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ABSTRACT

While imaging optically dense media such as atomizing sprays, the multiple light scattering induces image artifacts and blurring effects which limit visibility. Therefore, extracting quantitative spray information such as droplet size and concentration from qualitative images becomes very challenging. However, multiple scattering effects can be efficiently addressed by means of the SLIPI (Structured Laser Illumination Planar Imaging) technique. Recently, using SLIPI in combination with LIF/Mie droplet sizing (ratio of the liquid Laser Induced Fluorescence (LIF) and Mie scattering signals), a mapping of absolute Sauter Mean Diameter (SMD or D_{32}) could be extracted. It was observed that without SLIPI, reliable measurements of SMD could not be achieved. In another work, a 3D map of the droplet extinction-coefficient (μ_e) in an aerated spray was extracted using the SLIPI-scan technique. In this article, SLIPI-LIF/Mie droplet sizing is performed in combination with SLIPI-scan in order to construct a 3D representation of droplet SMD in the developed spray region and the corresponding optical depth in 2D.

1. Introduction

Droplet size and concentration are among the most important quantities when it comes to spray characterization [1]. Such information helps deciding the suitability of one spray for a given application; such as for fuel-air mixing in combustion devices, cooling hot environments, powder productions in pharmaceutical and food industry, treating crops in agriculture, applying chemicals and paints, drug inhalation in medicine *etc.* [1]. A fully developed spray forms a cloud of polydisperse and spherical droplets which spread within a three-dimensional (3D) volume and, thus, getting a 3D measurement of spray quantities is important. The LIF/Mie droplet sizing technique for 2D mapping of Sauter mean diameter (SMD) of droplet was first reported by Yeh *et. al* [2]. The extinction coefficient (μe) mapping was demonstrated by Talley and coworkers using optical transmission measurements [3]. However, these methods are affected by multiple light scattering, as many photons undergo repetitive scattering events prior to detection. This generates out-of-focus light that degrades the sharpness of the resulting images and impose

challenges for the quantitative imaging of atomizing sprays. To address this issue, Structured Laser Illumination Planar Imaging (SLIPI) has been developed in 2008 [4, 5]. SLIPI is based on spatially imprinting a sinusoidal modulation on a conventional laser sheet, making the incident illumination "tagged". In a spray illuminated using structured light sheet, the multiply scattered photons "forget" the modulation structure while the singly scattered photons preserve it. This technique has been applied for extracting quantitative information, e.g. droplets SMD using the SLIPI-LIF/Mie ratio [6] and the local extinction coefficient using, for example, SLIPI-scan [7, 8]. In this article the two techniques are now combined to reconstruct a 3D image of droplet size and 2D images of corresponding optical depth of the probed spray droplet.

To obtain 3D data, using SLIPI-scan, images are recorded with the stepwise movement of the spray from its outer edge towards its center while keeping the laser sheet and the focus of the camera fixed. Thus, several slices of the LIF/Mie ratio in 2D and optical depth in 2D are generated. These 2D images of ratio could be patched together to construct a 3D image of droplet SMD. A Phase Doppler Interferometry (PDI) system is used for correlation between non-calibrated ratio measured by SLIPI-LIF/Mie and absolute SMD measured from PDI [6]. The PDI probe volume is coincided with the SLIPI light sheet for a faithful calibration. Here, the combined approach is demonstrated for a hollow-cone (HC) water spray at a liquid injection pressure of 50 bars.

2. Laser sheet imaging techniques

2.1. SLIPI

SLIPI is a structured light sheet imaging technique developed for mitigating the multiple light scattering intensity from the optically dense spray systems [4, 5]. The amplitude of this structured modulation usually follows a sine function, and it is realized with the help of a Ronchi grating and a spatial filter. In order to deduce a SLIPI image, a minimum three images (sub-images) with a subsequent phase difference of 120° is required. This is performed by shifting the grating in vertical direction. A detailed description of the SLIPI technique and its uses in two dimensional imaging of sprays can be found in [8]. Also, SLIPI images reconstructed from one or two sub-images have been demonstrated [9, 10]. The images from one sub-image are deduced at the cost of image resolution [9]. However, two sub-image based SLIPI requires a structured modulation of very high frequency and nearly the full image resolution is maintained [10].

2.2 LIF/Mie ratio imaging

The ratio of the laser-induced fluorescence (LIF) and the Mie scattered signal (Mie) of spray droplets of a dye doped liquid has been used to deduce their relative SMD where, the LIF and Mie signals are proportional to droplets volume (d^3) and surface area (d^2) respectively [1, 8]. However, the method is limited within the following conditions: (i) The probed droplets must be spherical and (ii) the fluorescence contribution from the gaseous phase should be minimum. Also, several studies have been conducted to evaluate the faithfulness of d^3 and d^2 dependance on the LIF and Mie signals, respectively [11-16]. It is found that the exponents varies according to the droplet size distribution and when molecular absorption is non negligible.

2.3 SLIPI-scan

In the SLIPI-scan technique the spray is scanned in a bread-slicing manner using a structured light sheet [7, 8]. The movement of spray is controlled by a translation stage. The corresponding light transmission within the spray is recorded on a cuvette filled with a dyed solution. The light intensity reduction due to light extinction and signal attenuation is deduced. Thus, using this information for each 2D slice, the technique measures the spatially resolved extinction coefficient of a droplet in 3D. Here in this article, SLIPI-scan is only used for optical depth measurements in 2D. However, the future aim is to use the droplet SMD information from SLIPI-LIF/Mie and extinction coefficients from SLIPI-scan for a 3D reconstruction of droplet concentration.

3. Experimental setup

The combined SLIPI-LIF/Mie and SLIPI-scan technique is shown in Figure 1. In (b), the top-view of the setup for the simultaneous detection of SLIPI-LIF/Mie and SLIPI-scan signal is shown. A PDI (Artrium PDI-TK2 system) is used for calibrating the SLIPI-LIF/Mie ratio with the absolute SMD measured from it. In (b), the side-view of the sinusoidally modulated light sheet illuminating the spray and the dyed solution in a cuvette (used for transmission measurements in SLIPI-Scan) is shown. The optical arrangement for creating the structured light sheet is similar to the setup shown in reference [6]. When the incident laser sheet of 448 nm wavelength (from a collimated continuous wave diode laser) excites the dye-doped water spray droplets, liquid LIF signal peaking at 517 nm is generated. To simultaneously record the LIF and Mie signals for SMD mapping, a beam splitter is used to guide the signals towards the two EM-CCD cameras

denoted as "LIF" and "Mie" in (a). Then, two band-pass filters F1 and F2 are fixed in front of the LIF and Mie cameras, respectively. The F1 is a broadband filter centered at 510 nm with 94 nm FWHM (Full Width at Half Maximum) while F2 is a narrow-band filter of the centered wavelength 448 nm with 20 nm FWHM. All images are recorded with exposure time of 0.08 seconds and 20 accumulations for each sub-image. The f-number of both camera objectives is fixed at 5.6. To perform the SLIPI-scan, the spray is moved along the Z-direction with a step difference of 500 μm which allows the laser sheet to probe the spray in a "bread-slicing" manner. Thus, by combining the SLIPI-LIF/Mie along with the SLIPI-scan measures the SMD of the spray droplet in 3D and the resulting attenuation of light for each step can be measured on the cuvette in 2D.
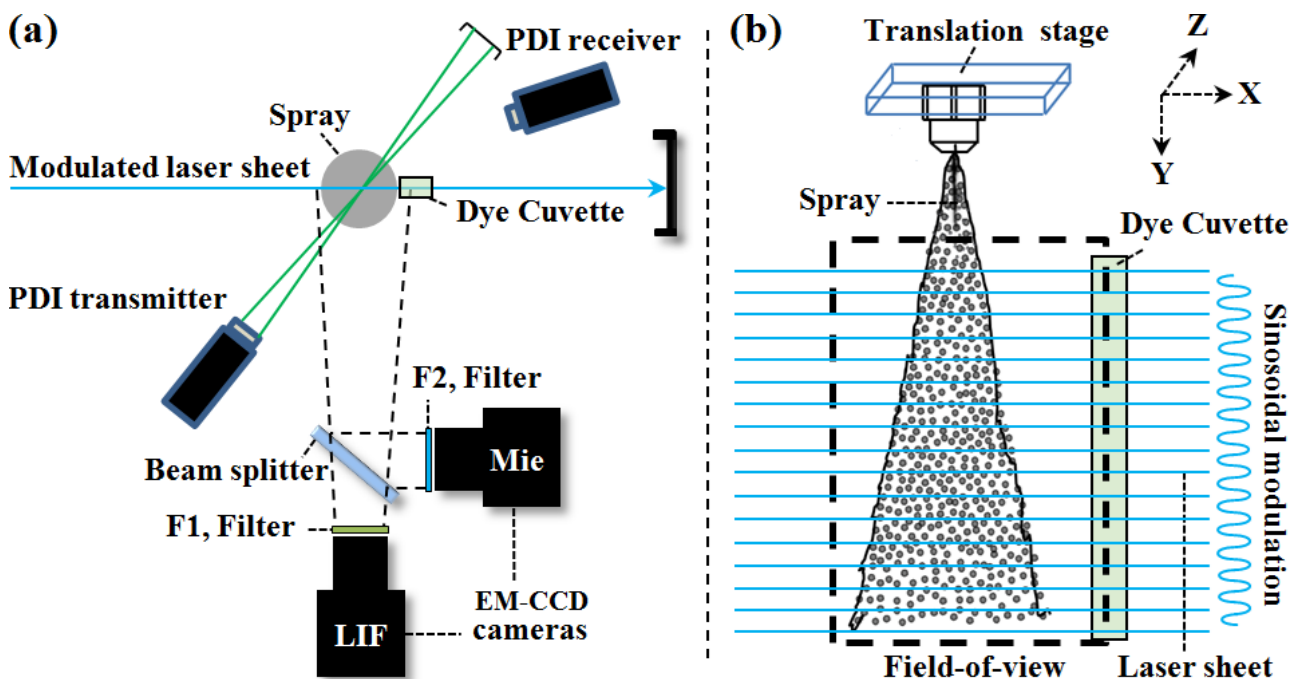

Fig. 1. (a) Top-view of the combined SLIPI-LIF/Mie and SLIPI-scan experimental setup. (b) Side-view of the setup showing the modulated laser sheet crossing the water spray and the dyed cuvette. The spray is fixed on a translational stage for a scanning procedure along the Z-direction.

4. Results and discussions

4.1 LIF and Mie images from SLIPI-scan:

The averaged LIF and Mie images recorded by SLIPI-scan at positions from 0 mm at the edge of the HC spray to towards its centre at 34 mm along the Z- axis are given in Figure 2. Out of a pair of total 69 images, only 8 are shown here. In (a), the conventional and in (b), the SLIPI images are

shown. The image background is calculated from the average of 100 pixels located at the top left corner of each image. From both the figures, it is evident that the SLIPI-LIF/Mie images gives a better representation of the hollow-cone spray. This is due to fact that the unwanted multiple scattered light effects are efficiently suppressed both in LIF and Mie images. However, if not suppressed, such effects produce blurring due to undesired out-of-focus signal, most visible at the top and bottom of the light sheet in the conventional images (e.g. a signal above the light sheet up to the nozzle tip is clearly visible).
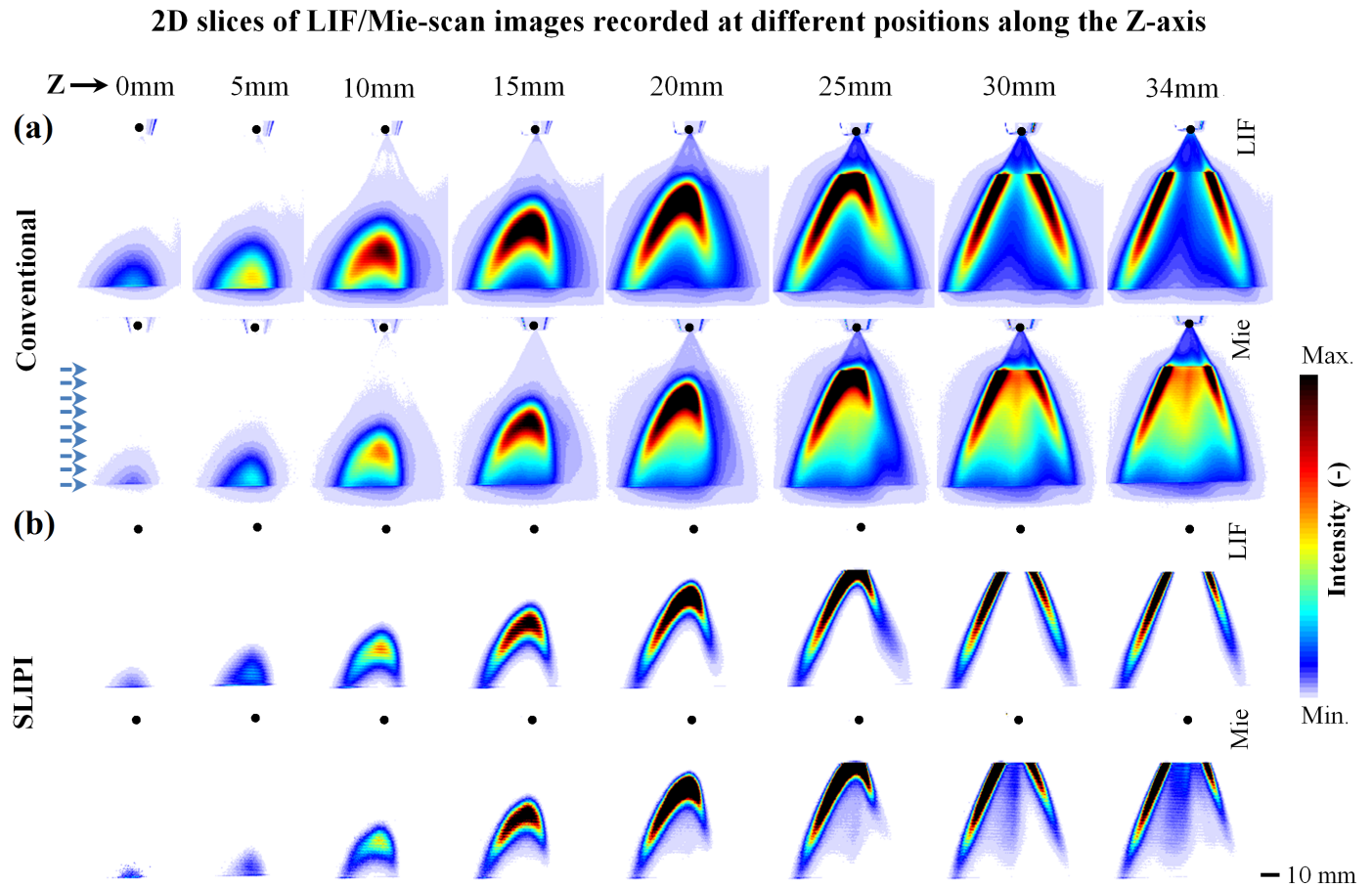
2D slices of LIF/Mie-scan images recorded at different positions along the Z-axis

Fig. 2. (a) The averaged conventional LIF and Mie images recorded along the Z-axis are given. Similarly, in (b), the averaged SLIPI LIF and Mie images are shown. When comparing (a) with (b), it is clear that the conventional images suffers from multiple light scattering effects.

4.2 Non-calibrated LIF/Mie ratio

Figure 3 shows the non-calibrated LIF/Mie ratio extracted after diving the LIF and Mie images of figure 2. The conventional and SLIPI LIF/Mie ratio images are shown in figures (a) and (b), respectively. Prior to the ratio, a threshold value equal to 0.00001 times the maximum peak

intensity of the image is set in SLIPI images. While for generating an image fairly comparable to SLIPI, the conventional require a threshold value 0.0015 times of the maximum peak intensity of the image. Any pixel value below this threshold is rejected to avoid numerical errors while ratioing the data. It is seen from both the figures that conventional images produce non-reliable ratio since it produces ratio gradients in the spray regions which are not illuminated, whereas SLIPI depicts an improved representation of the droplet size distribution in the hollow cone spray. The ratio producing higher gradients near the spray edges; showing the presence of large droplets while gradient decreases in the hollow region where smaller droplets are generated. The LIF/Mie ratio both for the conventional and SLIPI detections are found to be consistent with the one shown in reference [6]. Only SLIPI-LIF/Mie ratio is further considered for calibration with the SMD of droplet measured by the PDI system.
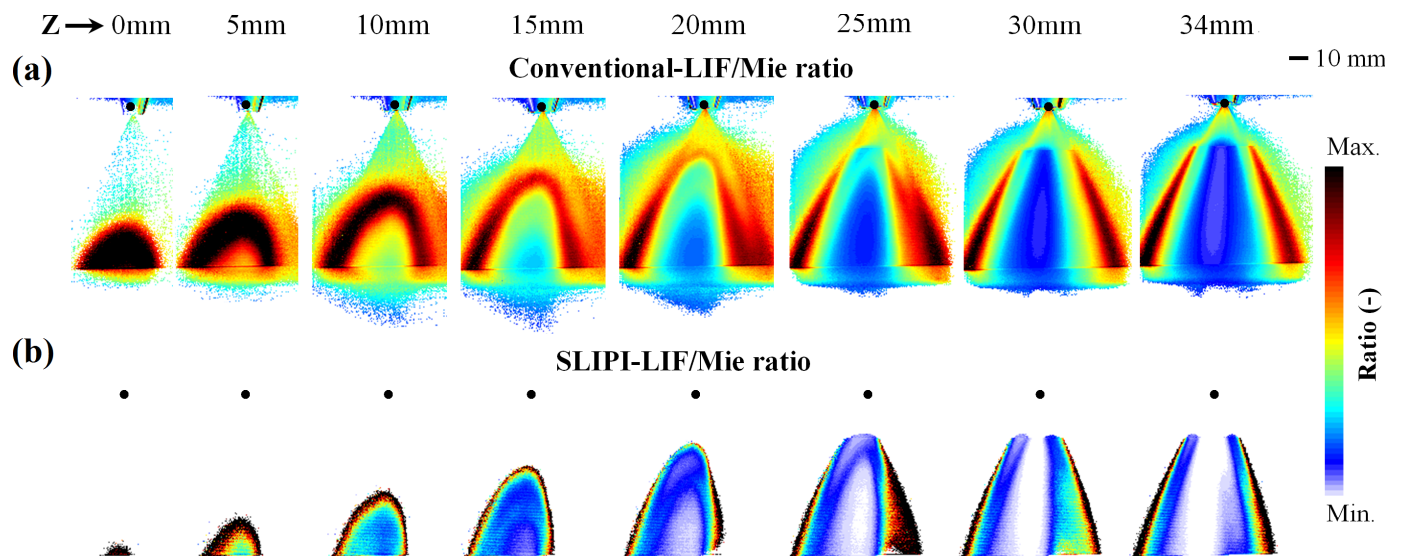

Fig. 3. (a) The averaged non-calibrated conventional LIF/Mie ratio images for positions $0 \leq Z \leq 34$ mm is shown. Similarly, in (b), the averaged SLIPI LIF/Mie images are shown. By comparing (a) with (b), it is observed that the conventional-LIF/Mie ratio is not reliable since it produces ratio gradients in the spray regions which are not illuminated. For example, a non negligible ratio values are appearing from the region residing between the nozzle tip and the light sheet illumination.

4.3 PDI measurements and LIF/Mie ratio calibration

Figure 4 shows the PDI measurements performed in order to calibrate SLIPI-LIF/Mie ratio with droplet SMD. In (a), the SMD measured at a given vertical position (Y = 7 cm) below the nozzle tip and along the X-axis (in dashed red line), from the center (at the X = -1 cm) of the spray to towards one of its edges (up to X = -3.7 cm). Note that the LIF/Mie ratio in the rectangular box

region is not valid for SMD calibration due to the presence of non spherical droplets. In (b), the SMD of droplet against distance along the X-axis is plotted. The large droplets of SMD = 70 μm are detected at the spray edge, while small droplet SMD = 12 μm are located in the spray center. For each location, 20000 validated size measurements are recorded by PDI and the corresponding absolute SMD is calculated. The histogram of the distribution of droplet size used to deduce the SMD at X = -1 cm and X = 3.7 cm is shown in figures 5(a) and 5(b), respectively. It is observed in all measurements that the diameter validation percentage was above 97%, confirming good sphericity of the droplets at a distance 7 cm below the nozzle tip.
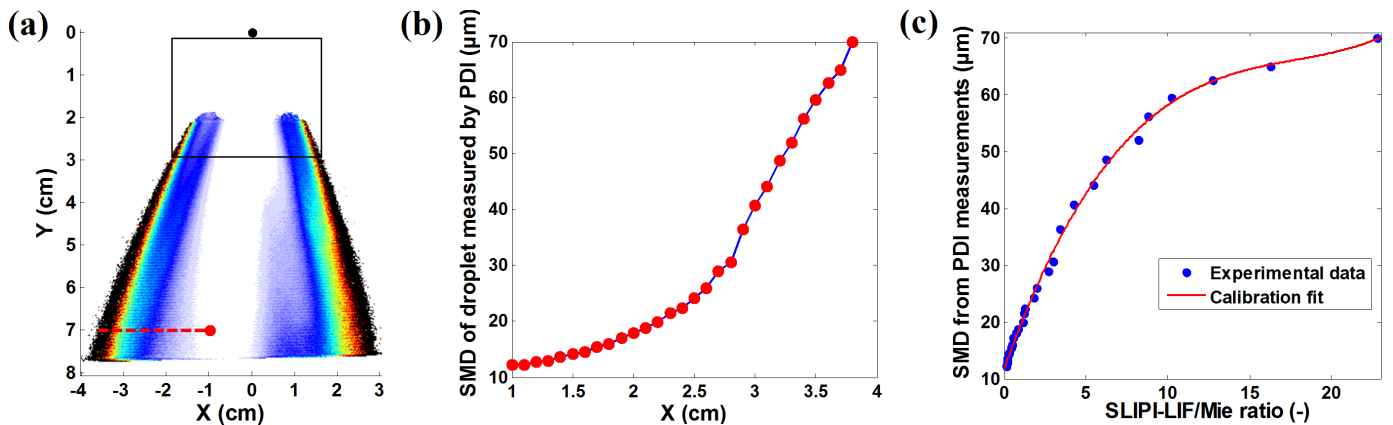

Fig. 4. (a) The SLIPI-LIF/Mie image showing the PDI calibration points located at Y = 7 cm and X = -1 to 3.7 cms. (b) Droplets SMD measured by PDI along the x-axis from one edge of the spray towards its center. For every millimeter measurement point the corresponding droplet size distribution is used to deduce the SMD in μms. (c) The plot of the SMD values measured with PDI against the corresponding SLIPI-LIF/Mie ratio. A cubic fit is found to be best fit for converting the SLIPI ratio into droplet absolute SMD (see figures 6 and 7).
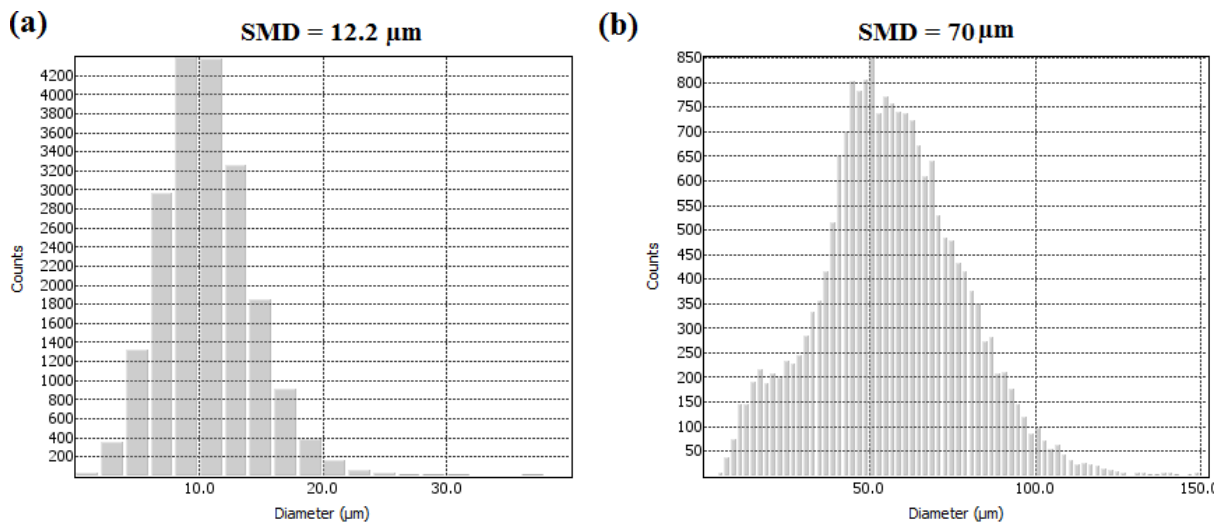
Fig. 5. The histogram of droplet size distributions used for SMD calculation by PDI. (a) The droplet size distribution for SMD = 12.2 μm measured by PDI calibration point located at Y = 7 cm and X = -1 cm. Similarly, in (b), the resulting SMD is 70 μm which is deduced from the droplet size distribution measured by PDI at X = 3.7 cm.

In (c), the SLIPI-LIF / Mie ratio is plotted against the droplet SMD measured from PDI. The curve shows the experimental data and the calibration fit used for converting the ratio into the absolute SMD value.

4.4 Absolute SMD mapping in 2D and 3D

In figure 6, the 2D mapping of calibrated SLIPI-LIF / Mie ratio representing the absolute SMD of the droplet is given. These slices of the spray scanning along the Z-direction from 0 mm to up to 34 mm provide a great insight on how the droplets are distributed within the spray. It is seen that near the spray periphery droplet size ranges from 60-73 μm while in the centre of the spray they are within the range of 10-12 μm.
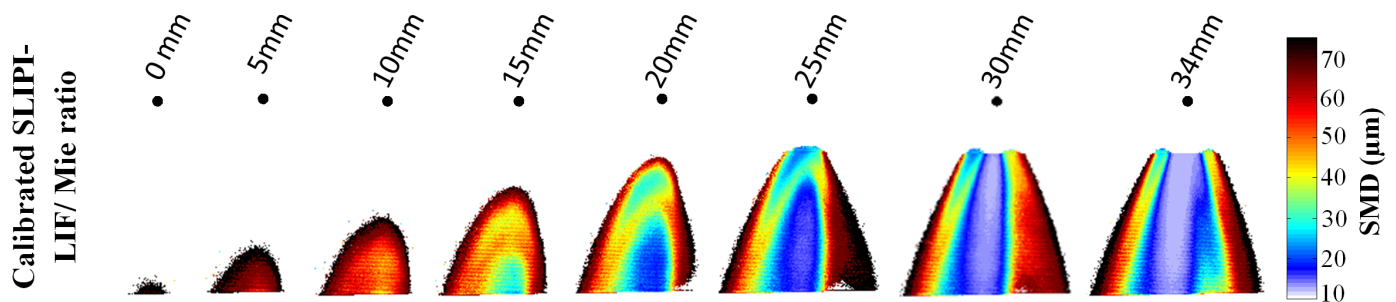

Fig. 6. The calibrated SLIPI-LIF/Mie ratio representing the map of the absolute SMD of droplet at different positions along the Z-axis are shown. Large droplet of SMD 70-73 μm are found near the two outer edges of the hollow-cone spray while in the centre droplet SMD is found to be in the range of 10-12 μm.

Figure 7 shows the 3D representation of droplet SMD from $0 \leq Z \leq 34$ mm, which corresponds to one-half of the HC spray. These 3D images are reconstructed by stitching all the 69 2D slices of SMD as shown in figure 6. In (a), the front-view of droplet SMD in 3D while in (b) and (c), the side and top view of the 3D-SMD of the spray is shown.

In (a), it is seen that droplet SMD starting from the left side along the X-axis is in the range of 73-70 μm between positions 0 to 3 mm. From 3 mm to 10 mm, the SMD is between 70-55 μm while it reduces down from 50-10 μm at X = 10 to 35 mm. When moving further from 35 mm to 65 mm, it is clearly visible that droplet SMD distribution on the right side is not identical to that on the left. Also from the side-view and top-view shown in figure (b) and (c), respectively it is more evident that the HC spray is not symmetrical.
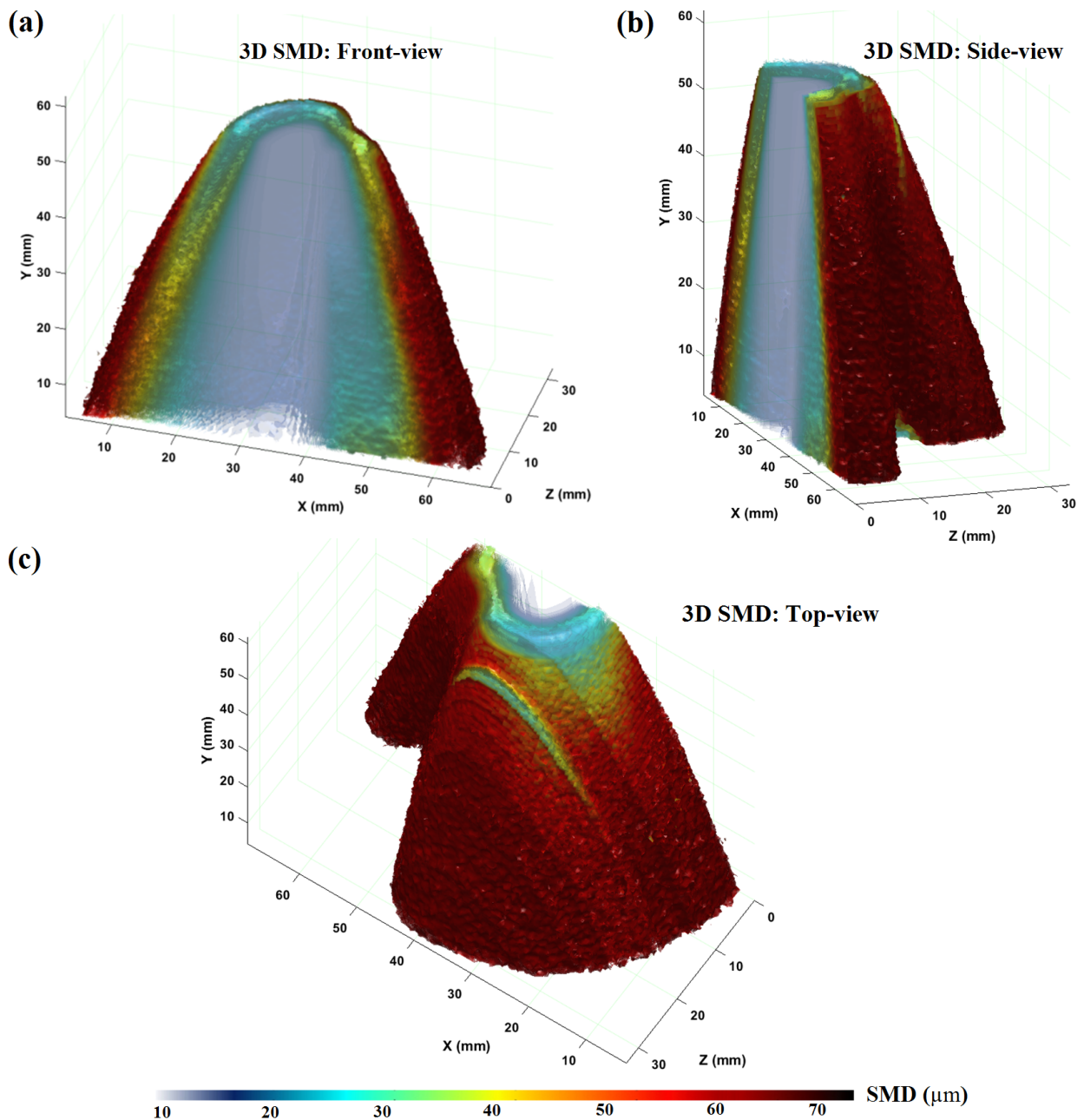
(a)

3D SMD: Front-view

(b)

3D SMD: Side-view

(c)

3D SMD: Top-view

SMD (μm)

10   20   30   40   50   60   70

Fig. 7. The 3D visualizations of droplet SMD in the hollow cone spray are given here. The front-view of the spray is shown in (a) while in (b) and (c), the side and top view, respectively are given. It is seen from the figures that the droplet near the spray periphery are large while they reduces down towards its centre. It is also found that the droplet SMD distributions on the both sides are not identical and spray is not symmetrical.

4.5 Optical depth measurements

Optical depth (OD) deduces an approximation of the number of scattering events occurring in the probed medium [8]. It is also referred to as the *optical thickness* of the probed sample. Here, it

is calculated according to the Beer-Lambert's law and from the transmission measurements similar to the one demonstrated in [6]. Figure 8 shows the 2D slices of the optical depth of sprays for each scanning step from $0 \leq Z \leq 34$ mm. For this plot, the OD value chosen for each Z step is a distance of approximately 13.5 mm along the X-axis and 54 mm along the Y–axis of the cuvette. Thus, a total of 69 scan steps corresponds to a total distance of 103 mm along the X-axis. At $Z = 0$ mm, it is seen that the OD in the cuvette varies from 0.2 to 0.5 (on the top) to up to 1 (near the bottom) which shows that on the top there are very few or no droplets and thus the number of scattering events is less than 1.
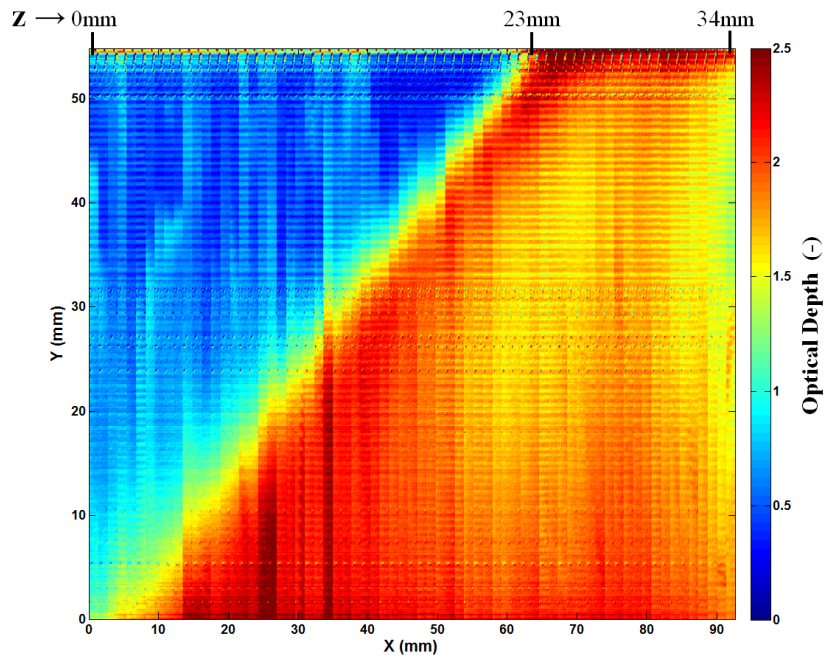

Fig. 8. The optical depth of the spray corresponding to each layer from $0 \leq Z \leq 34$ mm is plotted here. These 2D images show that near the outer edge of the spray ($Z = 0$ mm) the probability of interaction of a majority of photons with the droplet is less than 1 however, it increases up to 2 when the spray is intersected in the middle ($Z = 34$ mm) with the light sheet.

However, on the bottom, due to the presence of droplets the number of scattering events is close to 1. When moving inside the spray towards $Z > 0$ mm, the OD value increases up to 2.5. At $23 \leq Z \leq 34$ mm, the OD value throughout the spray is approximately in the range of 1.5 to 2.5, however, it is more than 2 on the top and the bottom of the spray due to the presence of ligaments and non spherical droplets near the nozzle and large droplet density at the bottom.

5. Conclusions

SLIPI techniques are used in combination with LIF/Mie ratio imaging for 3D droplet sizing and transmission measurements for 2D mapping of the optical depth of a hollow-cone spray. The conventional approach suffers from multiple light scattering effects. The 3D representation of SMD of spray provides a great insight into the distribution of droplet within the spray. It is found that the spray is not symmetrical. The optical depth mapping shows that the majority of photons within the spray have interacted more than twice with the droplet prior to their exit. The presented results show a way forward to the new possibilities for faithful droplet size and concentration mapping in sprays.

Acknowledgements

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