Planar droplets sizing of a hollow-cone spray using SLIPI-LIF/MIE

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Abstract

In this work, we report an original experimental approach for measuring the two-dimensional distribution of the droplets Sauter Mean Diameter (SMD) using the SLIPI-LIF/MIE technique. A hollow-cone spray is formed by continuously injecting water mixed with a non-toxic fluorescing dye at 20 bars injection pressure. The spray is illuminated using a continuous wave laser. The illumination wavelength (here, 447 nm) is carefully chosen to excite the injected dye/water mixture, which generates a significant Laser Induced Fluorescence (LIF) signal peaking at 514 nm. The LIF and Mie signals are simultaneously recorded using two CCD cameras and their intensity ratio is used to extract a two-dimensional distribution of the droplets SMD. In this article, we show that even for the case of a dilute hollow-cone spray, where single scattering events are in majority, the LIF/Mie measurement of droplets SMD still remains strongly affected by multiple light scattering. We demonstrate, then, that the use of SLIPI is unavoidable to obtain trustable SMD measurements based on the LIF/Mie ratio, even for optically dilute sprays.

1. Introduction

The practical demands of high performance of liquid atomizer based combustion devices have necessitated improving the atomization process since it is directly linked to the efficiency of the device. The performance of a spray is judged by its ability to disintegrate the bulk liquid into micrometric droplets which transport and evaporate prior to combustion. This characteristic of a spray decides the efficiency as well as features of any liquid driven combustion system. It is therefore significant to investigate the spray structure with both high temporal and spatial resolution. Droplets sizing is a key component for determining the spatial distribution of spray morphology and for quantitative characterization of spray.

In the past, various optical measurement techniques have been developed to determine droplet size distributions. One of the first optical approaches for drop-sizing was reported in 1976 and is known as ensemble light scattering [1]. The ensemble light scattering (ELS) is a line-of-sight technique, which detects forward scattered light from the particles in a light path formed by collimated laser beam. Prior to its arrival at the detector, the non-scattered signal from the droplets passes through a Fourier Transform lens to generate a diffraction pattern. For each spherical particle, this diffraction pattern represents a concentric laser light ring. Widely spaced rings represents small spherical particles whereas, a large spherical particle represents closely spaced rings. Apart from these features, the ELS measurement provides a poor spatial resolution and is very sensitive to multiple light scattering issues. In the early eighties, Phase Doppler anemometry (PDA) [2-3] was introduced as a point measurement technique for measuring the spray droplet diameters. Today, the technique is used as a standard tool for simultaneous real time measurement of the geometric size of droplets and velocity. Even though, it is a well-established and accurate tool for droplet characterization, the PDA measurements can take several hours due to point by point scanning over the wide-spread spray. Also, the technique fails to give any data in optically dense media.

In the year 1993, planar drop-sizing (PDS) was first time implemented in a transient spray as an imaging tool for instantaneous two-dimensional mapping of the droplets distribution [4]. In PDS, the LIF and Mie signals from a light sheet illuminated media are simultaneously recorded and the intensity ratio of the LIF and Mie signal yields relative SMD of spray droplets [4-7]. As an advanced technique, PDS has two main advantages over PDA, first, improved spatial resolution and second, the faster measurement over a wider section of a spray. However, discrepancies in PDS measurements remained prominent mainly due to the multiple light scattering and the SMD measurements were not reliable. Later, polarization ratio method (PRM) was developed for measuring the relative SMD [8]. In PRM, a 45^0 polarized laser beam crosses a spray and the vertical and horizontal components of Mie signal are simultaneously recorded with two cameras. The ratio of the vertical and horizontal components is used to deduce the geometrical mean diameter. PRM technique has not been explored much due to the multiple light scattering issues. Therefore, all the above mentioned techniques are efficiently applicable only in low droplets densities to avoid signal perturbations introduced by multiple light scattering. In optically dense sprays, measurements are “paralyzed” by both multiple light scattering and light extinction. A detailed study has been reported in reference [9], on the account for light extinction and multiple scattering in PDS of dense sprays. Recent results [10] from planar droplet sizing have shown that multiple light scattering

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contributions are not the same between the LIF and Mie signals and cannot, therefore, be simply removed from the LIF/Mie ratio. The intensity contribution from multiple scattering needs to be suppressed on both the LIF and Mie signals for accurate SMD measurements.

Structured Laser Planar Illumination Imaging (SLIPI) has been established as a recognized diagnostics for efficiently removing the multiple light scattering contributions in optically dense sprays [11]. In reference [10], the SLIPI approach has been used for the first time in combination with the LIF/Mie ratio for mapping the droplets SMD in a non-combusting diesel spray. It has been shown that SLIPI was leading to consequent improvement in measuring the SMD for the case of optically dense media such as diesel sprays. However, the necessity of using SLIPI-LIF/Mie in the case of dilute sprays has not been shown yet. Using the SLIPI as a tool for mitigating multiple light scattering, it is of relevance to investigate PDS approach on a standard hollow-cone water spray. Here in this report, we have applied the SLIPI-LIF/Mie drop-sizing technique to determine the SMD of a hollow-cone water spray droplets. Since, a large number of applications are based on the use of hollow-cone sprays, the presented results will be of interest to researchers spanning from academic to industrial areas.

2. Description of SLIPI-LIF / Mie Technique

2.1 SLIPI

SLIPI stands for **S**tructured **L**aser **I**llumination **P**lanar **I**maging. It works on the principle of combining structured illumination with planar laser imaging. The main goal of the SLIPI technique is to preserve all the singly scattered photons while removing most of the multiply scattered photons. A Ronchi grating is usually used to create the modulated light sheet. An image of a sample illuminated with a sinusoidal modulated intensity is described by:

$$I(x, y) = I_C(x, y) + I_S(x, y)\cos(2\pi x\nu + \phi) \quad (1)$$

where ν represent the modulation frequency, and ϕ the spatial phase. Here, $I_C(x, y)$ is the intensity of singly and multiply scattered photons and $I_S(x, y)$ represents the amplitude of singly scattered photons only. SLIPI extract and preserve $I_S(x, y)$ while removing $I_C(x, y)$ and $\cos(2\pi x\nu + \phi)$ from the image after post processing.
While crossing a scattering medium like a spray, multiply scattered photons lose the modulated signature while singly scattered photons preserve it. Thus the amount of single light scattering represents the local undisturbed amplitude of modulation. To extract this information, experimentally, a minimum of the three intensity modulated images are recorded with a spatial phase corresponding to 0°, 120° and 240°. To produce a SLIPI image, the root-mean square of the three recorded images is calculated as:

$$I_S = \frac{\sqrt{2}}{3}\left[(I_0 - I_{120})^2 + (I_0 - I_{240})^2 + (I_{120} - I_{240})^2\right]^{1/2} \quad (2)$$

A conventional image can be constructed from the simple averaging of the three images as:

$$I_C = \frac{I_0 + I_{120} + I_{240}}{3} \quad (3)$$

Thanks to the recently published thesis on SLIPI [12], the technique and its applicability have been reviewed and discussed in details.

2.2 LIF / Mie droplet sizing

The SMD of spray droplets is possible to determine by taking the ratio of a signal proportional to droplet volume (LIF) and a signal proportional to droplets surface area (Mie) [4]. For each pixel of a camera, the SMD corresponding to a distribution of droplets is expressed as:

$$SMD = \frac{K_{LIF}}{K_{Mie} \cdot Q_s} \frac{\int_{D=0}^{\infty} D^3 \cdot dN(D)}{\int_{D=0}^{\infty} D^2 \cdot dN(D)} \quad (4)$$

where $dN(D)$ is the droplet probability distribution and Q_s is related to incident ray detection angle. K_{LIF} and K_{Mie} include experimental components such as scattering efficiency, detector response, signal collection angle, laser power etc. Some publications [13-14] which focus on the accuracy of the LIF/Mie ratio for SMD calculations have found that the ratio of $K_{LIF}/(K_{Mie} \cdot Q_s)$ should not be considered as a constant (especially at 90° detection [10]) as it has been assumed in earlier papers [4, 5, 6]. Therefore, in SMD measurements several experimental complications remain in addition to numerically calculated uncertainties. To be able to extract the absolute SMD using SLIPI LIF/Mie approach, a number of assumptions and procedures must be considered as reported in reference [10]. In this study, only the relative SMD is considered in the two-dimensional distribution of the hollow-cone water spray droplets.

3. Description of the experiment

3.1 Experimental set-up

A hollow-cone water spray is investigated at ambient temperature, atmospheric pressure and with a liquid injection pressure set to 20 bars. In order to achieve a broad band LIF signal, the injected water is seeded with translucent fluorescing dye from yellow highlighter's ink. While exiting the nozzle, the dyed water solution forms a liquid sheet which quickly disintegrates into ligaments and fine droplets. A portable SLIPI setup has been designed and a schematic of the optical arrangement is shown in figure 1. The center of the spray is illuminated at $\lambda = 447$ nm (CW: DPSS solid-state laser) at a height of 1 cm below the nozzle tip. The vertically modulated laser sheet of height 5.8 cm excites the seeded dye present in the spray droplets. This results to a LIF emission peaking at 514 nm. The Mie and LIF signals are specifically detected using two high efficiency optical filters. For the LIF signal a long pass filter with a cut-off wavelength at 490 nm is used, whereas, for the Mie signal, a band-pass filter with transmission centered at 438 nm (± 12 nm) is used (optical density 6 in blocking).
The SLIPI LIF and Mie images are simultaneously recorded using the standard detection scheme (two cameras of same dynamic range positioned orthogonal to each other) at 90° from the illuminated plane. This scheme allows detecting the LIF and Mie signals simultaneously once the perfect overlapping in between the two images is obtained to ensure the actual spray symmetry deduced from the ratio. For the perfect overlapping, the LIF and Mie images must be warp in order to have the same field of view at the pixel scale. This warping process is performed from a calibration procedure and using an adequate test pattern. However, in order to obtained good statistics of the spray development over time, the LIF and Mie images were recorded with a relatively long exposure time. The LIF signal was recorded at camera exposure time of 200 ms with 200 accumulations, and the Mie signal was recorded at exposure time of 5 ms with 300 accumulations.

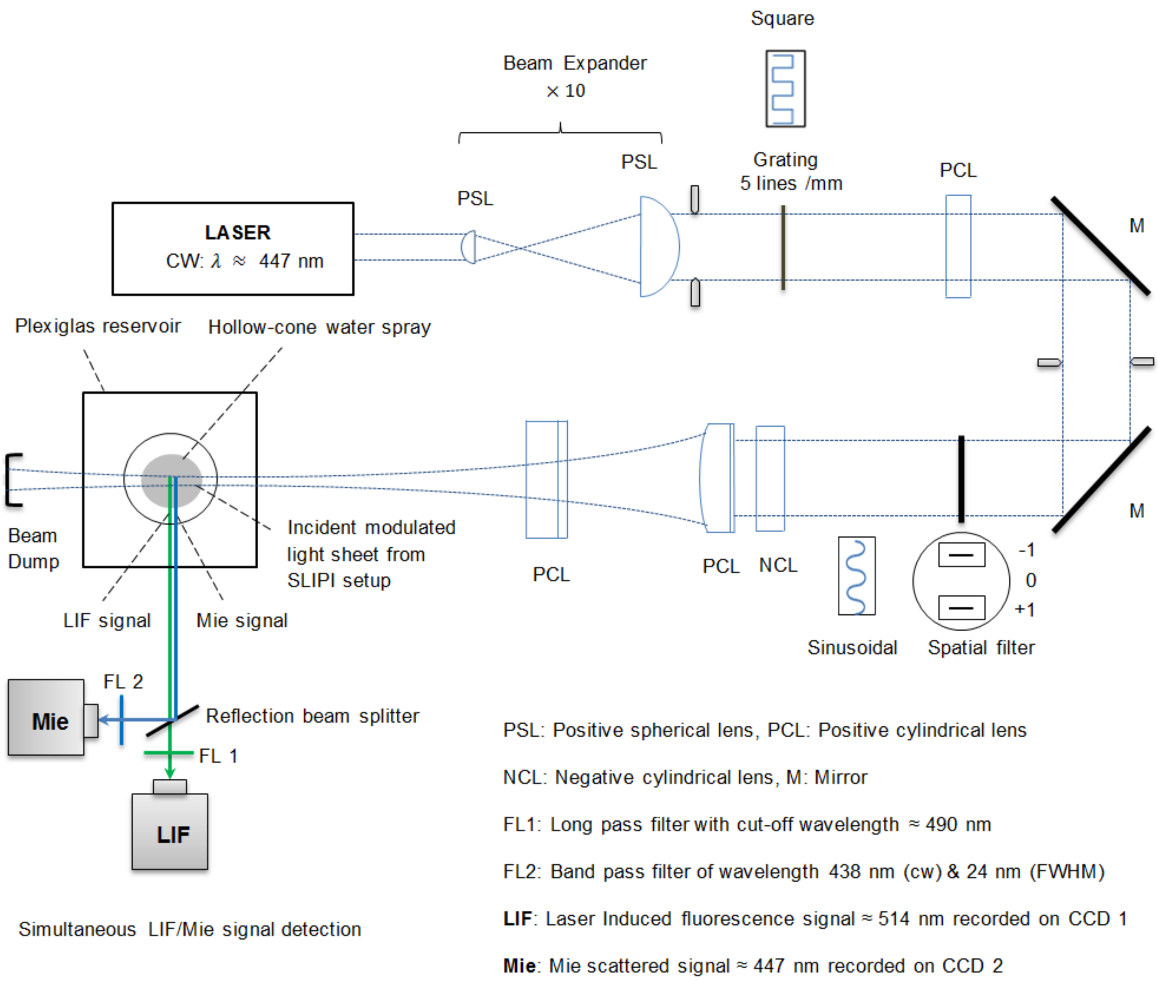

Figure 1: Top-view of the experimental setup

The exposure time was adjusted to avoid image saturation while optimizing the camera dynamic range. The CCD cameras used for this experiment are two 14 bit electrons multiplying CCDs (EMCCD Luca R from ANDOR), providing images of 1004×1002 pixels. While the incident laser power was equal to 900 mW, the final averaged power of the laser sheet was equal to 45 mW. The f-number of the collecting lens was adjusted to $f_{\#}$=8.

3.2 Transmission measurements

Transmission measurements have also been performed in order to deduce the optical thickness of the spray. These measurements were based on SLIPI using a glass cuvette filled with the fluorescing water solution used in the spray. The incident profile of the light sheet was deduced by imaging the cuvette when no spray was running, while the final light sheet intensity profile was deduced by imaging the cuvette while the spray was running.

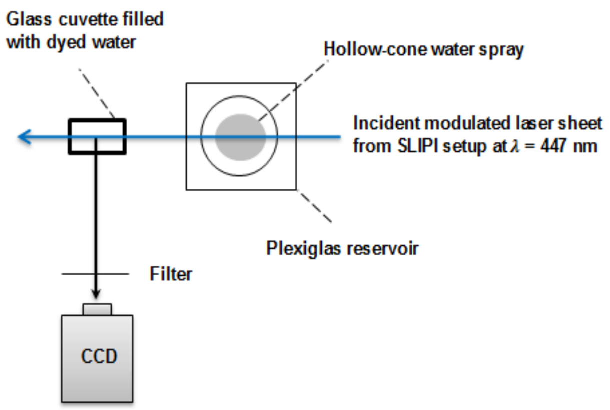

Figure 2: Top-view of the transmission setup. A glass cuvette filled with the fluorescing water was imaged to obtain an image of the laser sheet profile. For recording the incident and final intensity profiles, the spray is turned off and on respectively.

4. Results and discussions

4.1 Transmission measurements in the hollow-cone water spray

The incident and final intensity profiles are shown in figure 3 (a). The averaged transmission profile is shown in figure 3(b). These results show that while crossing the spray, light intensity has reduced to approximately 35-40%. The averaged transmission is calculated by taking the ratio of the final and incident profile images. The Optical Depth (OD) of the hollow-cone water spray is shown in figure 3(c). The OD is calculated based on the Beer-Lambert law [15] and corresponds here to an averaged value of OD~1.Therefore, most of the incident light is interacting only once with the droplets. From this measurement it is evident that the hollow–cone spray used in our experimental study is dilute.

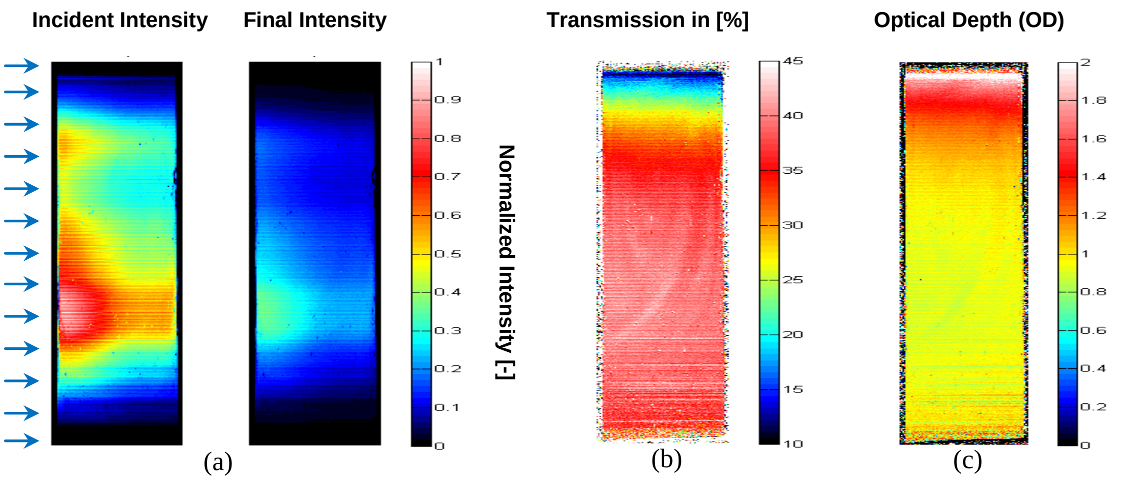

Figure 3: Incident and final intensity profile of the laser sheet. The measurement is performed using a rectangular glass cuvette containing the fluorescing water solution (see figure 2 for experimental description). Based on these measurements the light transmission could be deduced together with the optical depth of the spray along the vertical axis of the laser sheet (see figure 3(b) and (c)).

Figure 3(b) represents the light transmission along the vertical axis of the light sheet crossing the spray. These results are obtained by dividing the final intensity profile by the incident intensity profile shown in figure 3(a). Figure 3(c) shows the deduced optical depth. In this case, the OD is mostly close to ~1 which confirms that the spray is dilute.

4.1 Creation of conventional and SLIPI LIF/Mie images from three modulated images

Figure 4 shows the conventional LIF/Mie and the SLIPI LIF/Mie images generated by recording the three modulated images of LIF and Mie signals from the hollow-cone spray. The three modulated LIF and Mie images recorded with a phase difference of 120° degrees are shown in figures 4(a). The corresponding conventional LIF/Mie images are created by following equation (3) while SLIPI-LIF/Mie images are created by using equation (2) as shown in figure 4(b). The incident light is illuminating the hollow-cone spray from the right direction is represented by arrows.

(a)

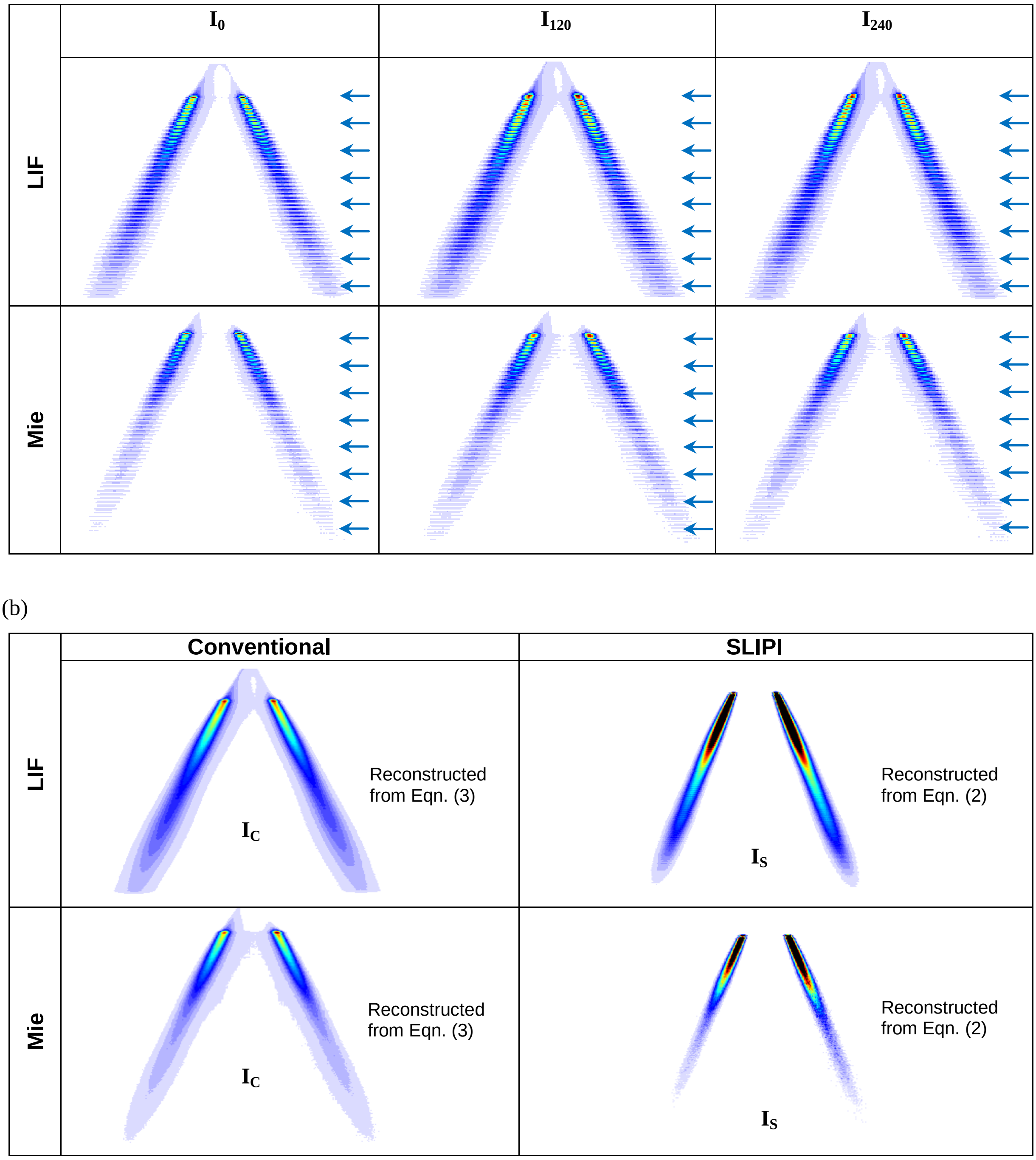

Figure 4: The Conventional LIF/Mie and the SLIPI LIF/Mie images of the hollow-cone spray are generated by recording the three modulated images of LIF and Mie signals as shown in figure 4(a). Images showing the three modulated images of LIF and Mie signals are recorded with a phase difference of 120°. The conventional LIF/Mie images created by averaging the three modulated images and the SLIPI LIF/Mie images generated by taking the root-mean square of the three modulated images are shown in figure 4(b).

Comparing the conventional and the SLIPI images in figure 4(b), it is evident that in the SLIPI-LIF /Mie images the signal intensity at right shoulder of the hollow-cone spray is higher as compared to its left shoulder (due to light extinction), whereas, in the conventional LIF/Mie images, the light intensity from the two shoulders of the hollow-cone spray has not reduced much. This is due to the presence of the cumulative contribution of multiple light scattering in case of conventional LIF/Mie images.

Therefore, the issues of multiple light scattering are apparent in conventional LIF/Mie images of the hollow-cone spray and images are affected by blurring effects. On the other hand, those effects are not visible in the SLIPI images because the SLIPI technique removes most of the multiply scattered photons. This result is consistent with the application of SLIPI approach in a hollow-cone water spray in previous paper [11].

4.2 Relative SMD mapping

The relative SMD of droplets distribution is shown in figure 5 from the LIF/Mie image ratios. A good symmetry of the hollow-cone spray can be observed on these images, both for the conventional and the SLIPI images. Color bars with black and white background have both been used on the same SMD images for comparison purposes. The Conventional LIF/Mie and the SLIPI-LIF/Mie images are presented in figure 5(a-c) and in figure 5(b-d) respectively. From the conventional SMD part, we could easily see the presence of blurring effects around the central part of the spray. This contributes to dislocation of local signature of droplets distributions.

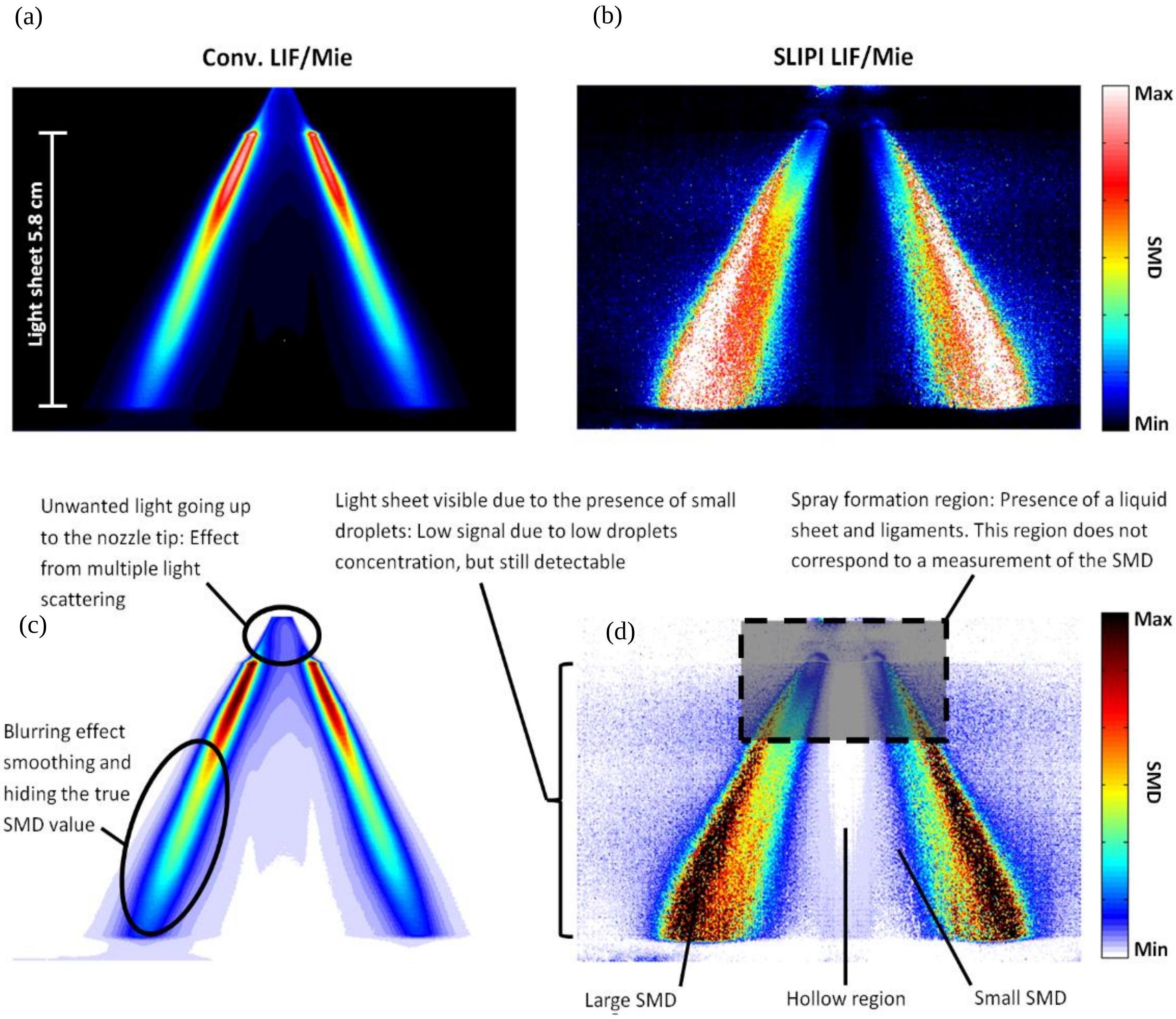

Figure 5: Comparison between the conventional and the SLIPI SMD images. Figures 5(a) and 5(c) represent the conventional LIF/Mie images with black and white background, respectively. The SLIPI LIF/Mie images with black and white background are shown in figures 5(b) and 5(d). This comparison concludes that the conventional SMD images suffers from multiple light scattering ; whereas, the SLIPI SMD images yield a faithful description of relative SMD distribution in the hollow-cone spray.

In conventional images, such issues are mostly apparent around the spray edges and towards the spray forming tails. In figure 5(c), the marked area refers to those effects; hiding the true value of SMD due to smoothing and unwanted light going up to the nozzle exit. On the other hand, the SLIPI-SMD images given in figure 5(b) and 5(d) are corrected from the multiple light scattering contributions and, therefore, reproduce a faithful two dimensional distributions of droplets SMD. However, the droplets SMD cannot be considered in rectangular marked area in figure 5(d) due the presence of a liquid sheet and ligaments. The spray droplets with large and low SMD can be easily distinguishable along with the hollow region as shown in figure 5(d). The global blurring effect from the center of the hollow-cone spray is completely removed. Also in figure 5(d), one could identify the presence of small droplets evaporating around the hollow-cone spray. Signal from these small droplets is low due to low droplets concentration but still detectable with SLIPI-LIF/Mie. It is also important to highlight that since the SLIPI-LIF/Mie images are free from the multiple light scattering contributions, the spray symmetry in SMD is achieved by taking the ratio of LIF and Mie images. More specifically, with the SLIPI approach, the influence of the light extinction is cancelled out by dividing the LIF/Mie signals of the two shoulders of the hollow-cone spray. Therefore, the SLIPI-SMD on the two sides of the hollow-cone spray represents a very good symmetry which was not possible to achieve with the earlier measurements performed using the PSD drop-sizing technique reported in reference [6].

5. Conclusions

The LIF/ Mie planar drop sizing approach was merged together with SLIPI, to extract the two-dimensional distribution of droplets SMD in a hollow-cone water spray. Results of two-dimensional SMD mapping were presented and compared for conventional and SLIPI images. However, the SLIPI-SMD results need to be calibrated with a PDA system for knowing the size of droplets which is currently in progress. The transmission measurements confirmed the dilute nature of the spray. It was found that even in this case, the multiple light scattering effects impose large errors on the SMD measurement. Therefore, for faithful SMD mapping it is important to use SLIPI-LIF/Mie over the conventional LIF/Mie approach to mitigate the multiple light scattering issues. The LIF/Mie signal detection strategy with one camera instead of two cameras can also be an important factor to consider for such measurements. In future studies, it would be very useful to verify the presented approach at different liquid pressures of injection, different incident laser power, different dye concentration and different camera $f_{\#}$. Such study would demonstrate the robustness of the technique. A second future work should focus on the calibration procedure to obtain the absolute SMD mapping.

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References

[1] P.N. Wild et al., Appl. Opt. 25(19) (1986) 3520-3526.
[2] W. D. Bachalo et al., J. Eng. Pow. 102 (1980) 798.
[3] L.G. Dodge et al., Appl. Opt. 26 (1987) 2144-2154.
[4] C.N. Yeh et al., 1 (1996) 297-308.
[5] P. L. Gal et al., Opt. Laser Technol. 31 (1999) 75- 83.
[6] B.D. Stojkovic et al., Appl. Phys. B 73 (2001) 75-83.
[7] R. Domann et al., Par. Part. Syst. Charact. 20 (3) (2003) 209-218.
[8] D. L. Hofeldt et al., Appl. Opt. 32 (1993) 7551-7558.
[9] D. Stepowski et al., 13th Int. symp Lisbon, Proceed. paper 1061 (2006).
[10] E. Berrocal et al., Appl. Phys. B 109 (2012) 683- 694.
[11] E. Berrocal et al., Opt. Express 16 (2008) 17870-17881.
[12] E. Kristensson, Ph.D. thesis, Lund University (2012).
[13] G. Charalampous et al., Appl. Opt 50(9) (2011) 1197-1209
[14] G. Charalampous et al., Appl. Opt 50(20) (2011) 3622-3637.
[15] H. C. van de Hulst, Dover (1981).