SLIPI Polarization Ratio combined with light transmission imaging to deduce droplet sizing and Liquid Volume Fraction in optically dense Sprays

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ABSTRACT

This paper addresses challenges in spray diagnostics, focusing on scenarios with high optical depths. Traditional laser-based techniques for droplet size measurements face issues related to light scattering and absorption. SLIPI polarization ratio method is used there in order to characterize the droplet diameter without the addition of dyes. The potential of the method for measurement of the Sauter Mean Diameter as well as the surface mean diameter is investigated using Phase Doppler measurement. The combinations of SLIPI polarization method and SLIPI transmission measurement in 3D allows for an estimation of the liquid volume fraction.

1. Introduction

The quantitative assessment of the spray region, particularly in situations with high optical depths where spherical droplets have already formed, poses challenge (Berrocal et al., 2010; Domann & Hardalupas, 2001; Le Gal et al., 1999; Mishra et al., 2014). Laser-based techniques commonly employed for temperature or droplet size measurements encounter complications arising from undesired effects linked to light scattering and absorption phenomena. Over the past decade, structured illumination techniques have emerged as a solution to address visualization challenges associated with multiple scattering (Berrocal et al., 2012). One such innovative approach, the Structured Laser Illumination Planar Imaging-Laser-Induced Fluorescence/Mie Ratio (SLIPI-LIF/Mie) technique, has demonstrated efficiency in visualizing and quantifying droplet Sauter Mean Diameter (SMD, D_{32}) in both transient (Koegl et al., 2019) and steady spray(Mishra et al., 2014). SMD measurements hinge on the ratio of Laser-Induced Fluorescence (LIF) and Mie optical signals. The utilization of structured illumination proves particularly advantageous in optically dense sprays, as it mitigates the complexities associated with multiple light scattering, ensuring the acquisition of reliable data. However, the LIF/Mie method necessitates the introduction of fluorescent dyes into the liquid, rendering measurements impractical under evaporative conditions. To circumvent the need for fluorescent dyes, the recently developed SLIPI polarization ratio method offers a promising alternative (Stiti et al., 2023). In this study, we used the SLIPI polarization ratio method to comprehensively characterize various scalar quantities of the spray in three dimensions. Specifically, we explore its potential not only to measure the surface mean diameter D_{21} but also to extend its utility to encompass the D_{32} and D_{30} diameters crucial for estimating the liquid volume fraction (LVF) within the spray.

2. Experimental setup

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. Three phases SLIPI requires the physical displacement of the grating that create the modulated image. Here, we're interested in the measurement of droplet size and the transmission of a laser signal as it passes through the spray. For this purpose, two experimental devices have been used for the study of a hollow cone water spray formed under atmospheric conditions.

The first measurement applied is the polarization ratio of light in a plane, providing information on the spray's D_{21} diameter. The optical arrangement depicted in Fig. 1a is employed to create a structured laser sheet measuring approximately 12 cm in height. This setup utilizes a continuous-wave laser beam with a wavelength of 532 nm and a maximum power of 5 W. The laser beam is transformed into a laser sheet through the use of cylindrical lenses, and the modulation of light intensity is achieved using a diffractive optical element (DOE). The scattering signal is captured by a large telecentric objective (0.066X, 1 in. C-Mount TitanTL Telecentric Lens) positioned at θ = 90◦ and connected to two sCMOS cameras (Andor, Zyla 5.5), providing a resolution of 0.29 mm per pixel.

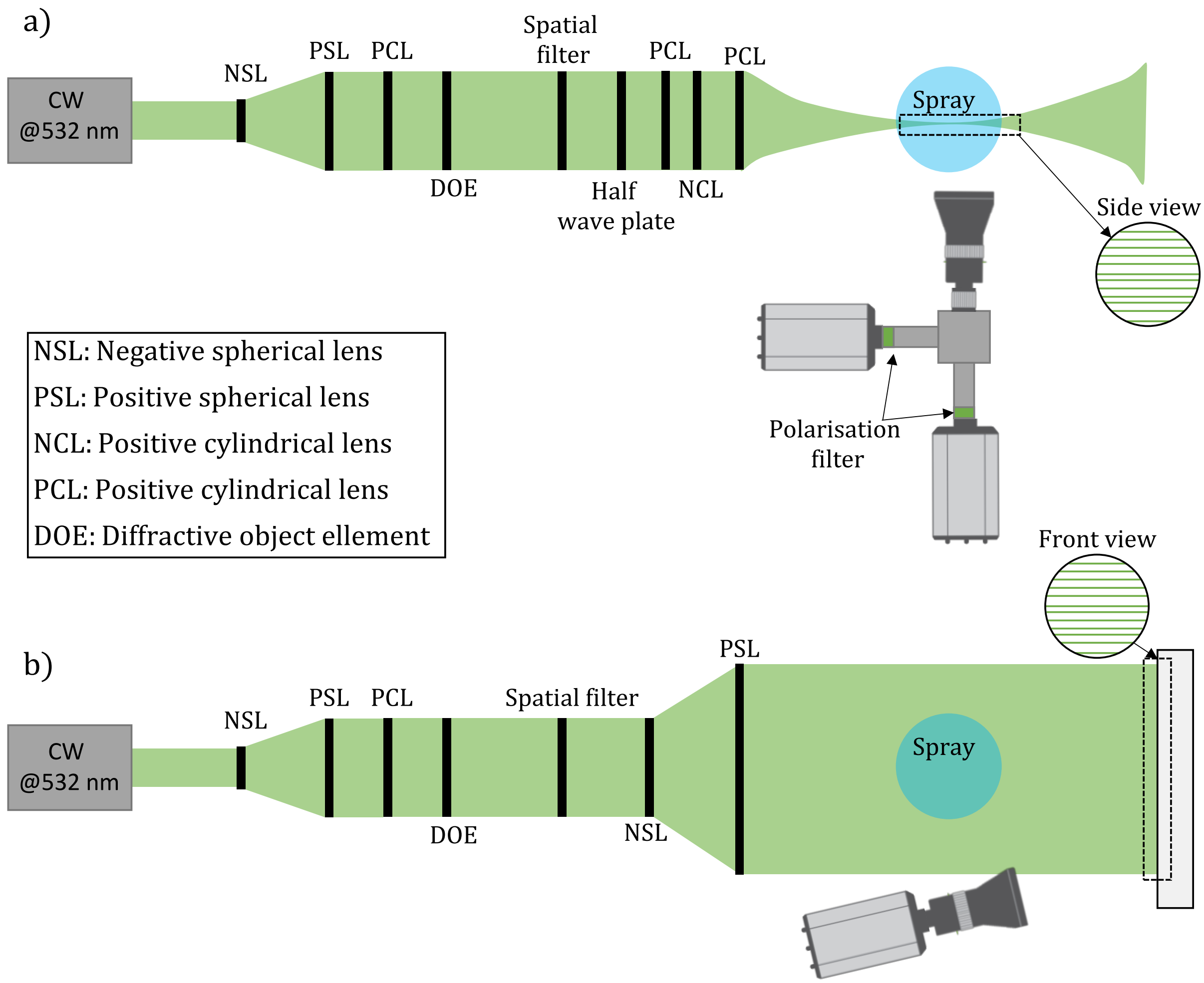

Figure 1: Top view of the optical setup of the a) SLIPI polarization ratio technique and b) SLIPI transmission imaging. A continuous wave laser @532 nm is used to produce a modulated laser sheet or beam.

As described in (Garcia et al., 2023), employing a telecentric lens eliminates the angular dependence of the scattered Mie signal within the field of view. To simultaneously capture the same image on both cameras using a single telecentric lens, a TwinCam system (CairnOptics) is utilized. This system includes an imaging relay forming the image on a beam splitter cube and two additional imaging relays projecting the image onto both cameras. Polarization filters are placed in front of each camera to selectively collect the desired polarization on each sensor. A zero-order, air-spaced $\lambda/2$ wave plate is employed to adjust the polarization axis of the incident beam. To implement the polarization ratio method, the polarizer is oriented at 80◦. An example of the SLIPI polarization ratio method is presented in Fig.2.

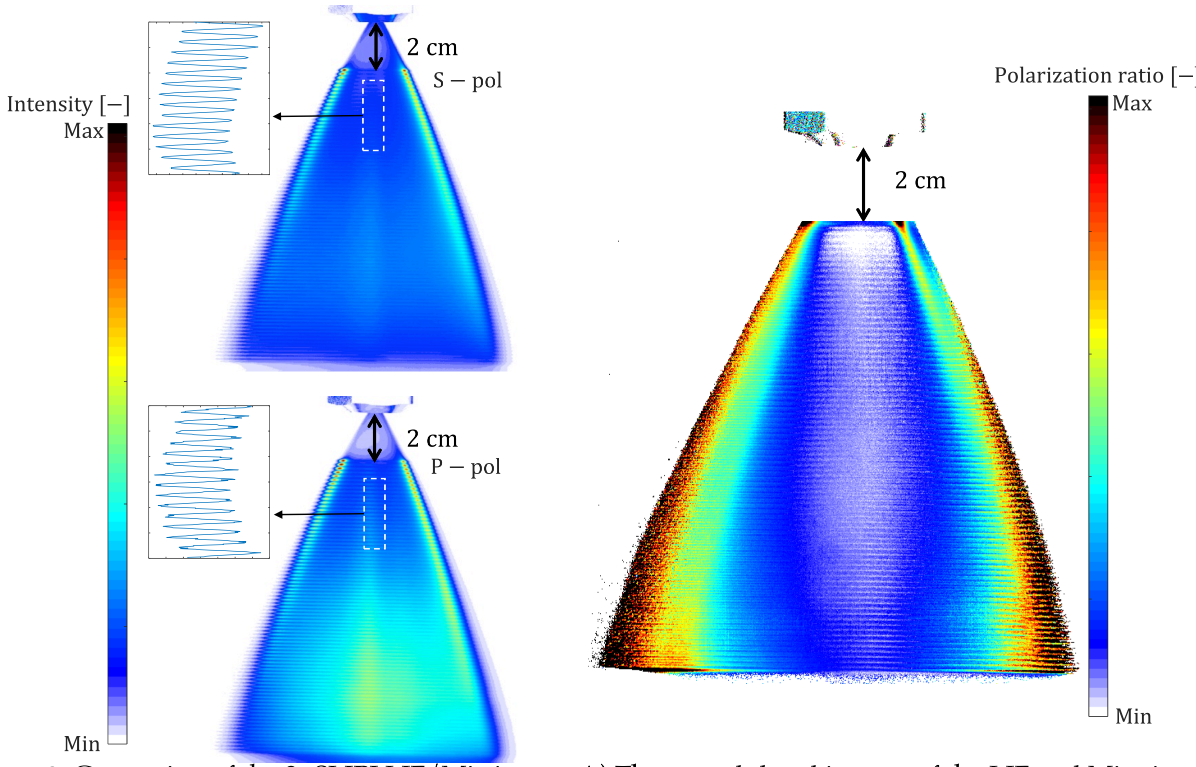

Figure 2: Genreation of the 3pSLIPI LIF/Mie image. A) Three modulated images of the LIF and Mie signal. B) resulting SLIPI LIF and Mie images and C) resulting 3pSLIPI LIF/Mie.

The second optical setup is used for transmission imaging measurement and is presented in Figure 1b. Transmission measurement allows for a measurement of the Optical Depth (OD) of the spray define as the averaged umber of scattering events that statistically occurred when crossing the spray. The first setup is updated by changing the last lenses by spherical one in order to create a large beam of 10 cm diameter. In order to kept only the transmitted light without multiple or single scattering signal an sCMOS camera mounted with a conventional objective lens is focused on the transmitted beam on a white panel. The optical depth is obtained by calculating the logarithm of the ratio between the transmitted light (I_i) without spray by the one with the spray (I_t):

$$OD = -\ln\left(\frac{I_t}{I_{Ref}}\right),$$

an example of the OD measurement is presented in Fig.3.

For both measurements method the three phases SLIPI method is used. The final image based on structured illumination is generated by recording three modulated images where the phase of the sinusoidal modulation of the intensity is shifted by $2\pi/3$. This is experimentally done by vertically and accurately displacing the DOE. The final image of light intensity I_{SI} is finally obtained using the following equation:

$$I_{SI} = \frac{\sqrt{2}}{3}\sqrt{\left[I_{2\pi} - I_{2\pi/3}\right]^2 + \left[I_{2\pi} - I_{4\pi/3}\right]^2 + \left[I_{2\pi/3} - I_{4\pi/3}\right]^2}$$

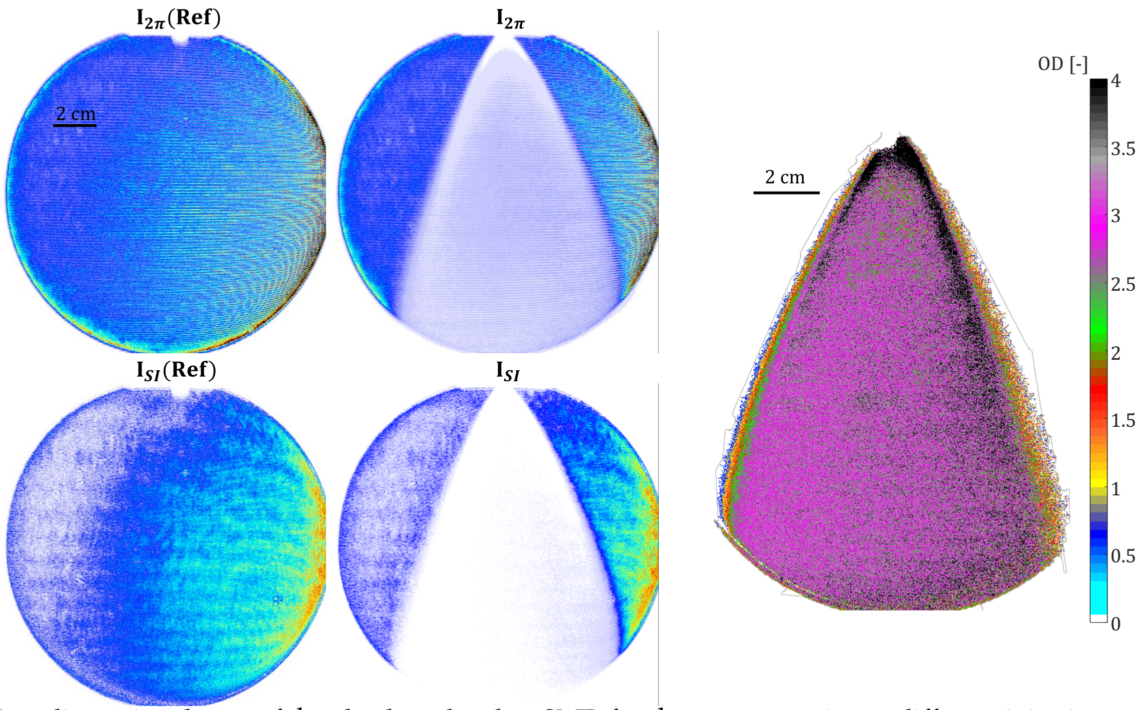

Figure 3: Two-dimensional map of the absolute droplets SMD for the spray running at different injection pressure. The result is obtained from SLIPI-LIF/Mie after calibration presented in Figure 5 B).

3. Calibration of the SLIPI polarization ratio

In order to convert the polarization ratio to diameter D_{21}, it is necessary to go through a calibration step. This is performed using PDI (Artium instrument PDI-TK2) measurements along the spray at a distance of 11 cm from the injector. Data are acquired every five millimeter and are validated when 10 000 droplets are acquired for each measurement point. Fig.4 represent the evolution of the diameter D_{32} and D_{21} as a function of the distance from the center of the spray, for a distance of 0, 30 and 50 mm from the center the droplet size distribution is also represented. As observed, in this spray the value of both diameters are quite close which will allows potentially the measurement of the diameter D_{21} and D_{32} using the SLIPI polarization method. It has to be noted that the value of D_{21} and D_{30} which is not represented here are very close (less than 3% variation between both value) which can open possibility for Liquid volume fraction measurement (Mishra et al., 2020).

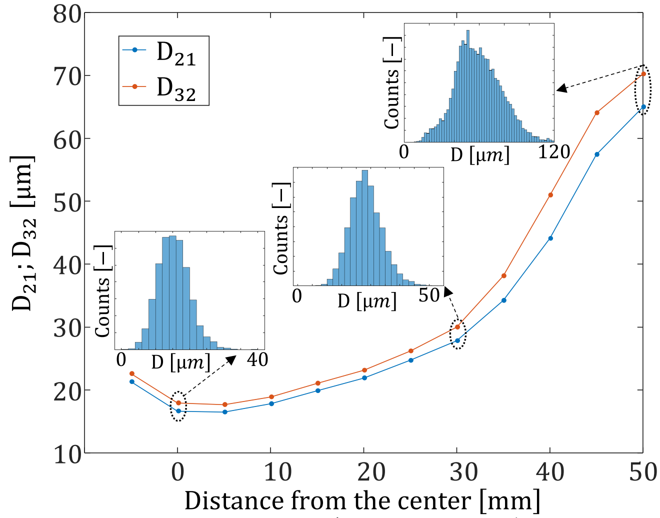

Figure 4: Comparisons between 3p and 1p SLIPI LIF/MIE images. The integration of the signal along a line transverse to the spray allows the comparison of the two reconstruction methods.

In order to obtain a geometrical correspondence between the PDI measurements and the polarization ratio, an image of the measurement volume is recorded on each camera. A value of the polarization ratio is assigned for each PDI measurement and is shown in Fig. 5. In order to increase the number of calibration points, the calibration was performed for different injection pressure and different type of injector. As observed, both calibration shows a relatively linear fit between the diameter D_{21}, D_{32} and the polarization ratio. The value for both fit are close due to the fact that in our spray as observed in Fig.4 D_{32} and D_{21} are close too. In this spray, SLIPI polarization ratio measurements can be used to image the D_{21} and D_{32} diameters simultaneously.

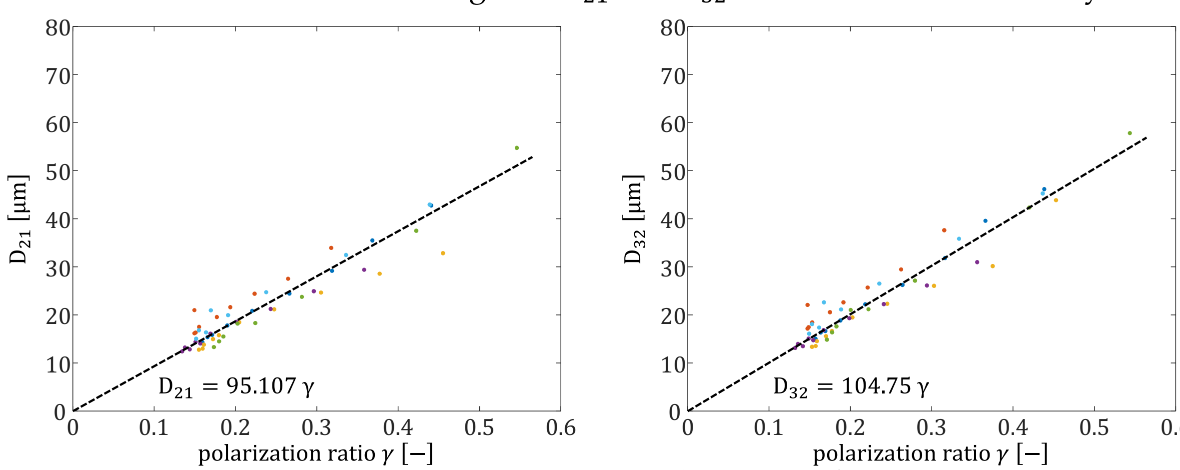

Figure 5: A) Experimental setup used for the calibration of the SLIPI-LIF/Mie ratio using a PDA system. B) Evolution of the Sauter Mean Diameter as a function of the LIF/Mie ratio obtained at different height in the spray. For each distance from the nozzle exit (Z_i) the calibration was obtained from measurement along the spray from the center to the edge.

4. Results and discussions

Figure 5 illustrates the utilization of the calibration curve depicted in Figure 4 for the purpose of deriving imaging data of the diameters D_{32} and D_{21}. As observed, the spray exhibits a symmetry, and both D_{32} and D_{21} yield proximate outcomes. By delineating the progression of both diameters along a designated line, as depicted in Fig. 5, the nuanced evolution of the diametric measurements becomes discernible. As anticipated, the obtained results closely align with each other and exhibit a tendency to deviate at the peripheries of the spray, where the D_{32} diameter assumes a comparatively higher value.

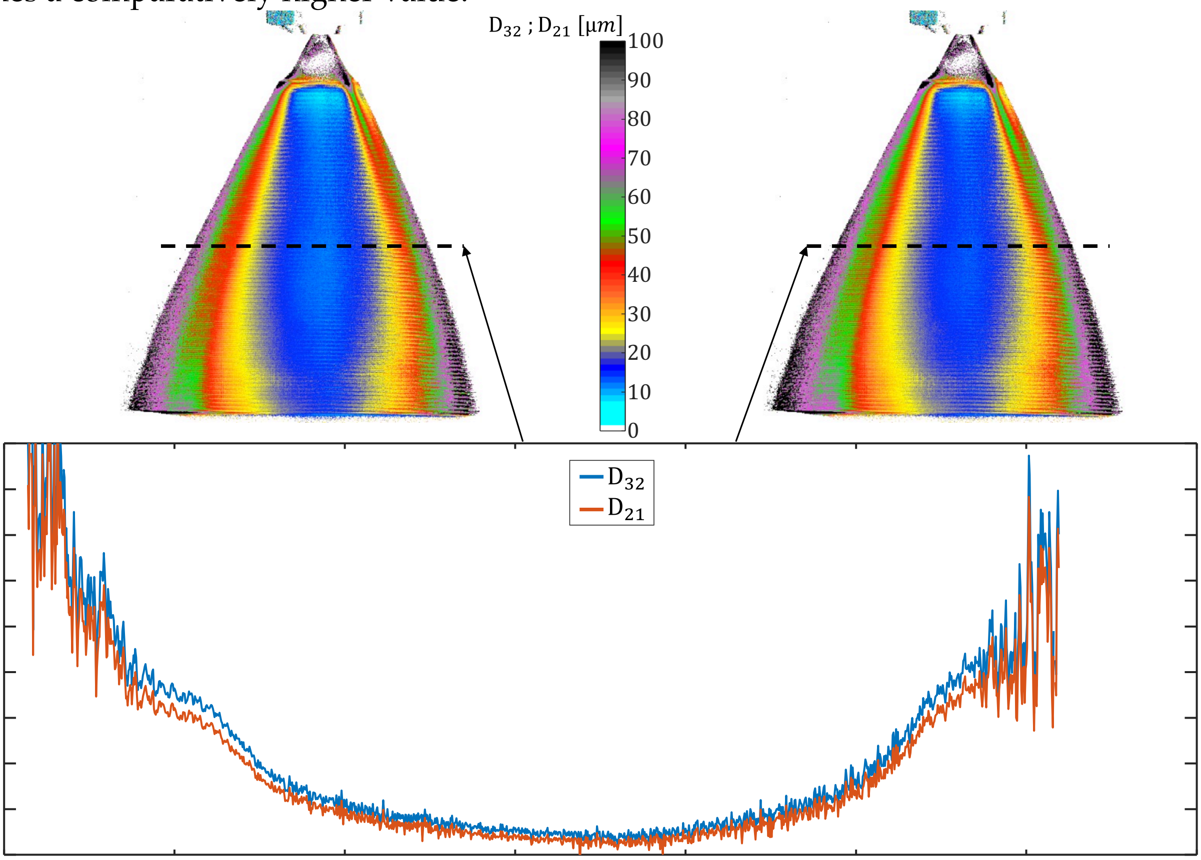

Figure 6: Evolution of the Sauter Mean Diameter as a function of A) the LIF/Mie ratio and B) the corrected LIF/Mie ratio for different injection pressure.

To acquire comprehensive 3D spray data and achieve concordance between size and OD measurements for the precise quantification of liquid volume fraction, a rotational system is employed to facilitate spray characterization. Polarization ratio and transmission measurements are therefore obtained in 3D. Subsequent to this, PDI calibration is employed, enabling the derivation of a three-dimensional matrix encompassing D_{32} and D_{30} diameters. Leveraging the PDI measurements, a transformative step ensues, wherein the droplet size imaging measurements are adeptly converted into droplet extinction cross-sections (σ_e). This conversion process is made through an algorithm grounded in Mie scattering principles. By applying the volume equation of a sphere, the 3D diameter matrix D_{30} is converted in Volume (V). Concurrently, the local extinction coefficient (μ_e) of the droplets within the spray is derived through transmission measurements. The combinations of the extinction coefficient μe and extinction cross-section (σ_e) measurements enables the determination of the droplet number density (N). In the conclusive stage of this analytical cascade, the liquid volume fraction is ascertained by the multiplication of the 3D matrices encapsulating volume (V) and droplet number density (N).

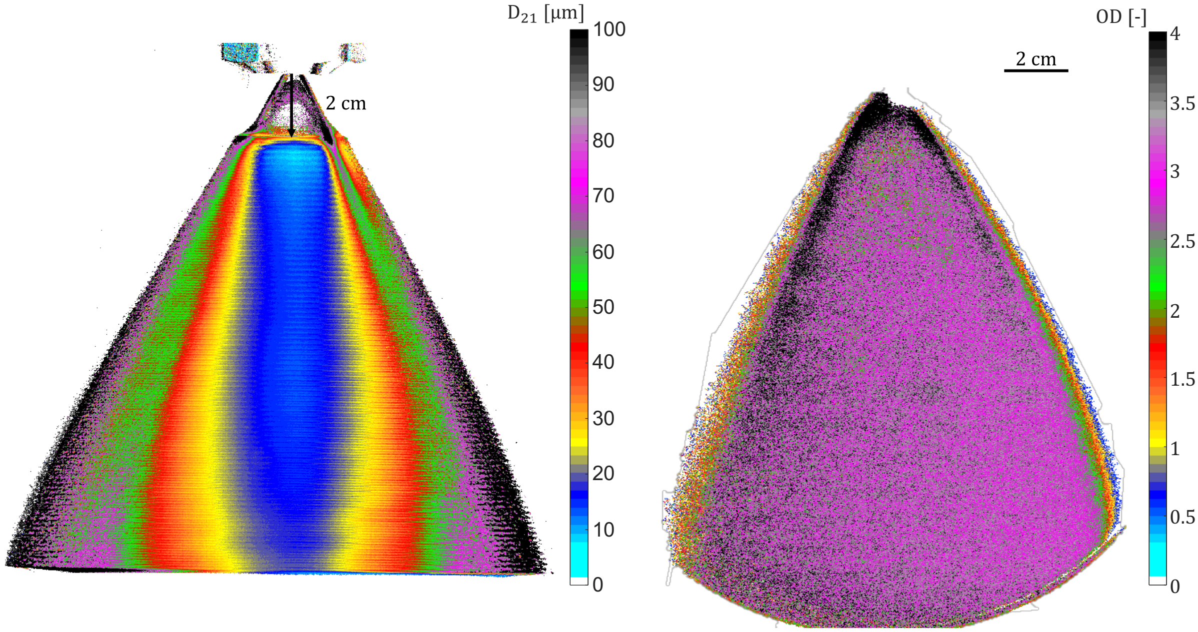

Figure 7: Two-dimensional map of the absolute droplets SMD for the spray running at 50 bars for different depth (X=0, 12, 20 and 28 mm).

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