Global Rainbow Refractometry development for droplet temperature measurement in hostile environment

P. Lemaitre [1,2]; G. Grehan [2]; E. Porcheron [1]; P. Brun [1]; J. Malet [1]; P. Cornet [1]; J. Vendel [1]

(1) Institut de Radioprotection et de Sûreté Nucléaire
DPEA/SERAC
Laboratoire de Physique et de Métrologie des Aérosols et du Confinement.
BP 68,
91192 Gif-sur-Yvette cedex.
(2) UMR 6614 CORIA, Laboratoire d'Electromagnétisme et Systèmes Particulaires
Site Universitaire du Madrillet
Avenue de l' université BP 12
76 801 Saint Etienne du Rouvray Cedex
Corresponding author: phone: 33 (0)1 69 08 91 24, Fax: 33 (0)1 69 08 97 36
E-mail: Pascal.Lemaitre@irsn.fr

In order so study the heat and mass transfers between the spray droplet and the atmosphere for thermohydrauliques conditions representative of a severe accident in a Pressure Water Reactor the IRSN developed the TOSQAN facility. This paper is devoted to present our work, upon the qualifications of the global rainbow refractometry used for droplet temperature measurement.

1. Introduction

During the course of an hypothetical severe accident in a Pressure Water Reactor (PWR), hydrogen can be produced by the reactor core oxidation and distributed into the reactor containment according to convection flows, water steam wall condensation and interaction with the spraying droplets. In order to assess the risk of detonation generated by a high local hydrogen concentration, hydrogen distribution in the containment has to be known. The TOSQAN experimental program has been created to simulate typical accidental thermal hydraulic flow conditions in the reactor containment and to study different phenomena such as water steam wall condensation in the presence of non-condensable gases.

TOSQAN facility is a large vessel ($7m^3$) suitable for optical diagnostics such PIV, LDV and Spontaneous Raman Scattering which are already operational on it [1].

In order to measure droplet temperature, different non-intrusive techniques where envisaged like LIF [2], infrared thermograthy, and global rainbow refractometry. According to our experimental constraint, we have focused on this last technique.

The aim of this work is to present global rainbow refractometry [2; 4; 6] technique to measure the mean size and temperature of falling droplets. This work is divided into four parts, the first one is devoted to explain the principle of the technique in the second one we will present the program we developed and the simulations we realized in order to quantify the effect of different parameters on temperature and diameter measurements. In the third part we will present our experimental setup, and finally we will present our results obtained with global rainbow refractometry.

2. Principle of the technique

The rainbow is a phenomenon that occurs for example when a single droplet intercepts a laser beam (fig. 1). The standard rainbow refractometry is a non-intrusive technique for measuring size and temperature of a single droplet [3]. This technique is based on the detection of the rainbow issued from the interference between one time internally reflected rays and externally reflected ray (fig. 1). This technique suffers of major problems related to temperature gradients inside the droplet [4], droplet non-sphericity [5]. In addition, especially for small particles, the ripple structure issued from the interference between internally and externally reflected rays strongly disturbs the rainbow pattern. It is to overcome the last two problems that van Beeck introduced the global rainbow refractometry. The principle of the technique is to superimpose the rainbow pattern issued from about a hundred [7] droplets, so that the ripple structure totally disappears. This phenomenon was first observed by Roth [6] for a single droplet with diameter variations. The non-spherical droplets, as far as they are randomly oriented, will interfere destructively and create a uniform background [7] that will not disturb the measurement anymore.

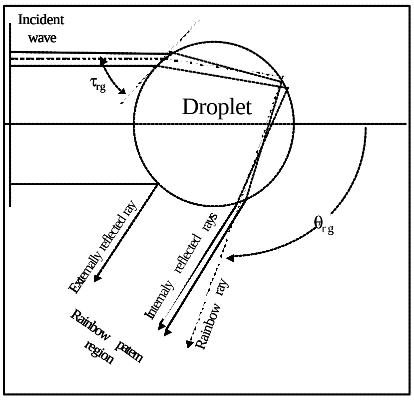

Figure 1. Rainbow phenomenon

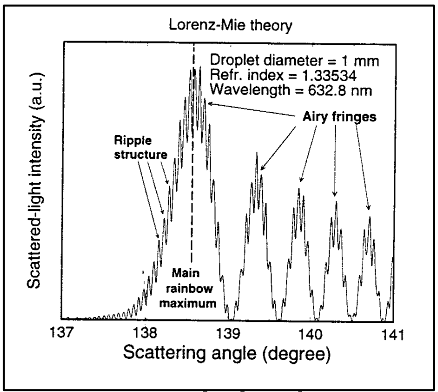

Figure 2. Standard rainbow pattern

3. Simulations of the global rainbow

To have a good understanding of the global rainbow pattern in order to be able to invert it to a mean temperature and diameter measurement, we made a Fortran program to compute the global rainbow pattern. As mentioned before the global rainbow is not sensitive to the ripple structure because it is totally dammed by small variations of the droplet diameter. As a consequence, the Airy theory is suitable to compute the light scattered intensity (Ω^2_{rw}) as a function of the scattering angle θ (eq. 1).

$$\Omega^2_{rw}(z)=\left(\int_0^{\infty}\cos\frac{\pi}{2}(z\eta-\eta^3)d\eta\right)^2=\left(2\left(\frac{-12}{\pi^2}\right)^{-1/3}Ai\left[\left(\frac{-12}{\pi^2}\right)^{-1/3}z\right]\right)^2 \quad (1)$$

$$z(\theta)=-(\theta-\theta_{rg})\left(\frac{16\tan\tau_{rg}\sin^2\tau_{rg}D^2}{\lambda^2}\right)^{1/3}\frac{180}{\pi} \quad (2)$$

Where θ_{rg} and τ_{rg} are represented on figure 1.

So, we are able to compute the global rainbow by summing the light scattered by every single droplet (eq. 3).

$$Globow(q) = \sum_{i}^{i_{max}} \Omega^2(di, q) d^{7/3} \qquad (3)$$

The $d_i^{7/3}$ factor describes the dependency of the scattered light intensity to the droplet diameter. As long as all the droplets are perfectly spherical we can compute the global rainbow pattern.

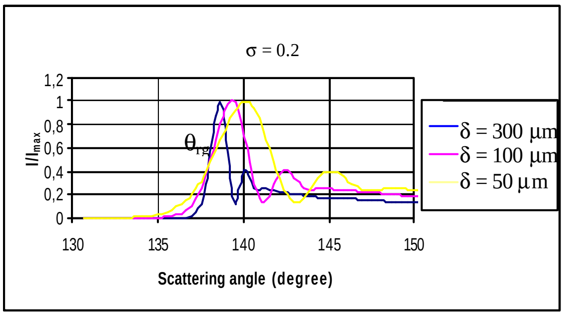

Figure 3. Simulations of the global rainbow.

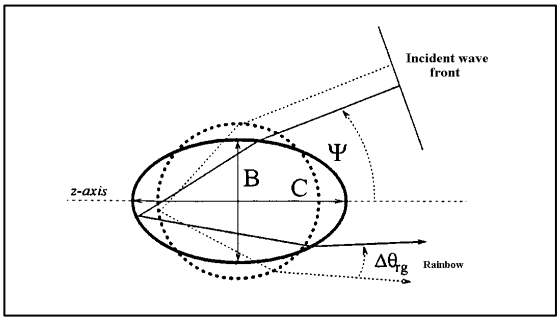

Figure 4. Effect of droplets non-sphericity on the rainbow.

Figure 3 presents the influence of droplet granulometry upon global rainbow patterns and shows that the curves are superimposed at the geometrical rainbow angle θ_{rg}.
This angle is very closed to the first inflexion point of the global rainbow. So as long as all the droplets are perfectly spherical we can deduce their averaged temperature by searching the angular position of the first inflexion point of the global rainbow, or more precisely using equations 4 and 5.

$$D_{Airy} = 531.555\, l \cdot (q_{\inf 1} - q_{\inf 2})^{-3/2} \qquad (4)$$

$$q_{rg} = q_{\inf 1} - 13.91 \left(\frac{l}{D_{Airy}} \right)^{2/3} \qquad (5)$$

To take into account the impact of nearly spherical droplets $\left(h = \frac{B}{C} < 0.4\%\right)$ on the scattered global rainbow we can compute their contribution using the Moebius theory. This theory assumes that the rainbow pattern issue from a non-spherical droplet will be shifted of a $\Delta\theta_{rg}$ quantity computed using equation 6.

$$\Delta q_{rg} = 16 \left(\frac{C-B}{C+B} \right) \frac{\cos t_{rg}}{m} \sin^3 \left\{ \arccos \left(\frac{\cos t_{rg}}{m} \right) \right\} \cos(q_{rg} - 2y) \qquad (6)$$

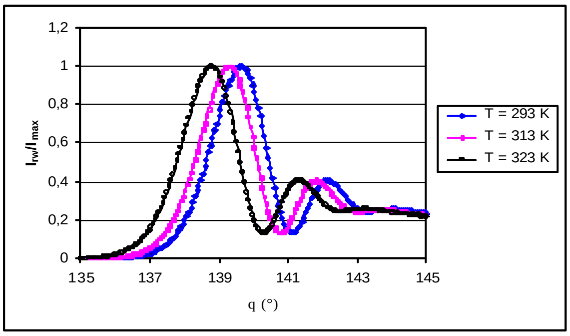

Figure 5. Effect of droplet temperature on the global rainbow pattern

In our application of the global rainbow refractometry, there is a relationship between the droplets size and temperature in the probed volume. We now interest in simulating the global rainbow scattered from spray with a lognormal size distribution (representative of the spray that will be used in TOSQAN facility). We suppose an arbitrary relationship between droplet size and refractive index, and we search the meaning of the mean temperature deduced.

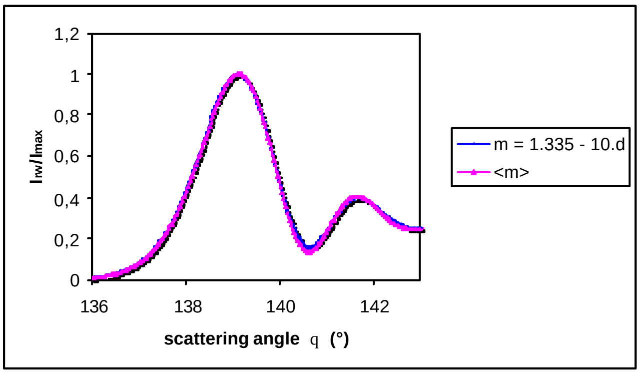

Figure 6. Effect of an arbitrary size temperature relationship on the temperature deduced

We can see on this simulation that if we suppose that all the droplets have the same temperature equal to <m> (<m> is computed using equation 7), the simulated global rainbows are superimposed around θ_{inf1} and θ_{inf2} which are the characteristic angles used for the inversion. Thus, the refractive index deduced from such global rainbow will be equal to $< m >$.

$$<m> = \frac{\int_0^\infty m(d).f(d).d^{7/3}dd}{\int_0^\infty f(d)\,d^{7/3}dd} \qquad (7)$$

The $d_i^{7/3}$ factor describes the dependency of the scattered light intensity to the droplet diameter (as in equation 3). This result means that the temperature deduced is more influenced by largest droplets.

4. Experimental set-up

Our experimental set-up sketched on figure 7 is composed of a laser beam issued from an argon laser (λ = 514.5 nm) and transmitted via a monomode optical fiber. Measurements are performed on a full cone spray at 20 cm from the nozzle (UniJet TG03, from Spraying System).

This nozzle has been characterized by laser sheet visualization (figure 8) and PDA under the same conditions (figure 9).

The optical set up for global rainbow collection is composed of two large diameter plano-convex lenses, a camera and a pinhole. The first lens has a 1000 mm focal length and is placed at 1 m from the probed volume. The second lens placed just behind the first one has a 250 mm focal length. The pinhole is situated at the image plan of the second lens; this pinhole allows us to spatially select a short volume of measurement to avoid an angular spread of the global rainbow.

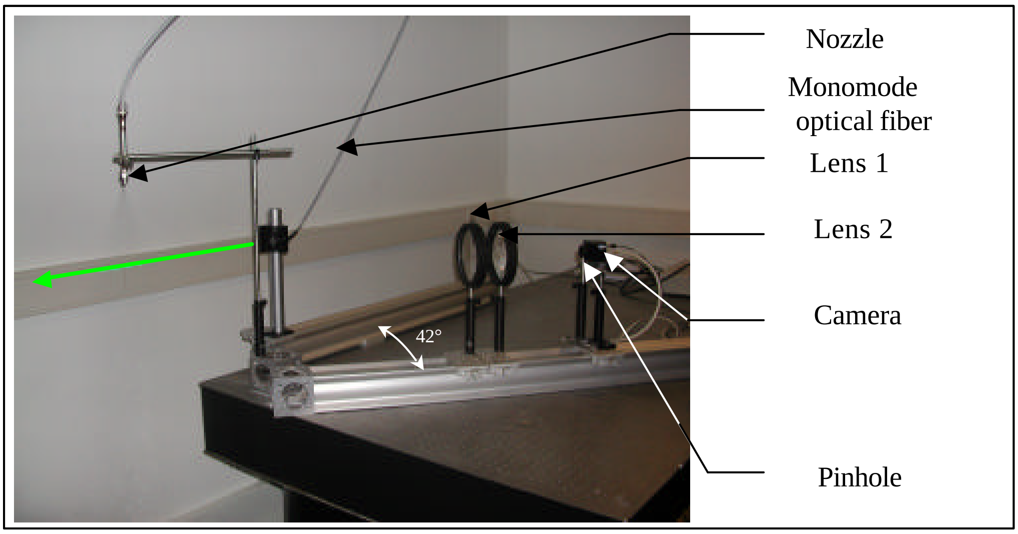

Figure 7. Experimental set-up

To calibrate the magnification factor of the camera a millimeter transparent paper is placed on the first lens. So that, we are able to deduce the relationship between the pixel number and the scattering angle θ. To make sure that there are enough droplets in the probed volume, for a statistically representative sample of the spray, we achieve a temporal summation of the signal.

Figure 8. Visualisation of spray of the TG03 injectors

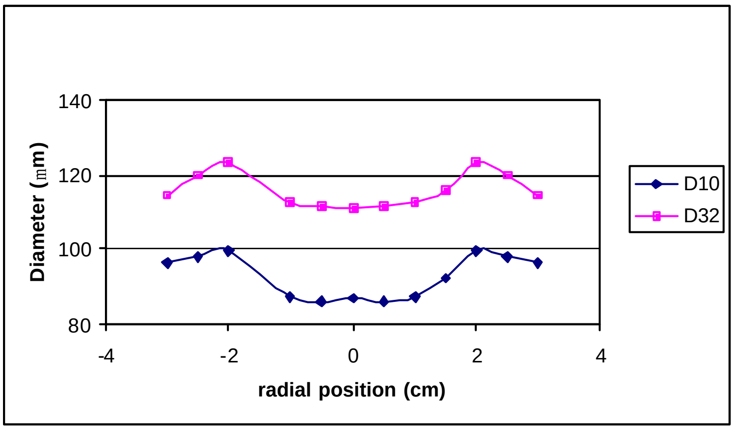

Figure 9. Droplet size profile of the TG03 injector at 20 cm from the nozzle using PDA.

5. Global Rainbow Experimental results

With this experimental set-up, we are able to acquire two-dimensional images of the global rainbow (figure 10). For eliminating the high frequencies due to the noise in order to have a better signal quality, we first achieve a FFT of the collected signal, we cut the high frequencies and then we realise the FFT inverse (figure 11).

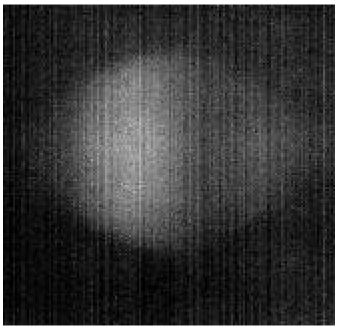

Figure 10. Global rainbow Pattern

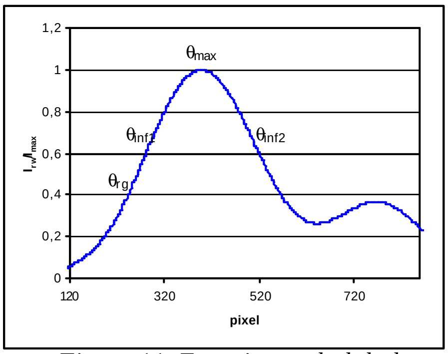

Figure 11. Experimental global rainbow pattern

Then, we wanted to have a comparison of the mean droplet temperature measurement using the global rainbow refractometry with another technique at different droplet temperatures. Our only issue was to achieve global rainbow measurements at 20 cm from the nozzle with different injection temperatures (from 293 K to 360 K). We measured with a thermocouple the mean droplet temperature by collecting the water spray in an isolated vessel located at the probed volume.

Figure 12 shows the relationship between the pixels of the first inflexion point of the global rainbow as a function of the temperature measured using thermocouple. This result is important because the relationship between θ_{rg} and the droplet temperature is linear between 293 K and 307 K.

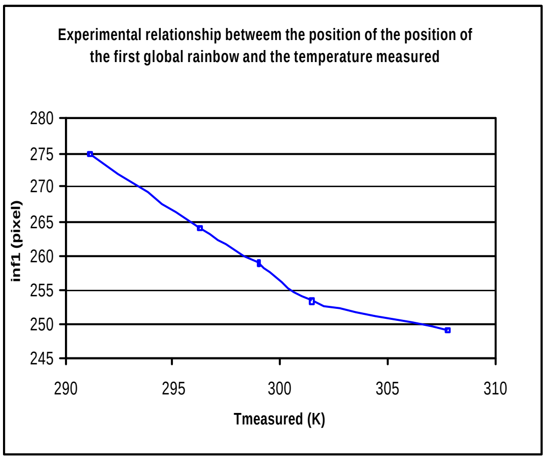

Figure 12. Experimental relationship between the positions of the first inflexion point and the mean droplet temperature measured.

In the future, we plan to apply the algorithm proposed by Vetrano [8], that consists in finding spray parameters. The principle is to minus the difference between the experimental and the simulated global rainbow to avoid mistakes on temperature measurements induced by droplet non-sphericity.

6. Conclusion

The simulations presented allowed us to qualify the global rainbow performances to measure droplet mean temperature. Then we developed an experimental setup to achieve global rainbow image acquisitions.

The simulations allowed us to invert theses images to mean droplet temperature too.

This technique is now going to be implanted onto the TOSQAN facility.

List of symbols

Ai	Airy function
D10	Arithmetic mean diameter
D32	Sauter mean diameter
Globow	Global rainbow intensity
PDA	Phase Doppler Anemometry
δ	Mean diameter of the log normal distribution
θ	Scattering angle
σ	Standard deviation
η	Sphericity factor
λ	Wavelength of the laser beam

Subscripts

Inf1	Relative to the first inflexion point
Inf2	Relative to the second inflexion point
rg	Relative to the geometrical rainbow

REFERENCES

[1] Porcheron E, Thause L, Malet J, Cornet P, Brun P, Vendel J, Simultaneous application of Spontaneous Raman Scattering and LDV / PIV for steam / air flow characterization, 10th International Symposium on Flow Visualization, Kyoto, Japan, 26-29 august 2002.

[2] Lavieille, Etude experimentale du comportement aérothermique de gouttes en écoulement, réactif ou non, par utilization de fluorescence induite par laser à deux couleurs. Ph.D - thesis, Université Henry Poincaré de Nancy I, ISN 91-386-0557-9. (1997) .

[3] van Beeck J P A J , Rainbow phenomena, developpement of laser based non intrusive technique for measuring droplet size, temperature an velocity. Ph.D - thesis, Eindoven University of Technology, ISN 91-386-0557-9. (1997) .

[4] Corbin F, Garo A, Gouesbet G, Grehan G, réfractométrie d'arc-en-ciel : application au diagnostic des gouttes avec gradient d'indice, in Recueil des actes du 5e congrès Francophone de Vélocimétrie Laser, Rouen, France, 1996, E1.1 - E.1.80.

[5] van Beeck J P A J, Riethmuller M L, Nonintrusive Measurements of Temperature and Size of Single Falling Raindrops.App.Opt.34 (1995) 1633-1639.

[6] Roth N , Andens K, Frohn A, Refractive-Index Measurement for the Correction of Particle sizing methods.Appl.Opt30(1991) 4946-4965 .

[7] van Beeck J P A J, Giannoulis D, Zimmer L and Riethmuller M L, Global Rainbow thermometry for average temperature measurement of spray droplet.10th International Symposium on Applications of Laser Techniques to Fluid Mechanics. Lisbon (2002).

[8] Vetrano M R, van Beeck J P A J et Riethmuller M L, Validation expérimentale de simulation par la méthode globale par arc-en-ciel. 8ème Congrès Francophone de Vélocimétrie Laser. Orsay (2002).