surface and it progressively begins to boil as time increased in contact to the wall. Vapor bubbles are formed and generate secondary droplets when they burst (fig.12.a). To study this impact regime, the droplet size was adjusted to 150 µm while the wall was maintained at 200°C. Fig.12.b shows the temperature field measured by the 2cPLIF technique. The entire temperature field cannot be visible with the microscope due its limited field of view. Therefore, the emphasis was on observation of the area where the boiling mainly occurs, i.e. on the right hand side of fig.12.a. The horizontal symmetry that can be seen in the image of the temperature field is due to the reflection of the droplet fluorescence on the smooth surface of the heated wall.

As expected, the liquid temperature in the boiling film is roughly lower than 100°C. It is in fact slightly lower than the boiling point since the liquid temperature increases with the residence time in contact with the wall. It should be noted that the contribution of secondary droplets may be less accurately taken into account than the liquid film, since most of the secondary are ejected out of the depth of field of the microscope. Furthermore, the fluorescence intensity of the secondary droplets is reduced because of their small size.
Fig. 12: Illustration of the temperature measurements by 2cPLIF thermography. Case of three streams of droplets impacting onto a hot surface, (a, b): a liquid film boiling, (c, d): a rebound (e, f): a splashing.

In the last examples, the wall temperature is maintained above the Leidenfrost point. For an incidence angle of 17°, a rebound is observed (fig.12.c) while there is a splashing for a normal incidence (fig.12.e). The corresponding temperature fields are presented in fig.12.d and 12.f. The droplet heating appears to be larger in the case of a splashing than in the case of a rebound. The same observation was made by Castanet, et al. (2009). However, the experimental conditions were not the same, in particular the incident droplet size was significantly lower.

**Conclusion**

This study presents the development of a new technique for measuring the temperature of droplets by planar laser-induced fluorescence. It is an extension of the point wise two-color laser-induced fluorescence technique that has been particularly tested to measure the temperature of droplets in the past. Measurement with this new approach requires taking some precautions, for example the non-linearity of the optical system response and possible optical aberrations. Because of the particularly reduced size of the measurement zone, an original procedure for the pixel-by-pixel correspondence of the camera images had to be developed. Tests performed on heated droplet streams reveal that the measurement errors are moderate in controlled conditions and the measurements are consistent with previous work in the case of droplets impinging onto a heated wall. In its current form, the measurement system is not adapted for time-resolved measurements in respect to the characteristic time of the droplet/wall interactions in the presented experiments. This is mainly due to the saturation of the tracer response with pulsed lasers which limits the range of possible excitation intensities. The signal-to-noise ratio is then particularly degraded if the cameras are not gated fast enough.
References


