INTERFEROMETRIC LASER IMAGING DEVELOPMENT FOR DROPLETS SIZING (ILIDS) IN HOSTILE ENVIRONMENT

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ABSTRACT In order to study the heat and mass transfers between the spray droplets and the atmosphere for thermal-hydraulics conditions representative of a severe accident in a Pressure Water Reactor, the French Institute for Radioprotection and Nuclear Safety (IRSN) developed the TOSQAN facility. This paper is devoted to present the development and qualification of the ILIDS technique, in order to measure droplets size in a large containment vessel.

KEY WORDS: Optical diagnostic, droplet size, ILIDS

1 INTRODUCTION

During the course of a hypothetical severe accident in a nuclear 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 spray 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 of the reactor containment and to study different phenomena such as water steam condensation on droplets in presence of non-condensable gases.

This large experimental facility (7 m$^3$) is suitable for optical diagnostics therefore the PIV, LDV, Spontaneous Raman Scattering and global rainbow refractometry are already implemented on it [6, 7].

In order to measure droplets size, different non-intrusive techniques were envisaged like Phase Doppler Anemometry (PDA) [1] and interferometric Laser Imaging for Droplets Sizing (ILIDS) [2]. Because of TOSQAN geometrical conditions, we adopted the last one.

Our work on the Interferometric laser imaging technique is presented in this paper that is divided into four parts. The first one is devoted to explain the principle of the technique, and how this phenomenon occurs. This part is illustrated with Lorenz-Mie Theory (LMT) simulations.

In the second part, we present the qualification of the ILIDS technique using comparisons with PDA measurements performed on a full cone spray.

In the third part, we present the implementation of the technique on the TOSQAN experiment and the associated droplets measurements.

On addition to that, in PWR, spray droplets are used for airborne aerosols washout. If the aerosols are soluble, the washout induces variations in the imaginary part of the droplets index of refraction. This increase of imaginary part of the index of refraction induces a decrease of the fringes contrast.

Thus, we present in this last part a reference experiment that highlights the feasibility of the measurement of the imaginary part of the droplets index of refraction using the ILIDS technique.

2 OPTICAL PRINCIPLE AND GENERAL BACKGROUND

2.1 General principle

In this first part of the paper, we recall the principle of Interferometric Laser Imaging for Droplets Sizing ILIDS, an optical diagnostic dedicated to measure droplets size. This out-of-focus imaging diagnostic has first been introduced by Glover [2]. It allows to determine droplets size in a poly-dispersed spray. A model based on geometrical optics is generally enough accurate to describe this technique which is based on the analyse of the interferences generated by externally reflected (p = 0) and refracted rays p = 1 (Figure 1).

![Figure 1. Out-of-focus imaging principle](image-url)
In the focal plane these two scattering modes generate bright spots called glare points (Figure 2). The size of the particle can be determined by measuring the distance between these two points [9].

The distance between these glare points is a few tens microns, thus it requires a very high resolution to determine precisely the droplets size. Another way to determine the droplets size is to defocus the optical set-up. Thus, fringes appear due to interferences between reflected and refracted rays (p = 0 and p = 1, Figure 3).

The relationship linking the angular frequency of the fringes \( f \) and the droplet size \( d \) can be determined using geometrical optics, by calculating the optical path difference between reflected and refracted rays.

\[
d = 2\lambda f \left( \cos\left(\frac{\theta}{2}\right) + \frac{m\sin\left(\frac{\theta}{2}\right)}{\sqrt{m^2 - 2m\cos\left(\frac{\theta}{2}\right) + 1}} \right)
\]  

(1)

In this equation, \( m \) is the ratio between the internal and external index of refraction, \( n_e \) the index of refraction of the medium outside the droplet, \( \lambda \) is the wavelength of the incident wave and \( \theta \) the scattering angle. 

In order to validate the use of geometrical optics, we make comparison with the Lorenz Mie Theory (LMT), which consists in resolving analytically the Maxwell equations inside and outside the droplet [5] (Figure 4).

We thus validate the use of geometrical optics near the scattering angle of 80°.

In order to have the best contrast of the fringes, we compute the intensity of each scattering mode (by computing the Fresnel coefficients) and look for the angle at which we have the same intensity for reflected and refracted rays. On Figure 6, p corresponds to the scattering mode. Thus, p = 0 corresponds to externally reflected ray, p = 1 to refracted ray, p = 2 to internally reflected ray and so on.

We observe on these simulations that for an incident wave perpendicularly (respectively parallely) polarized, the intensities of reflected and refracted rays are equal for a scattering angle of 67° (respectively 80°). On addition to that, we observe that whatever the polarization or the incident wave, the intensity of refracted rays falls down to zero at about 82°. However, the LMT still predicts fringes, for an incident wave parallely polarized (Figure 7).

Thus, near \( \theta = 90 \)°, the geometrical optics model is not available anymore. A special calibration curve needs to be computed using LMT. This calibration curve is presented on Figure 8.
It is of interest to notice that even if the geometrical optics model is not suitable to correctly predict the intensity of the scattering modes near 90° (Figure 6), the LMT simulation presented on Figure 8 shows that the equation 1 deduced from the geometrical optics model is still suitable to compute the relationship between the droplets diameter and the angular frequency of the fringes. This observation is very important because in our application of out-of-focus imaging, the measurement will be achieved at a scattering angle of 90°, due to the limitations of the optical accesses of the TOSQAN facility.

### 2.2 Influence of the droplets temperature

For our measurements inside the TOSQAN facility, heat and mass transfers occur between the droplets and the gas. As a consequence, droplets temperature is not precisely known during the out-of-focus measurement. In this part, we interest in the sensitivity of the relationship between the angular frequency of the fringes and the droplets size, for different droplets temperature, thus for different index of refraction (Figure 9). Thus, we compute the theoretical relationship between the angular frequency and the droplets size near an off axis angle of 80° but for different droplets temperature using LMT.

Table 1 presents the relationship linking water index of refraction and its temperature [10].

<table>
<thead>
<tr>
<th>T (°C)</th>
<th>m</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>1.3309</td>
</tr>
<tr>
<td>90</td>
<td>1.3223</td>
</tr>
<tr>
<td>100</td>
<td>1.3196</td>
</tr>
</tbody>
</table>
Thus, we observe on this simulation that the index of refraction variations induced by the droplets heating does not disturb the relationship between the droplets diameter and the frequency of the fringes. Consequently, this technique is able to give a precise particle size measurement, without any previous knowledge of its temperature.

3 EXPERIMENTAL QUALIFICATION OF THE OUT-OF-FOCUS TECHNIQUE

With the object of validating the technique, comparisons are achieved with PDA measurements on a full cone spray. These measurements are achieved using a commercial DANTEC PDA and compared with the out-of-focus imaging technique. The PDA measurements are achieved at an off axis angle \( \theta \) equal to 72 °, and with an incident light parallelly polarized. This angle corresponds to the Brewster angle for water. At that angle the intensity of reflected light falls to zero (Figure 6).

This comparison is performed on the spray produced by a TG_3.5 nozzle operating with a water mass flow rate of 30 g.s^{-1}, at a distance of 1 m from the orifice of the nozzle. These measurements are not achieved simultaneously, but with exactly the same temperature and pressure conditions for the injected water and for the surrounding gas \(T_{\text{inj}} = 293 \, K, P_{\text{inj}} = 5 \times 10^5 \, Pa \quad T_{\text{gas}} = 293 \, K, P_{\text{gas}} = 1 \times 10^5 \, Pa\).

Thus, we make sure that the atomization process is exactly the same and on addition to that we ensure that, we have exactly the same droplets vaporization flux. As a consequence, the measurement should be exactly the same. The droplets size distribution measured with the ILIDS technique is presented on Figure 10.

The histogram of diameter is well fitted using a log-normal distribution. The arithmetic mean diameter \(D_{10}\) and the Sauter mean diameter \(D_{32}\) are respectively equal to 130 µm and 190 µm. The arithmetic mean diameter and the Sauter mean diameter are respectively computed using equation 2.

\[
D_{ij} = \frac{\int_0^\infty d^i \cdot f(d)dd}{\int_0^\infty d^j \cdot f(d)dd}
\]

The histogram measured with the PDA technique can be as well fitted using a log-normal distribution, but the arithmetic mean diameter of the droplets is now equal to 115 µm, which represents a difference of 12 %. This difference might seem important but it is mainly explained by the difference of measurement range of these two techniques, which is more important for the ILIDS technique. To confirm this hypothesis, we impose artificially to ILIDS measurements the same measurement range than for PDA ones, the new arithmetic mean diameter computed is 116 µm (115 µm with the PDA). This allows us to validate our previous hypothesis on the origin of the difference between the measurements using these two techniques, and finally to validate the ILIDS measurement.

4 MEASUREMENT INSIDE THE TOSQAN EXPERIMENT

4.1 Experimental set-up

As mentioned in the introduction, the TOSQAN experimental program has been created to simulate typical accidental thermal hydraulic flow conditions of the reactor containment and to study different phenomena such as water steam condensation on droplets in presence of non-condensable gases.
This large experimental facility presented on Figure 11 is 4 m height, with an internal diameter of 1.5 m. Droplets can be injected in the upper part of the experiment using a single nozzle.

On addition to that, the experiment is equipped with 14 viewing porthole windows, placed at 90 ° the one from the other on four levels (Figure 12).

The optical set-up adopted to achieve droplets size measurements inside the TOSQAN experiment is presented on Figure 12. The coherent light necessary for this technique issues from a pulsed Nd : Yag laser (λ = 532 nm). The laser beam is then extended using a cylindrical lens in order to create a laser sheet. The width of this laser sheet is about 1 mm. As the TOSQAN experiment is equipped with viewing windows with 90 ° angle the one from the other, we work with an incident laser beam parallely polarized in order to have the best fringe contrast (part 1.1).

The cameras used are High-Sense CCD cameras with 1024x1280 pixel². Inside the TOSQAN experiment, the droplets density is important, thus this creates overlapping between the fringes pattern from different droplets. That overlapping (Figure 13) makes the measurement of the fringe frequency difficult to perform.

Thus, to simplify the processing of the measurement, a second camera is used (Figure 12).

### 4.2 Image processing

The second camera is focused in the laser sheet plan and thus observes the glare points of the droplets. These two cameras are placed in order to observe the same field. The focused camera detects the glare points using the same algorithm as for the PIV technique. Thus, knowing the degree of defocusing (γ), the focal length of the collecting system (f) and the dimension of the optical aperture (L), we compute the dimension (T) of each interferometric images in the out-of-focus image $T = L \frac{γ}{f}$.

As a consequence, we can determine the non overlapping zones using the position of the glare points on the focused image and the size of the defocused image $T$.

Knowing the non overlapping areas, on the defocused image we achieve a 2 Dimensional Fast Fourier Transform (2D FFT) to determine the fringes frequency. Finally, using the calibration curve determined with the help of the LMT we deduce the droplets diameter.

### 4.3 Experimental results

This set-up has been applied to the TOSQAN experiment during the 101 spray test [8]. This one is included in a benchmark [3] dedicated to qualify the capacity of different CFD codes to simulate the transfers between droplets and gas for thermal-hydraulics conditions representatives of a hypothetical nuclear accident in a PWR.

The thermal-hydraulic conditions during the measurement are presented in Table 2.

<table>
<thead>
<tr>
<th>$T_{gas}$ (K)</th>
<th>$P_{vap}$ (bar)</th>
<th>$P_{air}$ (bar)</th>
<th>$Q_{spray}$ (g.s⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>378.5</td>
<td>1.15</td>
<td>1</td>
<td>30</td>
</tr>
</tbody>
</table>

Figure 14 presents an example of defocused image obtained with this experimental set-up.
The analysis of about 20 images allows us to determine the droplets size distribution, presented on Figure 15.

These measurements are useful in order to characterize heat and mass transfer processes between the droplets and the gas [8].

## 5 Extension of the Technique

During the course of a hypothetical accident, with fusion of the core, radioactive aerosols might be produced and distributed into the containment vessel. The spray release is one of the issue to collect these harmful particles, and thus to washout them from the containment vessel [4].

With the aim of characterizing the phenomena involved in the aerosol collection by a droplet (inertial impaction, interception, phoretic effects) [4], it would be useful to be able to measure the mass of aerosols collected by the droplets.

If we interest in soluble aerosols, their collect by the droplets induces a variation of the imaginary part of the index of refraction of the droplets. A solution to quantify the number of aerosols collected by the droplets is thus to measure the imaginary part of its optical index.

As mentioned in part 1, the contrast of the fringes depends on the ratio of intensity of the scattering mode (p = 0 and p=1) and it is maximum when these two modes are equal. Moreover, when the droplets are absorbents, the intensity of the mode p = 1 decreases and, as a consequence, for the same optical configuration there is a modification on the fringe contrast.

Thus, it would be of interest to find an optical configuration for which it exists a biunivocal relationship between the contrast of the fringes and the imaginary part on the optical index ($k$).

Different simulations were achieved using the LMT, for different scattering angles and different polarizations of the incident wave.

The influence of the imaginary part of the optical index is highlighted on Figure 16. This simulation is achieved with an incident wave perpendicularly polarized.

We first notice that the frequency of the fringes is not modified by changes in the imaginary part of the optical index. Thus, the droplets size measurement can still be determined using exactly the same method as seen previously. Figure 17 presents the relationship between the imaginary part of the optical index and the contrast of the fringes.

With this optical configuration, we observe a biunivocal relationship between the contrast of the fringes and the imaginary part of the optical index. Thus, it would allow to give a quantitative information of the number of aerosols collected by the droplets.
6 Conclusion

In this paper, we present the implementation of the ILIDS technique on the TOSQAN experiment which is a large experimental vessel. The validation of the method is also performed using comparisons with PDA measurements. Then measurements are presented inside the TOSQAN experiment during a spray test. Finally an extension of the method is proposed in order to be able to measure the imaginary part of the optical index, and thus to characterize aerosol collection processes by droplets. In the future, we plan to achieve simultaneously ILIDS and backlighting measurements on a drop-by-drop jet in order to validate the ILIDS measurement on each single drop. On addition to that, we plan to perform an analytical optical set-up allowing to validate experimentally the method proposed in the fourth part, to measure droplets imaginary part of the optical index.

7 Nomenclature

Latin

\( d \) : Diameter \[ \text{[m]} \]
\( f \) : Angular frequency \[ \text{[deg}^{-1}] \]
\( T \) : Temperature \[ \text{[°C]} \]
\( P \) : Pressure \[ \text{[Pa]} \]
\( Q \) : Mass flow rate \[ \text{[kg}.\text{s}^{-1}] \]
\( f(d) \) : Probability density function \[-\]
\( n_e \) : Index of refraction outside the droplet \[-\]
\( n_i \) : Index of refraction inside the droplet \[-\]
\( m \) : \( m = \frac{n_i}{n_e} \) \[-\]
\( k \) : Imaginary part of the optical index \[-\]
\( p \) : Scattering mode \[-\]

Greek

\( \theta \) : Scattering angle \[ \text{[deg]} \]
\( \lambda \) : Wavelength \[ \text{[m]} \]

8 References


