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Modelling of UnSteady Combustion in Low Emission Systems

Work Package 3
Advanced diagnostics in two phase flow field

Task 3
Development of advanced optical diagnostics

Subtask 3.1.2
Development of optical techniques for simultaneous characterization of the two phases on laboratory experiments

Deliverable report D3.13
Experimental Set up and first results of rainbow thermometry

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1. Background
Thermometry is a technique for measuring size and temperature of transparent droplets. For data inversion a rainbow pattern is employed, which is formed by a single droplet or by constructive interference of laser light scattered by an ensemble of spherical droplets. In the first case, one speaks about Standard Rainbow Thermometry (SRT), investigated since 1988. The standard technique is applied to a monodisperse burning droplet stream, where the problems with particle shape do not exist. The objectives of this study is to validate droplet evaporation and combustion model from the isolated droplet to high interaction droplets case. This deliverable (6 months) report describes the rainbow technique, presents the experimental setup and the first results showing the limitation of the performances of the Rainbow technique in comparison with the two colors Laser Induced Fluorescence (Subtask 3-1-2) technique.

2. Description of the experimental set up and the associated techniques
Experimental results obtained with SRT are shown in a non-burning and burning single droplet stream. The experiment, shown in figure 1, is set up around a monosized droplet generator, in which a piezo ceramic induces Rayleigh instability on a continuous liquid stream, thereby breaking it into a series of monodispersed droplets [1]. The droplet stream is injected upwards. To increase the droplet spacing, an electrostatic droplet deflector has been designed [2,3]. The number of deflected droplets is adjustable, allowing a maximum droplet spacing of the order of fifty droplet diameters. The monodispersed droplet stream can be ignited by a heated coil located downstream from the electrostatic droplet deflector. After ignition the droplet is surrounded by a laminar diffusion flame.

![Figure 1: Experimental Setup and Droplet Stream Observed From 2D CCD Camera.](image)

The experimental setup is shown on figure 1. All measuring devices are radially disposed around a monosized monodisperser. Since 1988, Standard Rainbow Thermometry has been investigated [4,5,6 and 7]. This technique measures the temperature and size of individual droplets or of an ensemble of monodisperse droplets, formed by a piezo ceramic driven monodisperse droplet generator. Even though the technique has been applied to a polydisperse combustion spray through the use of a spatial filter [8], confidence could not be established there because of major problems. These are related to the temperature gradient inside the droplet [9,10,11], droplet nonsphericity [12] and a ripple structure that strongly perturbs the rainbow interference pattern, from which one deduces the droplet parameters [11].
3 Experimental results on a monodisperse droplet stream

The measurements of droplet size and temperature are based (Figure 2) on the interactions between a spherical droplet and a light ray [1]. In our case, a laser beam is focused along the axis of the droplet stream. The fringe scattering pattern (Figure 3) can be observed in forward direction. The fringe scattering is generated from an interference between the first reflection rays and refracted rays of order 0. The angular spacing is measured between two maximum stationary interference because of the high droplets frequency production (camera 2D CCD, Figure 1). The intensity distribution of the scattered light is described by the Mie’s theory, according to the value of the Mie parameter:

$$\alpha = \frac{D_g}{\lambda}$$  \hspace{1cm} (3)

where $D_g$ is the droplet diameter and $\lambda$ is the laser wavelength.

Droplet velocity

The droplets jet is visualized by shadowgraphy and the spacing parameter $S_g$ is measured from image processing. Knowing the droplet frequency $f$, the droplet velocity $V_g$ is determined from $V_g = S_g \cdot f$.

Droplet diameter

In our study, where $D_g$ is about 100µm and $\lambda$ is 514.5nm, the Mie parameter $\alpha >> 1$. In this case the equations of the geometrical optics can be used instead of the more complicated Mie theory. The geometrical optic theory is used to calculate the intensity distribution of the scattered light. The prediction of the fringe pattern by the equations of the geometrical optics is correct for scattering angles $\alpha$ between 30° and 80° in the forward direction.

The measurement of the angular interfering pattern $\alpha$ (Fig.3), for a forward scattering angle $\alpha$ allows to determine the droplet diameter following the relation:
\[
D_h = \frac{2}{\sqrt{\cos \frac{1}{2} + n \sin \frac{1}{2} / \sqrt{1 + 2n \cos \frac{1}{2} + n^2}}}
\]

\( n \) is the liquid refraction index. The forward-scattered fringe analysis can determine droplet sizing, without knowing the refractive index accurately. The optical signal is recorded on a linear CCD camera on 2048 pixels and the auto correlation is calculated in order to eliminate the background noise. With this method, the determination of the droplet size is done with an accuracy of 1.5%, however, the relative size variation measurement accuracy is expected to be better.

**Droplet Temperature**

For refracted ray with order larger than zero, the classical rainbow phenomena are observed in the backward direction. However only the first rainbow created by the rays of order 1 is strong enough to be easily detected. The position of the first rainbow is recorded by another linear CCD array (Camera 1, Figure 1). The Airy/Walker theory [13] explains that the position of the rainbow \( \Omega_{\text{airy}} \) (Figure 4) is also function of the liquid refractive index and droplet size:

\[
\Omega_{\text{airy}} = \Omega_{rg} + \frac{1.0845 \sqrt{2 \cos \Omega_{rg}}}{16D_g^2} \Omega_{rg}^{1/3}
\]

where \( \Omega_{rg} \) is the position of the rainbow predicted from the geometrical optics theory:

\[
\Omega_{rg} = 2 \pi \arccos \left( \frac{n}{n} \sqrt{1 - \frac{n^2 - 1}{3}} \right) \arcsin \left( \frac{n^2 - 1}{3} \right)
\]

and

\[
\sin \Omega_{rg} = \sqrt{\frac{(n^2 - 1)}{3}}
\]

The relation between refractive index and the droplet temperature is obtained by calibration [14].

**Figure 4** A typical rainbow pattern coming from a monodisperse burning droplet stream, recorded using a set-up similar to that of figure 1. The horizontal axis is inverse proportional to the scattering angle. A ripple structure is superimposed on the Airy fringe maxima \( \Omega \) and \( \Omega' \).

**Figure 4** shows a typical rainbow pattern recorded by the set-up depicted in figure 1. One can distinguish a low and a high-frequency interference structure, the Airy fringes (or supernumerary bows) and the ripple structure, respectively. They are formed by optical interference between external and internal reflections of the laser beam by the droplet surface. The first and second Airy fringe maxima are denoted as \( \Omega \) and \( \Omega' \), respectively.
Data inversion scheme for Standard Rainbow Thermometry

Figure 5 depicts the relationship between the droplet temperature and the primary Airy fringe maximum, $q_1$, for ethanol. A decrease of the ethanol droplet temperature of $10^\circ$C induces a shift of the geometrical rainbow angle of about $0.5^\circ$. This relationship results from the Airy theory for the rainbow [15], which includes the droplet diameter $D$, the wavelength of the laser light $\lambda$, and the refractive index $m$, the latter being a function of droplet temperature:

$$q_1 = q_{rg} + \frac{1.0845}{\sin q_{rg}} \frac{\cos q_{rg}}{16D^2}$$

(1)

where

$$\sin q_{rg} = \sqrt{\frac{m^2 - 1}{3}}$$

and

$$q_{rg} = 2 \arccos \left\{ \sqrt{\frac{m^2 - 1}{3}} \arcsin \left\{ \sqrt{\frac{m^2 - 1}{3}} \right\} \right\}$$

$q_{rg}$ is the rainbow angle according to geometrical optics and depends only on the refractive index. Consequently, this angle is an indicator for the droplet temperature and is thus an important parameter for the rainbow technique. Unfortunately, it cannot be measured directly from the rainbow pattern. It is deduced indirectly from $q_1$ and the droplet diameter $D$, using eq. (1). This droplet diameter can be obtained from any fringe spacing visible in the rainbow pattern itself, without knowing the refractive index accurately, a priori [16]. As such, the rainbow technique is a stand-alone device. If one requires a more accurate droplet sizing, one can connect the rainbow receiver with an alternative technique, e.g. based on forward-scattered fringe analysis [1].

Figure 5 Relationship between the droplet temperature and the scattering angle of the primary Airy maximum, $q_1$, for ethanol. The relationship shifts with respect to the droplet diameter.

To determine the extrema of the Airy fringes, such as $q_1$, one has to filter out the ripple structure (see figure 2). This interference structure gains importance for smaller droplets and thus influences the angular position of the Airy fringes, which renders the determination of the droplet temperature less accurate [16]. For fuel droplets smaller than $30\mu m$, the accuracy of the temperature measurement by Standard Rainbow Thermometry can therefore not be done better than about +/-6°C [11].

Figure 5 shows the evolution of the droplet temperature with time for a non-burning droplet stream. Two droplet sizes have been studied, $D=109\mu m$ and $D=220\mu m$. In both cases, the ambient temperature is $22^\circ$C. The droplet spacing is about 3 times its diameter at the outlet of the injector. The experimental results (Figure 6) of the rainbow technique are compared to results obtained by Laser Induced Fluorescence (LIF)
The rainbow experimental results are compared with results obtained from Laser Induced by Fluorescence (LIF developed by LEMTA, [15]). The results shown in figure 7, are in a good agreement in the case 1.

For the last two cases, the non homogeneity of refractive index inside the droplet is more significant. During the heating phase, the high temperature gradient inside the droplet induces a large error in the temperature measuring results. Particularly, this effect is more important for the beginning of combustion procedure where the droplet received a thermal shock effect after the ignition. The rainbow scattering technique gives a lower accuracy to determine the droplet temperature in this case.

### 4 Optical device improvement

Future research will be oriented toward two directions. First, the rainbow technique will be improved in the frame of a cooperation with CORIA (University of Rouen, Subtask 3-1-1 Light Scattering Prediction) by combining computations from generalized Lorenz Mie theory and experimental results by measuring position of high order rainbows to deduce the temperature gradient inside the droplet. The second direction concerns the cooperation with LEMTA (University of Nancy, Subtask 3-1-2 Development of Optical Techniques for Simultaneous Characterization of the Two Phases in Laboratory experiments) to develop a LIF technique to get the temperature field inside the droplet. Some interesting results are already obtained in the case of monodisperse droplet stream (MUSCLES First Experts Meeting, 10-11 dec. 2002, Naples).
5 Conclusions
The light scattering technique has been presented. The forward interference pattern determines the droplet diameter with a good accuracy (in order 2 µm). The mean temperature of droplet is calculated from the first rainbow angle. In the case of high temperature gradient inside droplet, the rainbow technique is not very appropriate. However, the evolution of the drag coefficient, the droplet evaporation rate can be determined without knowing precisely the droplet temperature. However, in such a stream, most of the time the droplets are sufficiently spherical, so that the droplet-shape influence can be neglected. When the droplet stream is burning, the temperature gradient within the droplet prevents a good measurement in the initial heating phase. For smaller droplets this temperature gradients very quickly disappear due to the smaller heat capacity, and a temperature accuracy of a few degree Celsius can be achieved. This is sufficient to apply the technique to the determination of dense spray characteristics.

6 References


