

SLIPI-LIF/Mie for droplet sizing in 3D: A study of calibration variations as a function of injection pressure

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ABSTRACT

SLIPI-LIF/Mie (standing for Structured Laser Illumination Planar Imaging Laser-Induced Fluorescence / Mie scattering ratio) is a well-recognized technique for providing spatially resolved 2D measurement of the droplet Sauter Mean Diameter (SMD) within optically dense sprays. This can indeed be achieved as the SLIPI approach allows suppressing the unwanted intensity contribution of multiple light scattering. For droplet sizing, a calibration procedure is then required, where the LIF/Mie intensity ratio as a function of the SMD is deduced, using for example Phase Doppler Anemometry (PDA). We show here that for a given operating condition a single calibration curve is reliable at any position in the spray. However, we observe that this calibration is dependent on the liquid injection pressure. Thus, the calibration curves must be modified for each injection pressure employed. The knowledge of this calibration curve variation is essential during any parametric spray study, where the operating conditions are modified. The need of performing the calibration procedure in the exact same conditions than for the experimental measurements is shown here. A correction of the calibration curve as a function of injection pressure is also proposed in this article. Note that further investigations will be needed to understand the observed trend. Finally, the methodology has been applied over a series of 15 planes spaced by 2 mm to reconstruct the droplet SMD in 3D.

1. Introduction

The quantitative characterization of the spray region, where spherical droplets are already formed, remains very challenging at high optically depths Mishra et al. (2016). Laser based techniques used for temperature or droplet size measurements suffer from unwanted effects related to light scattering and absorption phenomena. For the past decade, techniques based on structured illumination have made it possible to solve visualization problems related to multiple scattering Berrocal et al. (2012). Indeed, the SLIPI-LIF/Mie ratio technique allows the visualisation as well as the droplet Sauter Mean Diameter in either transient Koegl et al. (2019) or steady sprays Mishra et al. (2020). SMD measurements are based on the ratio of the LIF and Mie optical signals. The use of a structured illumination allows in the case of optically dense spray to get rid of the phenomenon of

multiple light scattering and therefore to obtain reliable data. However, these measurements require a calibration in size of the measurement, generally carried out using PDA measurement. Corber et al. (2020) showed that an universal calibration could not be used since the LIF/Mie ratio could depend on external conditions (ambient pressure in their case). We propose here to collect the LIF and Mie signals using a telecentric lens in order to avoid the effect of the collection angle of the signal. In addition, a study conducted on a steady spray for different injection pressure are performed to determine the dependence of the LIF/Mie ratio as a function of this parameter.

2. Experimental setup

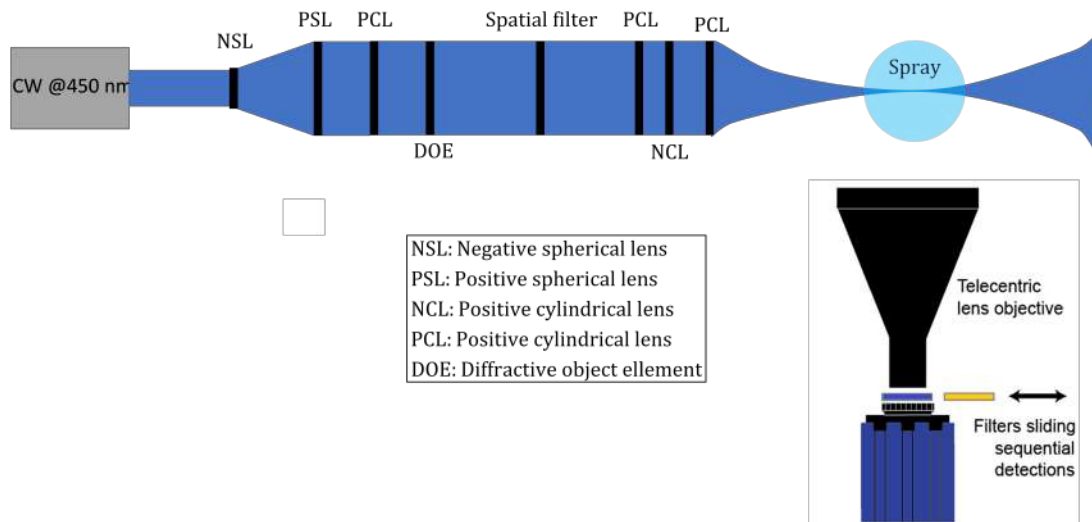


Figure 1. Top view of the optical setup of the SLIPI LIF/Mie ratio for droplet sizing. A continuous wave laser @450 nm is used to produced a modulated laser sheet of 12 cm length and 1.5 mm thick.

SLIPI is an imaging technique for suppressing multiply scattered light in optically dense sprays initially based on using three individual images of structured light with different phases. With SLIPI the laser sheet is modulated by a sinusoidal pattern. Thus, the singly scattered photons keep the modulated signature, however, the multiply scattered photons will lose the modulated pattern. Historically, averaged SLIPI-imaging used three intensity-modulated images (sub-images) corresponding to the phases 0° , 120° and 240° . Then, SLIPI image can be created after taking the root mean square of the differences of the modulated images. 3pSLIPI requires the physical displacement of the grating that create the modulated image. In order to reduce the acquisition time, we here used one phase SLIPI. The experimental setup can be divided in two-part, (1) excitation and (2) acquisition (Figure 1). The excitation is made using a CW laser @450 nm and the modulated laser sheet of 12 mm height is formed using the optical setup presented in Figure 1. This experimental setup used a diffractive optics element (DOE of 5 l/mm) to generate the modulation. Images are acquired sequentially on a Scmos camera (Andor Zyla 5). LIF (long path at 520 nm) and MIE ($450 \text{ nm} \pm 5 \text{ nm}$) signal are separated using filters mounted on a sliding element. The LIF

spectral band was chosen in order to maximise the LIF signal of Fluorescein when excited at 450 nm. The measurement was made using an industrial spray (Tetrapak injector with a cone angle of 45°). The water was previously seeded using fluorescein at a concentration of 5×10^4 mol/L.

3. Comparisons between 1p and 3p SLIPI

First, in order to decrease the measurement time needed from three phases SLIPI (3pSLIPI) measurement due to pattern displacement, 1p and 3p approach were compared. 3pSLIPI measurement are obtained by the displacement of the pattern to three phases, 0°, 120° and 240° (Figure 2). The resulting SLIPI images is then:

$$I_{3p} = \frac{\sqrt{2}}{3} \sqrt{(I_0 - (I_{120})^2 + (I_0 - (I_{240})^2 + (I_{120} - (I_{240})^2)} \quad (1)$$

With I_0 , I_{120} and I_{240} images from a given pattern phases. Example of the images obtained for an injection pressure (P_{inj}) of 20 bars is presented in figure 2. The 1pSLIPI approach consist of reconstructing SLIPI image from one modulated sub-image. Different technique can be used to reconstruct the image, one called "peak detection" Mishra et al. (2020) and one called "Spatial lock-in algorithm" Mishra et al. (2020). In this study, the "Spatial lock-in algorithm" is used to allow a good demodulation of the 1pSLIPI images. It should be noted that by doing so, the spatial resolution of the 1pSLIPI image is reduced compared to that the one obtained from 3pSLIPI. An example of the 1pSLIPI and 3pSLIPI LIF/Mie image are shown in Figure 3. Comparisons between 1p and 3pSLIPI image show that the 1p images appear an average image of the 3P image without losing any spray structure. LIF/MIE data plot on the same arbitrary line from both 1p and 3pSLIPI images are presented in Figure 3. As observed, with one phase approach, data are averaged compared to the three phases images and less deviation of the LIF/Mie ratio are then observed. Thus, in order to achieve rapid 3D reconstruction of a steady spray, the 1p method will be chosen in the following.

4. Sizing calibration

It is possible to show that the ratio of LIF and Mie images is proportional to the Sauter Mean Diameter.

$$R_{LIF/MIE} = \frac{I_{LIF}}{I_{MIE}} = \frac{K_{LIF} \sum_{i=1}^n N_i d_i^3}{K_{LIF} \sum_{i=1}^n N_i d_i^3} \quad (2)$$

where K_{LIF} and K_{MIE} are coefficients related to dye concentration, laser power, signal collection angle, detector response... This method assumes that the fluorescence signal I_{LIF} is proportional to the droplet volume ($\propto d^3$) and that the Mie scattered light intensity I_{MIE} is proportional to the

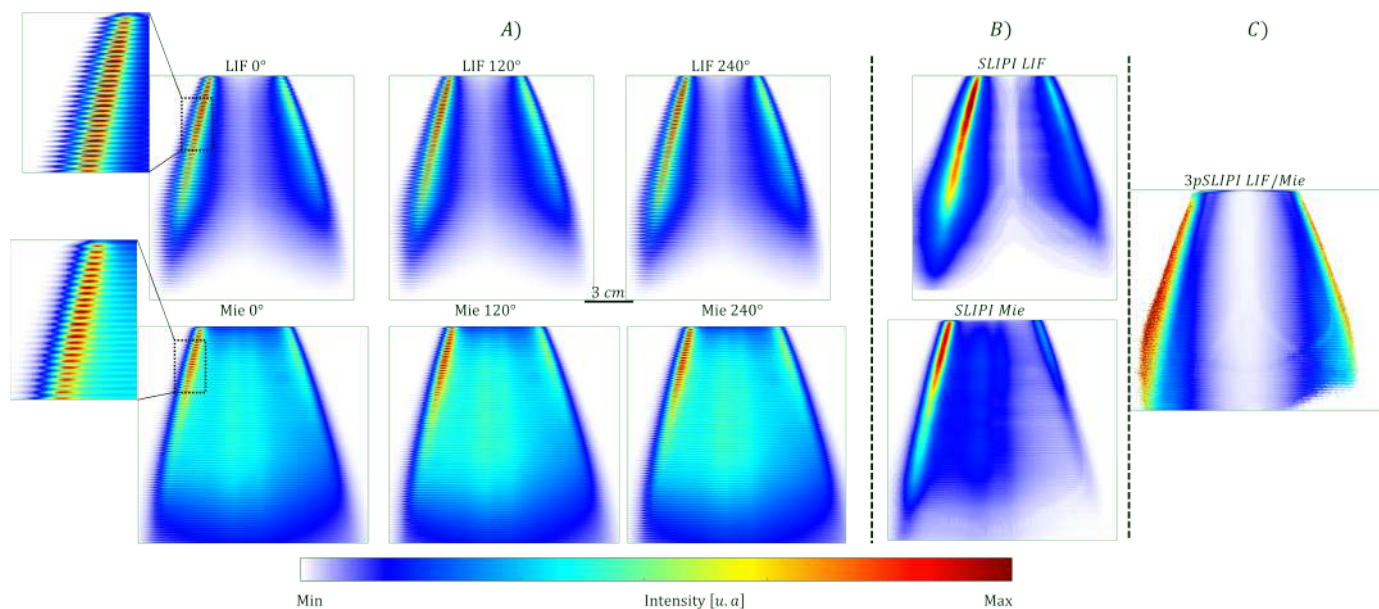


Figure 2. Generation of the 3pSLIPI LIF/Mie image. A) Three modulated images of the LIF and Mie signal. B) resulting SLIPI LIF and Mie images and C) resulting 3pSLIPI LIF/Mie.

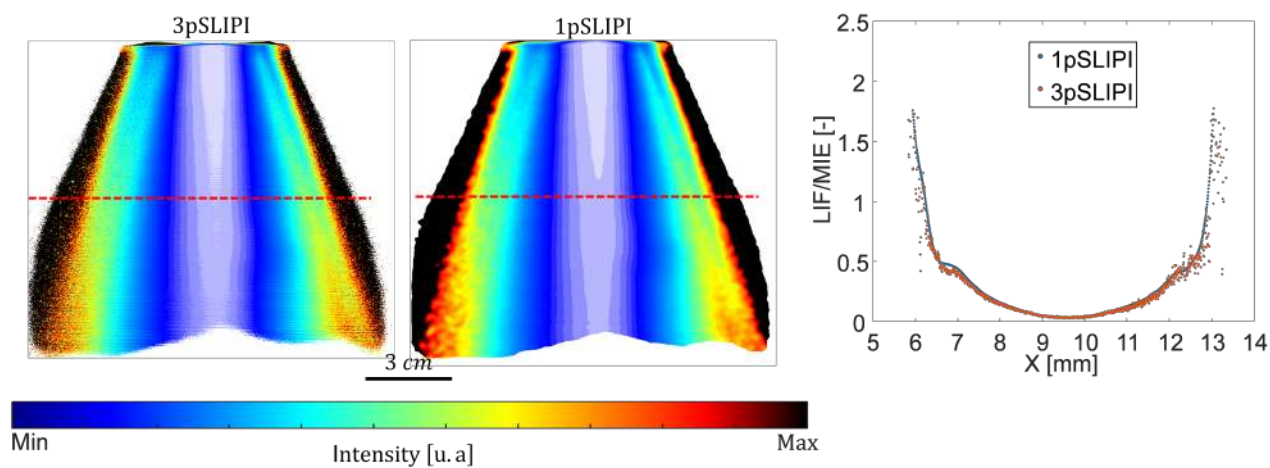


Figure 3. Comparisons between 3p and 1p SLIPI LIF/MIE images. The integration of the signal along a line transverse to the spray allows the comparison of the two reconstruction methods.

droplet's surface ($\propto d^2$). It has to be noted that technique is valid only for spherical droplets and that all photons reaching the camera should have experienced only one scattering event prior to detection Yeh et al. (1993); Domann & Hardalupas (2003). Some fundamental studies have been performed to evaluate the accuracy of the ratio and its limitations Domann & Hardalupas (2001); Charalampous & Hardalupas (2011).

Thus, in order to make measurements of D32 a calibration step is necessary. The calibration step is made using PDA measurement realised along the spray at a given distance from the nozzle. Measurement are realized from the spray center to the edge with one point each millimetre. Note that PDA measurements are performed with care and a measurement is only validated if the PDA validation rate is greater than 90% and a minimum of 100 000 droplets is acquired. To ensure the representativeness of the calibration, PDA measurements are performed at different distances from the injection (Figure 4.A). Figure 4.B present the evolution of the droplet diameter (PDA measurement) in function of the LIF/Mie ratio. As observed, the calibration seems independent of the position in the spray. This finding obtained with large field of view is due to the use of a telecentric objective. Although the LIF/Mie ratio seems to be no longer sensitive for droplet diameters greater than 70 μm , it should be noted that these droplet diameters are obtained at the edge of the spray and that at this position the SNR is very low. Also, it seems that at this position the LIF signal is extremely weak compared to the Mie signal, which could explain this impression of loss of sensitivity.

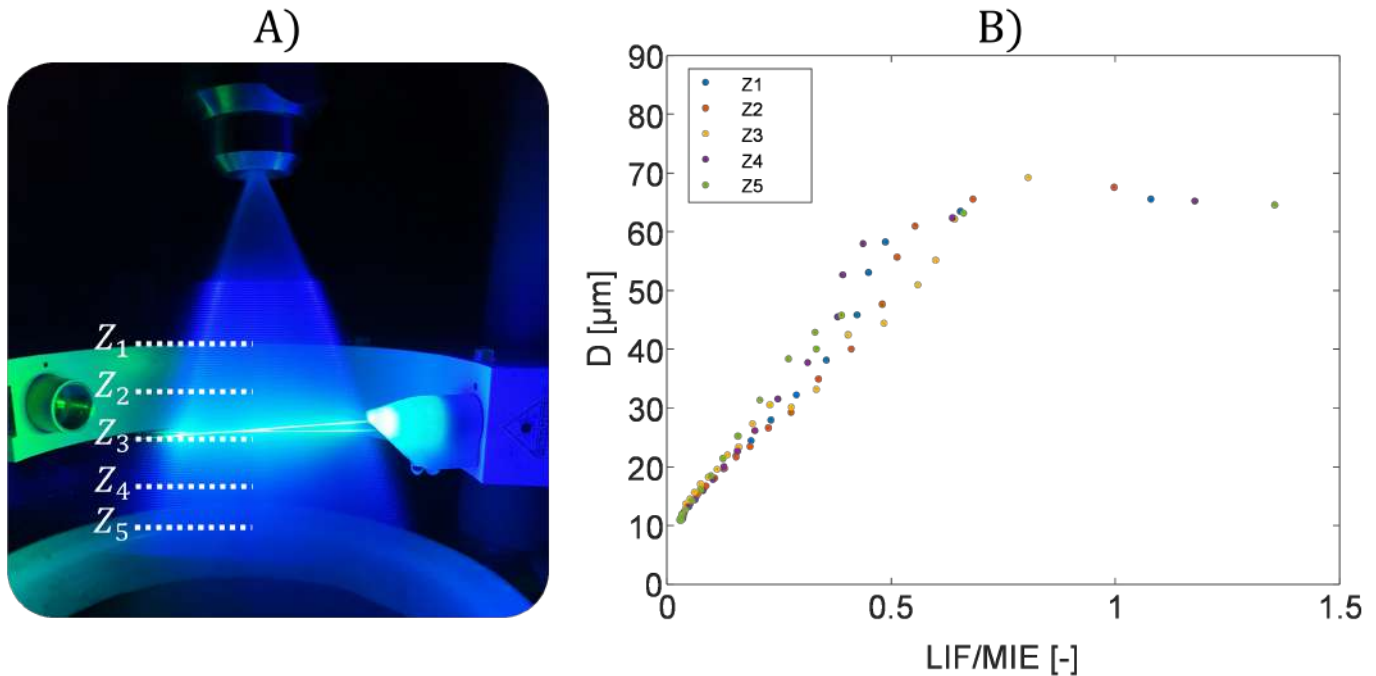


Figure 4. A) Experimental setup used for the calibration of the SLIPI-LIF/Mie ratio using a PDA system. B) Evolution of the Sauter Mean Diameter as a function of the LIF/Mie ratio obtained at different height in the spray. For each distance from the nozzle exit (z_i) the calibration was obtained from measurement along the spray from the center to the edge.

In order to determine if the calibration was universal, the same calibration step was performed for different liquid injection pressures ranging from 20 bar to 70 bar. Figure 5.A present the evolution of the D_{32} diameter as a function of the LIF/Mie ratio for the different injection pressure tested. A decrease of the LIF/Mie ratio is observed for a given diameter when increasing the injection pressure. In the current configuration, this change cannot be due to the way the signal is collected due to the use of the telecentric objective. One hypothesis would be that this change comes from the reabsorption of the fluorescence signal along the detection path. However, if this was the case, differences in the calibration made at different positions (Figure 4.B) in the spray should have been observed. Thus, although the physical effects leading to a change in the Mie and LIF signals as a function of the injection pressure are not understood, a correction of the calibration is proposed. This correction factor (K) consists in the ratio between the LIF/Mie ratio obtained at a given pressure taken as reference (here a pressure of 20 bars) and the one obtained for another injection pressure for a fixed droplet size:

$$K(P) = \frac{\frac{I_{LIF}}{I_{MIE}}(P = 20)}{\frac{I_{LIF}}{I_{MIE}}(P)} \quad (3)$$

Note that K is calculated only for the diameter where PDA measurement were well validated. Indeed, for high injection pressure, scattering, result in a low validation rate of the measurement (less than 50% in the center of the spray for an injection pressure of 70 bar). K is then calculated when the validation ratio is equal to at least 50%. Figure 5.B present the evolution of D_{32} as a function of the corrected LIF/Mie ratio for all the injection pressure tested. The calibration points are then fitted using a 5th order polynomial and this fitted curve is used for measurement. It has to be noted that for diameter lower than 30 μm a high deviation of the experimental points from the fitted law is observed for the highest injection pressure (70 bars). This deviation is due to PDA measurement made in the spray center resulting in a validation rate lower than 50%. Thus, in view of these calibrations it seems important to note that in order to obtain droplet size measurements by SLIPI-LIF/Mie the calibration step must be performed conscientiously under conditions similar to those of measurements. The correction proposed here allows a major time saving in the calibration phase because, a single point is required when changing the injection pressure.

5. Results

Measurement of the SMD in the spray using SLIPI-LIF/Mie are presented in Figure 6 for an injection pressure of 20, 50, 80 and 120 bars. As observed, the spray angle is decreasing with the increase of the injection pressure, resulting in an increase of the droplet density. Smaller droplets are observed in the spray center and an increase of the D_{32} is observed when moving away from the center of the spray. When increasing the injection pressure up to 120 bar the spray optical density become so important that measurement over the full spray is impossible. Using this experimental setup and calibration correction, measurements are possible independently of the injection pressure and over a wide range of more than 10 cm.

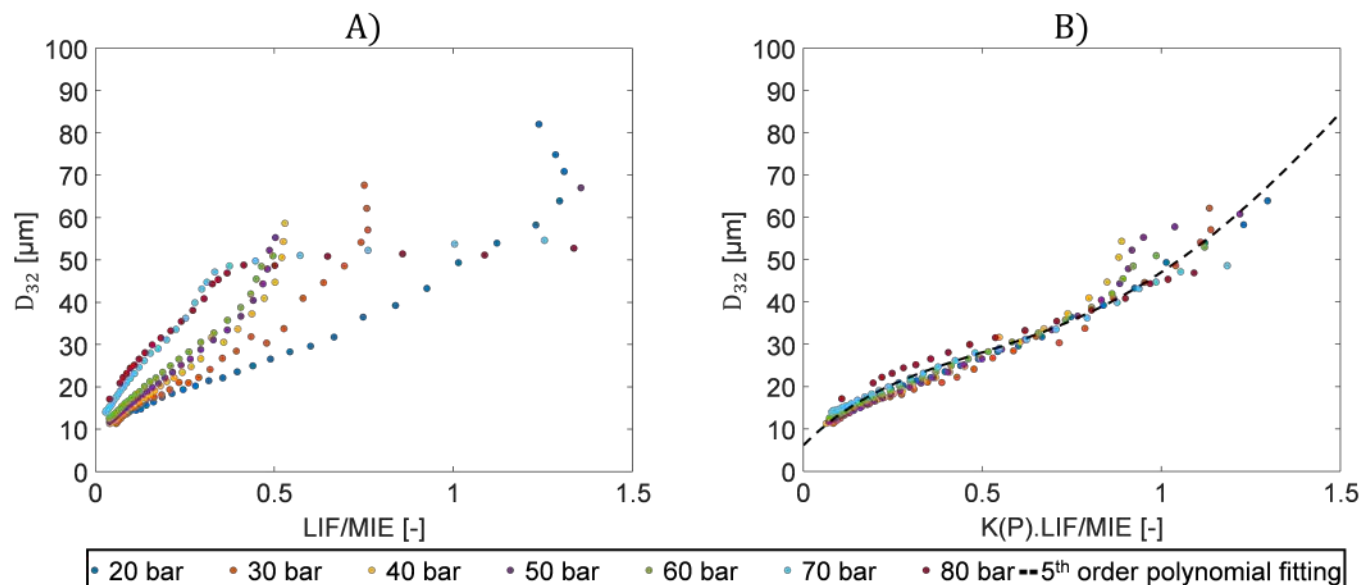


Figure 5. Evolution of the Sauter Mean Diameter as a function of A) the LIF/Mie ratio and B) the corrected LIF/Mie ratio for different injection pressure.

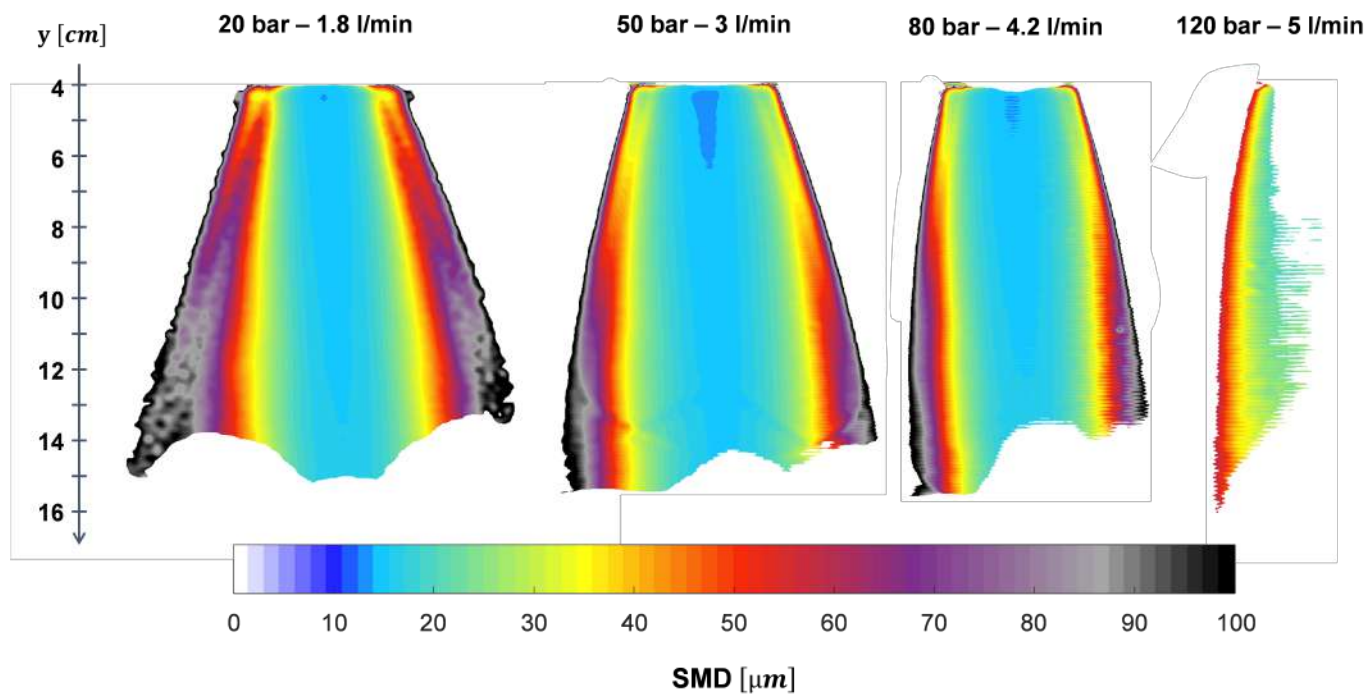


Figure 6. Two-dimensional map of the absolute droplets SMD for the spray running at different injection pressure. The result is obtained from SLIPI-LIF/Mie after calibration presented in Figure 5 B).

Using the same experimental setup, SMD measurement in the spray at different depth is possible. Thus, measurements at different location in the spray (depth of $X=0$; 12 20 and 28 mm from the center) are presented in Figure 7. Since the study was conducted on a symmetrical spray, the results obtained at different positions are in agreement with those observed previously. Thus, we observe an increase in the SMD as we move away from the center of the spray. A 3D reconstruction of the spray is possible if the distance between the different measurement layers is equal to the width of the laser sheet. Note that section and measurements allowing the full 3D reconstruction of the spray are in progress.

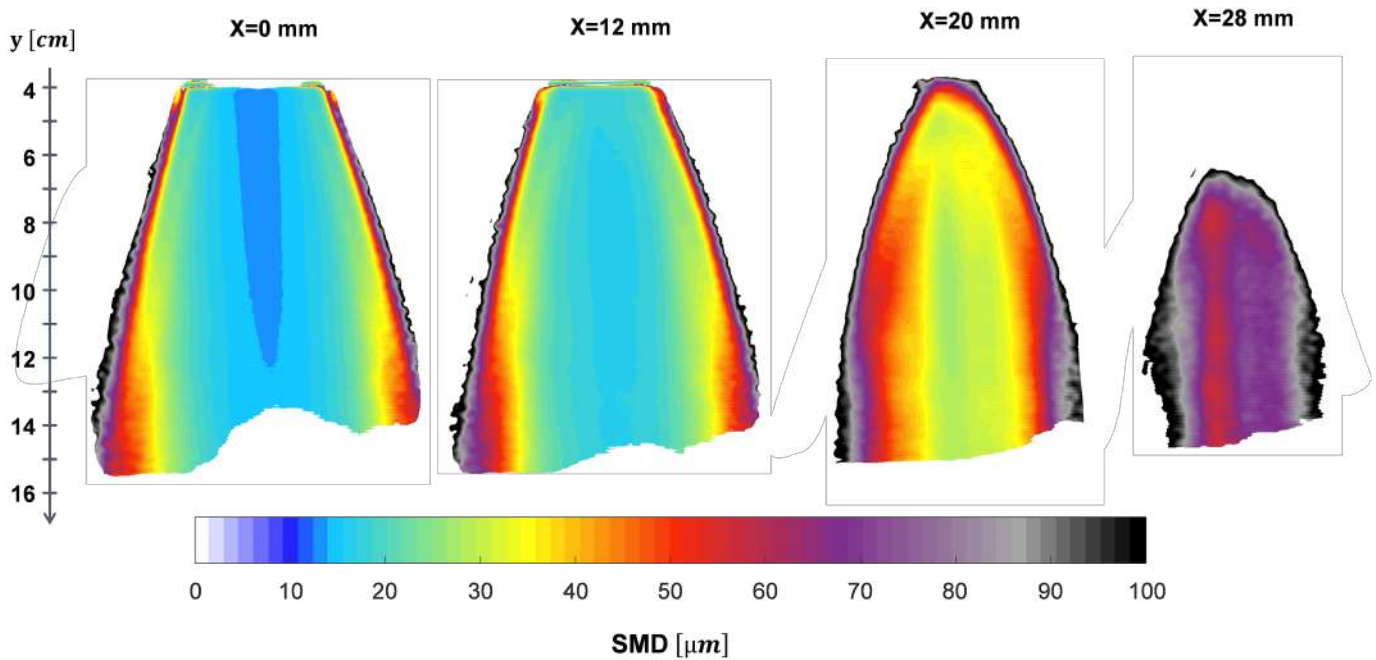


Figure 7. Two-dimensional map of the absolute droplets SMD for the spray running at 50 bars for different depth ($X=0$, 12, 20 and 28 mm).

6. Conclusion

SLIPI-LIF/Mie ratio allow to spatially resolved the Sauter mean diameter in a spray. During the study of stable spray, the use of 1SLIPI allows to greatly reduce the measurement time compared to those obtained when using 3pSLIPI while keeping the measurement precision. However, the SLIPI-LIF/Mie ratio calibration is dependent on external conditions as shown by its variation with injection pressure. The increase of the injection pressure is characterized by an increase of the droplet speed and an increase of the droplet density. Although more experiments are needed to understand the physical phenomena involved in the variation of the LIF/Mie ratio, a methodology to overcome this problem has been proposed. This method requires the measurement of the LIF/Mie ratio and the Sauter diameter at a single point for each measurement condition in a case allowing an excellent convergence of the PDA measurements.

Nomenclature

d	diameter [m]
I	Image [-]
P	Pressure [bar]

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