EINDHOVEN UNIVERSITY OF TECHNOLOGY

Comparative analysis of drop-size measurement in highly dense sprays using shadowgraphy, PDA, and SLIPI

Citation for published version (APA):
Swami, V. V., Buist, K. A., Baltussen, M. W., Schröder, J., Arbon, M., van Dijk, K., & Kuipers, J. A. M. (2023). Comparative analysis of drop-size measurement in highly dense sprays using shadowgraphy, PDA, and SLIPI. In *ILASS Europe 2023 Meeting : European Meeting on Liquid Atomization and Spray Systems* Article DT 2.10 ILASS Europe.

Document status and date:
Published: 01/09/2023

Document Version:
Publisher's PDF, also known as Version of Record (includes final page, issue and volume numbers)

Please check the document version of this publication:

• A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
• The final author version and the galley proof are versions of the publication after peer review.
• The final published version features the final layout of the paper including the volume, issue and page numbers.

Link to publication

General rights
Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

• Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
• You may not further distribute the material or use it for any profit-making activity or commercial gain
• You may freely distribute the URL identifying the publication in the public portal.

If the publication is distributed under the terms of Article 25fa of the Dutch Copyright Act, indicated by the "Taverne" license above, please follow below link for the End User Agreement:

www.tue.nl/taverne

Take down policy
If you believe that this document breaches copyright please contact us at:

openaccess@tue.nl

providing details and we will investigate your claim.

Download date: 08. Feb. 2024

Comparative Analysis of Drop-size Measurement in Highly Dense Sprays using Shadowgraphy, PDA and SLIPI

V. V. Swami*[1], M. W. Baltussen[1], J. Schröder[2], M. Arbon[2], K. van Dijke[2], J. A. M. Kuipers[1], K. A. Buist[1]
[1]Multiscale Modelling of Multiphase Flows, Department of Chemical Engineering and Chemistry, Eindhoven University of Technology, the Netherlands
[2]Danone Nutricia Research, Utrecht, the Netherlands
*Corresponding author: v.v.swami@tue.nl

Abstract
Atomization is a physical phenomenon that is widely encountered in many engineering and industrial applications, such as in combustion engines, spray coating, spray dryers and many more. Spray characterization involves the determination of the droplet size and velocity distributions (both probability density function and spatial). To determine these parameters experimentally, traditionally, microscopic shadowgraphy and Phase Doppler Anemometry (PDA) are used, because of their relative ease of use and high accuracy. However, the application of these techniques is limited to relatively less dense sprays. In highly dense sprays, the strong multiple scattering effects cause significant errors in the determination of relevant parameters. Therefore, the Structured Laser Illumination Planar Imaging (SLIPI) technique is adopted. In this work, comparative measurements are reported to assess the capabilities of these techniques for drop-size measurements in a highly dense spray originating from a pressure swirl nozzle.

Introduction
Atomization and spray formation are widely encountered in many engineering and industrial applications ranging from combustion & propulsion, spray coating, spray drying, to agricultural sprays. The droplet size distribution within such sprays is of great importance in all these applications. The determination of the drop-size distribution is of paramount importance to assess the applicability, efficiency and dynamics of such sprays for a particular application.
A range of different experimental techniques is available to measure the droplet sizes in a spray. The experimental techniques differ in operating principle and range from imaging to non-imaging techniques such as shadowgraphy, planar drop-sizing, laser diffraction methods, and Phase/Doppler method [1]. Each of these methods has its own advantages and disadvantages and are suitable to a particular type of spray. The applicability of a technique depends on ease of operation and accuracy. Most commonly used techniques in both industrial applications and low droplet density sprays include shadowgraphy, usually commercially available with imaging systems from LaVision and Oxford Lasers, Phase Doppler Anemometry (PDA) and laser diffraction measurement systems such as Malvern droplet size analyser. These techniques have been widely utilized for a variety of different sprays. However, there is not much information available on the accuracy of a particular technique and comparison between different techniques for any particular type of spray. Some previous works compare few of the techniques regarding their accuracy and for a limited range of sprays or drop sizes [2, 3, 4]. Moreover, there is also limited information on accuracy and comparison of these techniques, particularly in dense sprays where the effect of multiple scattering light is a very well-known problem. Recent developments in drop-sizing in dense sprays include structured illumination, Structured Laser Illumination Planar Imaging (SLIPI), as an extension to planar imaging and provides a promising way to deal with such multiple scattering problems in sprays [5, 6]. Initial works on SLIPI shows quite some improvements in reliable droplet size measurements in dense sprays [7, 8].
In this work, therefore, two widely used measurement techniques shadowgraphy and PDA are compared with each other. The measurements are carried out in a hollow cone spray produced by a pressure swirl nozzle. The droplet size data obtained from these measurements is compared to assess the reliability of these techniques to measure the droplet size in such a dense spray. Furthermore, the SLIPI-LIF/Mie drop-sizing is implemented. The SLIPI-LIF/Mie intensity ratio in the spray is separately calibrated with the two other techniques to obtain the final SLIPI-Shadow and SLIPI-PDA droplet size maps. Finally, a comparison between the data obtained from the measurement methods employed here in the work is provided.

Materials and Methods
The measurements are carried out in a spray produced by a pressure swirl nozzle (Delavan SDX III). A liquid solution of 45% TS Maltodextrin in water is prepared and sprayed at desired flow rates using a high pressure 3-piston pump. The liquid flow rate, injection pressure, temperature and density are monitored with in-line sensors. The operating conditions and properties of the liquid used in this work are tabulated in Table 1. The viscosity is measured before each experiment (at shear rates of 1-1000 1/s to check for Newtonian behavior of the fluid and at a temperature of 30°C) with an Anton Paar MCR 302 (at Danone Nutricia Research) using a cylinder geometry for shadowgraphy and a TA Instruments' AR-G2 rheometer using a plate-plate geometry for PDA & SLIPI measurements.

Table 1. Experimental conditions and physical properties of the used fluids.

Technique	Liquid (by weight)	Viscosity (kg/m.s)	Density (kg/m^3)	Pressure (bar)	Flow Rate (l/hr)
Shadowgraphy	Maltodextrin (45 % TS)	0.0385	not measured	50	88
PDA	Maltodextrin (45 % TS)	0.0415	1119	50	88.2
SLIPI	Maltodextrin (45 % TS)	0.0415	1119	50	88.2

A general schematic representation of the measurement techniques, measurement scheme, and a pressure swirl nozzle used in this work are shown in Figure 1. The measurement scheme and the details of the measurements are provided in the following Table 2. Care is taken that the measurements cover the same area of the spray for the calibration and that any data outside the range of the other techniques is not used for calibration. The specific description on the techniques and setups is given in the following sub-sections.

Table 2. Measurement scheme.

Technique	Measurement Resolution	Distance from orifice (mm)	Distance from axis (inner pos.) (mm)	Distance from axis (outer pos.) (mm)
Shadowgraphy	Point-wise, step 2 mm	70	18	40
PDA	Point-wise, step 2 mm	70	0	44
SLIPI (Illuminated region)	Planar	50-90	-12	54

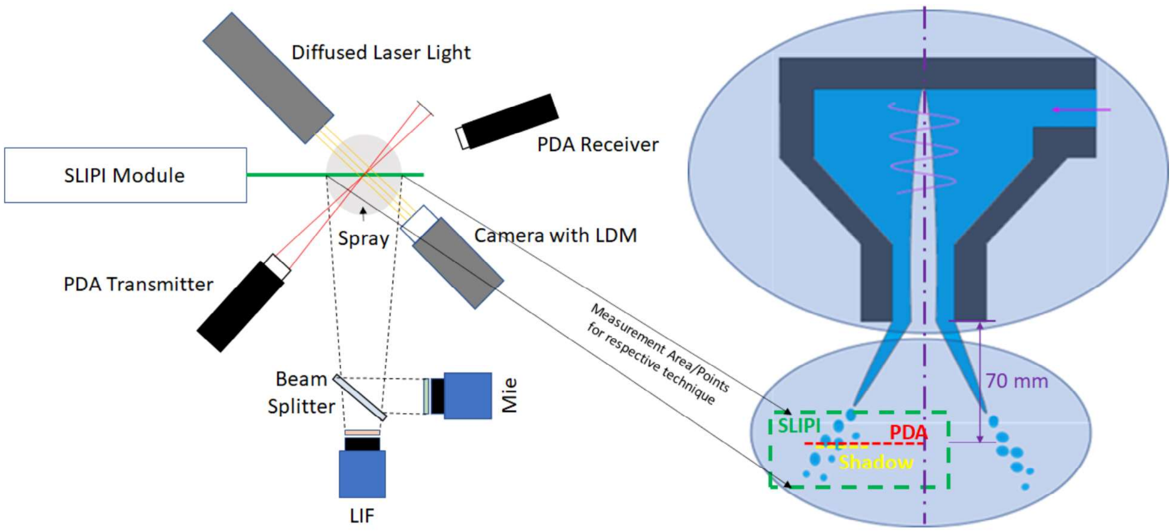

Figure 1. Schematic representation of measurement techniques (left) used for droplet size measurement in pressure swirl nozzle (right); Shadowgraphy: Diffused Laser Light & Camera with LDM, PDA Transmitter & Receiver, Structured Laser Illumination Planar Imaging (SLIPI): Module, Beam Splitter, and LIF & Mie Cameras (Measurement region for each technique is provided in right figure).

Shadowgraphy

The first technique used in this work is a shadowgraphy technique available at Danone Nutricia Research. The setup is an imaging system, VisiSizer N60V from Oxford Lasers, equipped with a laser light source and optical unit. The optical unit and the zoom setting is chosen to allow measuring spray droplets between 8 and 500 μm. The area of view is 1495 μm by 1495 μm. The maximum probe depth is 2125 μm. A photograph of the setup in operation along with it's schematic is shown in Figure 2.

The measurements are carried out from the edge of the spray towards the center of the spray by traversing the imaging setup in 2 mm steps into the spray. The images are acquired until at least 10000 droplets are recorded. The measurement is executed in the zones of the spray where the required number of droplets are detected within a maximum duration of 60 seconds. The use of the shadowgraphy technique in a dense spray is challenging due to the obscuration of the light by the spray. Therefore, a spray splitter is used to improve the contrast between the droplets for the available imaging system. The spray splitter removes a part of the spray behind the focused area. This increases the available light reaching the camera and allows acquisition of droplets also in denser regions of the spray. The acquired images are processed using VisiSize software for detection and determination of the droplet sizes. The minimum and maximum droplet size detected using the setup is 8 μm and 338 μm, respectively.

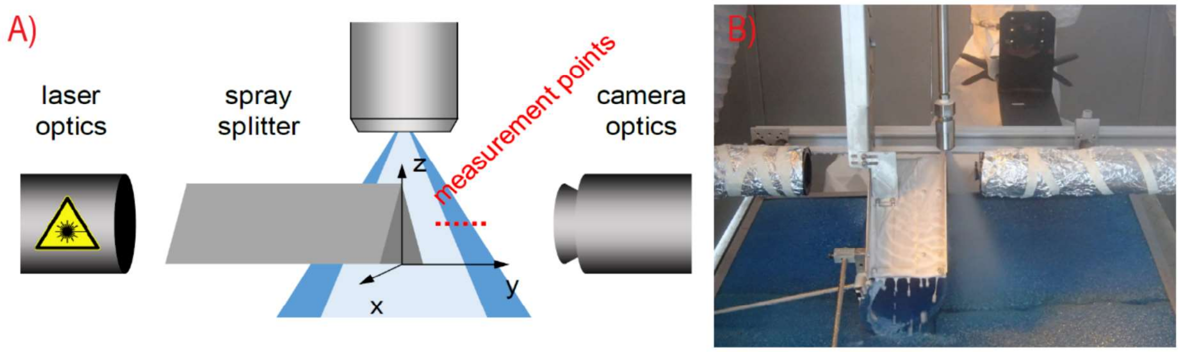

Figure 2. Schematic representation A) & a photograph B) of shadowgraphy setup at Danone Nutricia Research.

Phase Doppler Anemometry (PDA)

The second technique employed is the PDA technique from Dantec Dynamics. The instrument consists of a transmitting optics and a detector/receiver, both having front lenses with 310 mm focal length. The receiver is aligned at a scattering angle of 70^o in the forward refraction mode and mask B is used based on previous work on water-based spray using the same instrument [9]. A photograph of the PDA setup is shown in Figure 3. The measurements were carried out from the center of the spray (0 position) to the edge of the spray with a step size of 2 mm. The total count and measurement time at each point is kept at 20000 and 20 seconds, respectively. In order to obtain reliable PDA data across the radial positions, the overall validation and spherical validation is maintained at > 85 % and > 90 %, respectively. With these settings during the measurement, data rates of approximately 11000 #/s are obtained in the core region of the spray. The edge of spray (traversing from 0 position towards outside with 2 mm step) is found when data rates fall below 1000 #/s, and the measurement is stopped. The minimum and maximum droplet size measured is 1 μm and 100 μm, respectively.

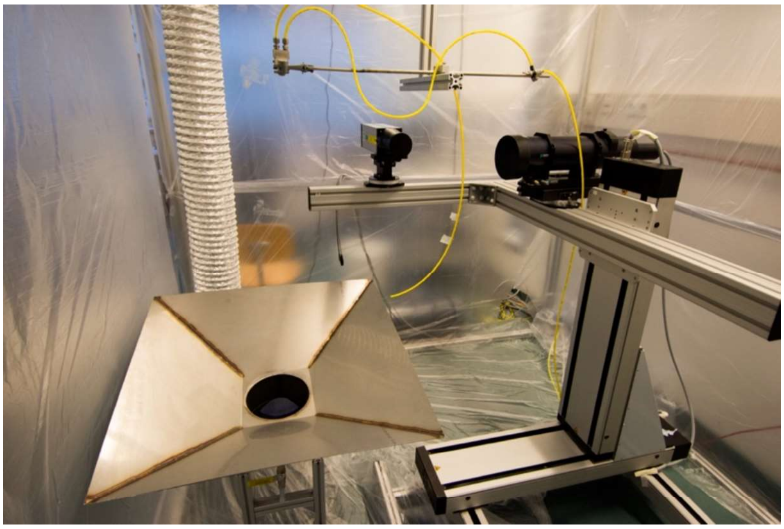

Figure 3. Photograph of PDA setup in the lab with transmitting and receiving optics from Dantec Dynamics.

Structured Laser Illumination Planar Imaging (SLIPI)

Structured Laser Illumination Planar Imaging (SLIPI) is one of the most recent developments in spray diagnostics as an extension to planar LIF/Mie drop-sizing in dense sprays [5, 10]. The SLIPI technique has been successfully implemented in dense sprays by significantly reducing the multiple scattering light [6, 7, 11], which otherwise pose serious problems to obtain accurate measurements using other traditional methods. The 3p-SLIPI-LIF/Mie (3 phase SLIPI) drop-sizing technique is adopted here for pseudo-steady state drop size measurement by illuminating the spray with structured modulated light. The optical arrangement for the structured laser sheet is adopted from [7]. A photograph of the optical setup for SLIPI is shown in Figure 4. Both Laser Induced Fluorescence (LIF) and Mie scattering signals are simultaneously recorded in order to capture the same flow field using two sCMOS cameras (LaVisions Imager sCMOS) equipped with the respective optical filters. 1000 images are recorded and averaged at each phase (0, 120, & 240 degree) to combine them to obtain the final SLIPI-LIF & SLIPI-Mie images according to equation 1. The root-mean-square (RMS) of the absolute differences between these sub-images allows to mathematically suppress the multiple scattering light. The ratio of the two SLIPI images provide a final ratio-metric

SLIPI-LIF/Mie image, which is essentially proportional to the Sauter Mean Diameter (SMD) (see equation 2).

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

$$SMD_{SLIPI-LIF/Mie} = k.\frac{I_{SLIPI-LIF}}{I_{SLIPI-Mie}} \tag{2}$$

The steps involved in obtaining the final drop-size map from SLIPI technique are summarized using actual images obtained during the measurement in Figure 5. The final intensity map is converted to the actual drop-size map by obtaining the calibration factor (k in equation 2) with an independent technique (here, PDA and shadowgraphy). The linear fit is obtained from calibration data and used further to obtain drolet size maps. Given that the droplet velocities in the spray are in the order of 20 m/s, it is challenging to obtain a perfect linear correlation between the droplet size and corresponding SLIPI-LIF/Mie ratio (see Figure 5 for calibration curve).

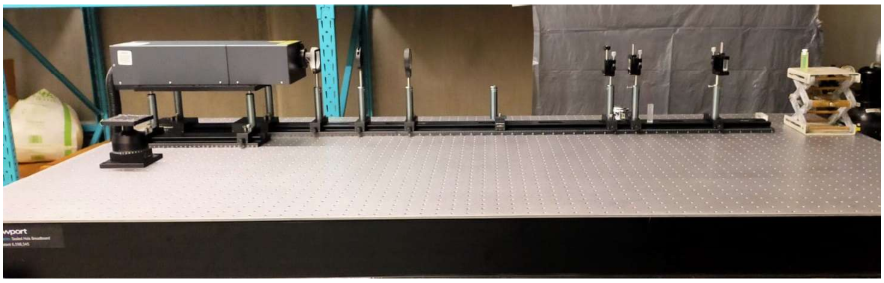

Figure 4. Photograph of the SLIPI setup.

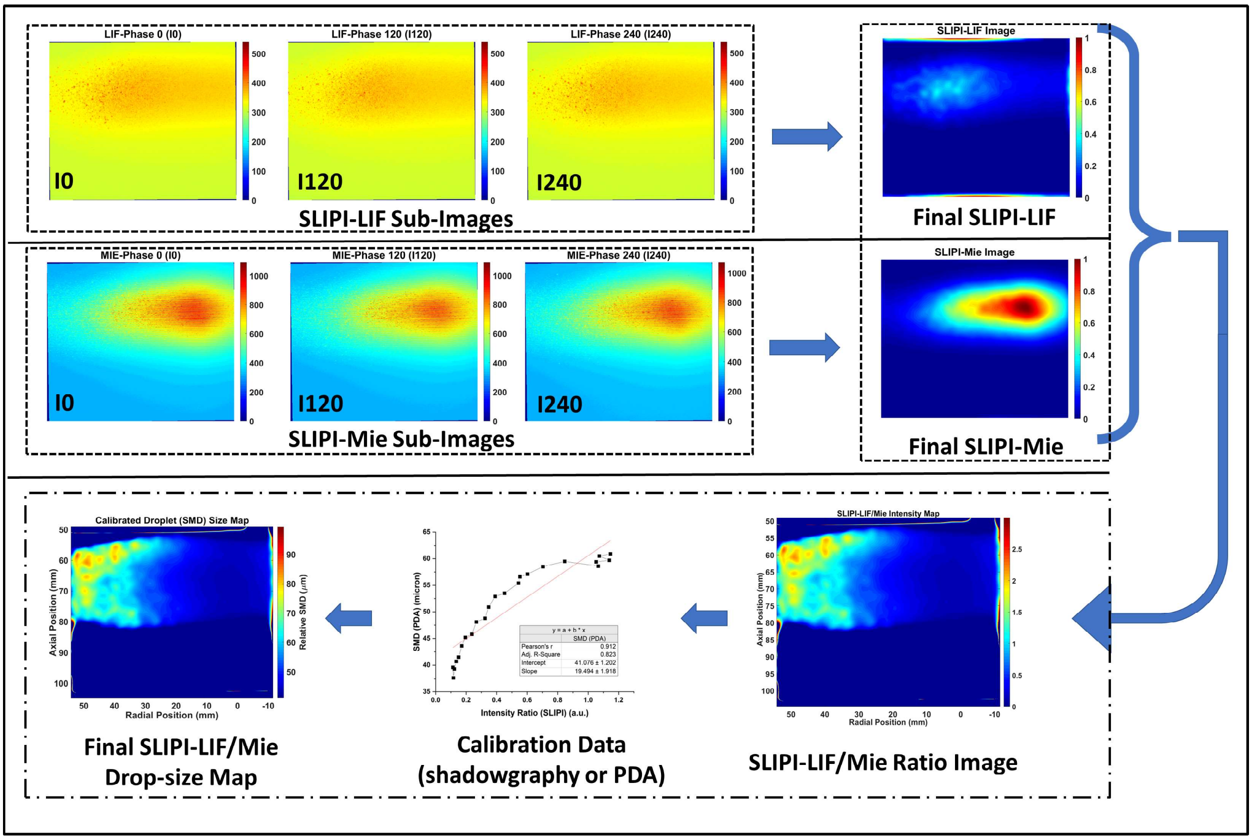

Figure 5. Processing of SLIPI images from sub-images to final droplet size map.

Results and discussion

The drop-size measurements are carried out using three different techniques, shadowgraphy, PDA, and SLIPI. Initially, shadowgraphy and PDA are compared with each other using the data obtained at comparable measurement points. For the results with SLIPI technique, a calibration with an independent technique is required. In this work, appropriate droplet size data is used from shadowgraphy and PDA for calibration of the SLIPI-LIF/Mie ratio towards final SLIPI-Shadow and SLIPI-PDA droplet size maps, respectively. Besides the local SMD, the shadowgraphy and PDA provide the droplet size distributions as well. At this point, however, the SLIPI does not provide the distributions, and therefore, only local SMD data will be compared and discussed further in more detail. In the end, the overall comparison of the SMD is made between all the techniques employed in this work.

Shadowgraphy vs. PDA

The droplet size data obtained using shadowgraphy and PDA are compared. The radial SMD profiles and volume distribution in the form of cumulative volume distribution are shown in the Figure 6. It can be seen that the PDA estimates larger SMD values at all measurement points along the spray. The difference between the SMD values can be explained when the cumulative volume distributions from shadowgraphy and PDA are compared. Figure 6 (right) shows this profile at 40 mm and is representative for all measurement positions, i.e 18 to 40 mm. The figure clearly shows a non-negligible contribution of droplets larger that 100 μm, especially droplets between 100 - 200 μm are present in the spray while droplets larger than 200 μm are almost not obtained. However, the PDA can only measure droplets upto 100 μm. In addition, shadowgraphy distribution shows a higher contribution of the smaller droplets (<70 μm) which outways the larger droplets (>100 μm) in SMD calculation and leads to overall smaller SMD.

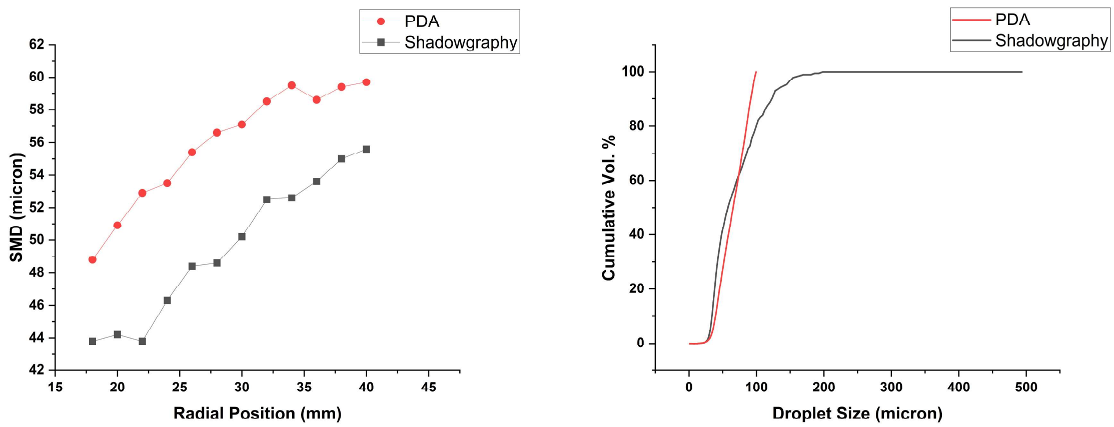

Figure 6. Droplet size data using shadowgraphy and PDA; SMD (left), cumulative volume distribution at 40 mm location(right).

Overall these differences in the size distribution do not lead to a large deviation in the SMD data obtained along the spray (<15%). Besides, the deviation can be attributed to a small difference in the viscosity values of the used liquids used in shadowgraphy and PDA measurements, and the measurement or rejection criteria used for successful measurements in both the techniques, as mentioned in the Materials and Methods section.

SLIPI-Shadow vs. Shadowgraphy

First, the shadowgraphy data is used to convert the SLIPI intensity map to the droplet size map (SLIPI-Shadow). The final SLIPI-Shadow droplet size map along with the calibration data obtained at 70 mm from the nozzle are shown in Figure 7. In Figure 8, the droplet size data obtained using shadowgraphy is compared with the SLIPI data calibrated with the shadowgraphy data. As the total droplet count needs to be sufficient, the shadowgraphy measurements are performed between the radial positions of 18 to 40 mm only and thus, this width is assumed to be the spread of the spray. For comparison of the data, therefore, the SLIPI data is also obtained between these points. As can be seen from Figure 8, the calibrated SLIPI data very well match with the raw shadowgraphy droplet size data.

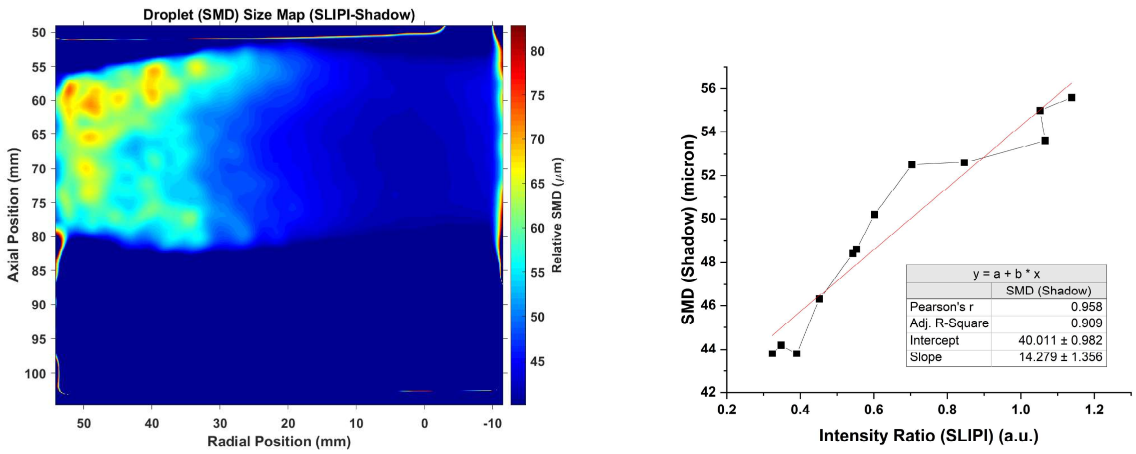

Figure 7. SLIPI-Shadow droplet (SMD) size map (left) and calibration data from shadowgraphy (right).

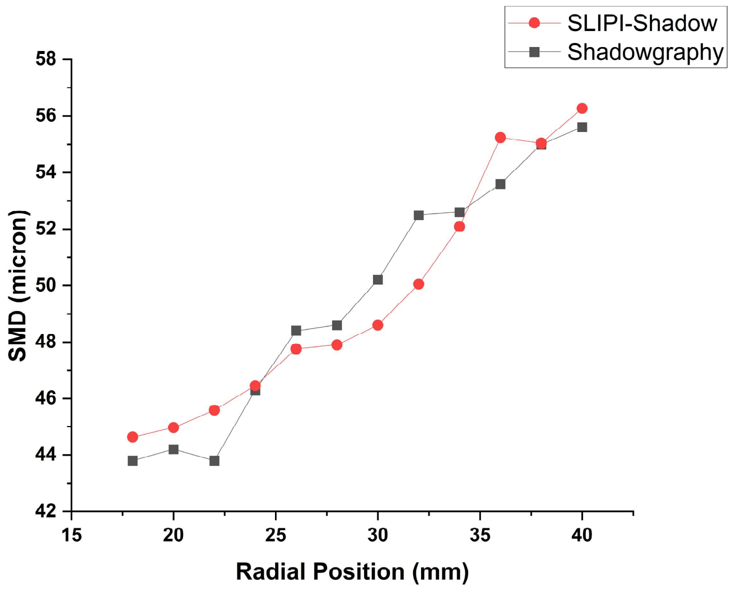

Figure 8. Droplet size data using SLIPI and shadowgraphy.

SLIPI-PDA vs. PDA

To compare the droplet size data obtained from the PDA and SLIPI, the SLIPI data is also calibrated with the PDA data (SLIPI-PDA). The calibrated SLIPI-PDA droplet size map and corresponding calibration data are shown in Figure 9.

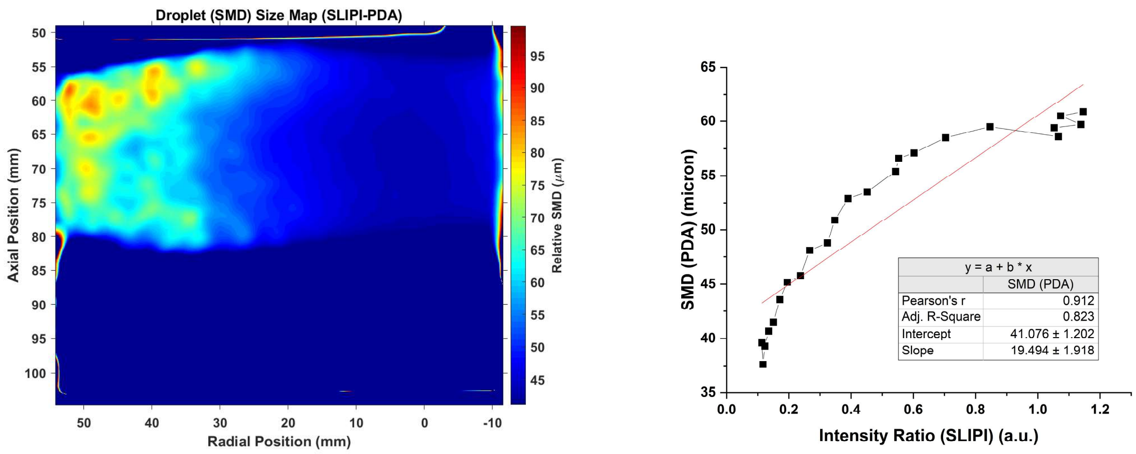

Figure 9. SLIPI-PDA droplet (SMD) size map (left) and calibration data from PDA (right).

Figure 10 shows the comparison of the droplet size measurement using the calibrated SLIPI-PDA data and independent PDA data at similar measurement points. The comparison is made here for the measurement points from 0 mm to 44 mm, as the data rate for the PDA reduced to below 1000 #/s compared to very high in the core of the spray. The SLIPI-PDA seems to slightly overestimate the droplet sizes towards the two edges of the spray and slightly underestimate between the radial positions of 15 mm to 35 mm.

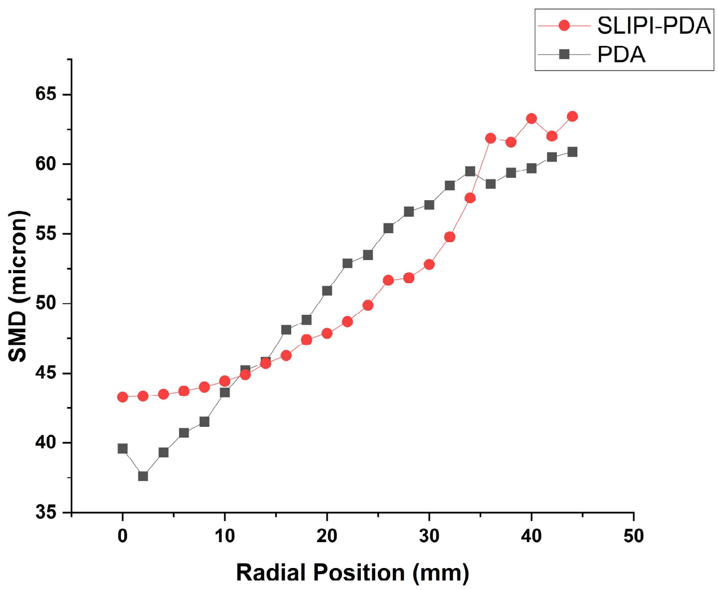

Figure 10. Droplet size data using SLIPI-PDA and PDA

Comparison of all Investigated Techniques

Figure 11 shows the droplet size data obtained using all the employed techniques in this work. In general, the drop-size measurement obtained using PDA are slightly higher than those obtained using shadowgraphy.

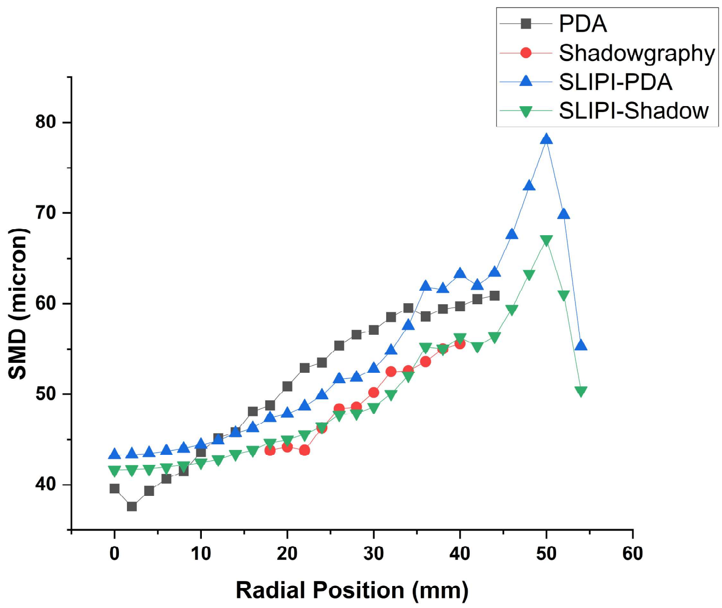

Figure 11. Comparison of drop size measurements from all the techniques

The drop size maps obtained from SLIPI-LIF/Mie drop-sizing, either calibrated with PDA or shadowgraphy data, compare well with the data from both the techniques. Additionally, the figure shows that SLIPI also captures the regions outside the edge of the spray (>44 mm), with larger SMD values, which otherwise considered to be outside the edge of the spray in other PDA and Shadowgraphy measurements due to low amount of droplets. Therefore, the data obtained in this region of the spray using SLIPI needs further investigation.
The overall mean SMD values obtained with each measurement technique are tabulated in Table 3. These mean values are calculated for the comparable measurement points (18 to 40 mm i.e. the range for the shadowgraphy technique which is the smallest). Again, it can be seen that PDA estimates a slightly larger drop size (SMD), but within an acceptable overall deviation of <10%.

Table 3. Comparison of overall Sauter Mean Diameter.

Techniuqe	SMD (μm)
Shadowgraphy	48.40
PDA	55.91
SLIPI-Shadow	49.55
SLIPI-PDA	51.24

Conclusions

In this work, three experimental techniques, shadowgraphy, PDA and SLIPI, are employed for the measurement of droplet sizes in a dense spray produced from a pressure swirl nozzle. The data shows that the mean SMD values (local and global) compare well with each other at comparable measurement points. The PDA measurement tends to predict larger droplet sizes (SMD) at all the measurement points compared to the shadowgraphy but with an acceptable local deviation <15%.
The SLIPI data is calibrated separately with shadowgraphy and PDA. The droplet size data obtained from either calibration compares well with each other. Thus, the obtained LIF/Mie ratio map using structured illumination reflect the local droplet sizes across the spray and provide reliable droplet size data. However, an important condition is that the calibration is carried out properly using a reliable available technique.

Acknowledgements

This work is part the EEMS - Energy Efficient Milky Sprays project which took place within the framework of the Institute of Sustainable Process Technology (ISPT) and was co-financed by the TKI-Energy & Industry, Danone Nutricia Research, dsm-firmenich and FrieslandCampina. More information can be found at the EEMS website. Special thanks to Danone Nutricia Research for the use of the shadowgraphy setup.
Authors also would like to acknowledge the financial support from The Netherlands Center for Multiscale Catalytic Energy Conversion (MCEC) for the SLIPI setup. The information about the MCEC can be found on the MCEC website.

Nomenclature

I_{SLIPI}	Intensity Map of SLIPI image [arbitrary unit]
I_o	Intensity Map of sub-image at phase 0 [arbitrary unit]
I_{120}	Intensity Map of sub-image at phase 120 [arbitrary unit]
I_{240}	Intensity Map of sub-image at phase 240 [arbitrary unit]
$SMD_{SLIPI-LIF/Mie}$	Sauter Mean Diameter from SLIPI-LIF/Mie ratio [μm]
k	Calibration Factor
$I_{SLIPI-LIF}$	Intensity Map of Final SLIPI-LIF [arbitrary unit]
$I_{SLIPI-Mie}$	Intensity Map of Final SLIPI-Mie [arbitrary unit]

References

[1] Arthur H Lefebvre and Vincent G McDonell. *Atomization and Sprays*. Second. CRC Press, 2017. ISBN: 9781315120911.

[2] E Cossali and Y Hardalupas. "Experiments in Fluids Comparison between laser diffraction and phase Doppler velocimeter techniques in high turbidity, small diameter sprays". In: *Experiments in Fluids* 13 (1992), p. 422.

[3] R. Sijs et al. "Drop size measurement techniques for sprays: Comparison of image analysis, phase Doppler particle analysis, and laser diffraction". In: *AIP Advances* 11.1 (Jan. 2021). ISSN: 21583226. DOI: 10.1063/5.0018667.

[4] Nicolas Fdida et al. "Drop size measurement techniques applied to gasoline sprays". In: *Institute of Liquid Atomization & Spray Systems*. Oct. 2008.

[5] Edouard Berrocal et al. "Application of structured illumination for multiple scattering suppression in planar laser imaging of dense sprays". In: *Optics Express* 16.22 (Oct. 2008), p. 17870. ISSN: 1094-4087. DOI: 10.1364/oe.16.017870.

[6] E Berrocal et al. "Analysis of the SLIPI technique for multiple scattering suppression in planar imaging of fuel sprays". In: *11th Triennial International Annual Conference on Liquid Atomization and Spray Systems*. Vail, 2009.

[7] Yogeshwar Nath Mishra, Elias Kristensson, and Edouard Berrocal. "Reliable LIF/Mie droplet sizing in sprays using structured laser illumination planar imaging". In: *Optics Express* 22.4 (Feb. 2014), p. 4480. ISSN: 10944087. DOI: 10.1364/oe.22.004480.

[8] Yogeshwar Nath Mishra et al. "Application of SLIPI-based techniques for droplet size, concentration, and liquid volume fraction mapping in sprays". In: *Applied Sciences (Switzerland)* 10.4 (Feb. 2020). ISSN: 20763417. DOI: 10.3390/app10041369.

[9] Giulia Finotello. "Droplet collision dynamics in a spray dryer". PhD thesis. Eindhoven University of Technology, 2019. ISBN: 978-90-386-4685-5.

[10] E Berrocal et al. "Quantitative laser imaging of a non-reacting diesel spray using SLIPI". In: *3rd Annual Conference on Liquid Atomization and Spray Systems*. Ventura, CA, 2011.

[11] Yogeshwar Nath Mishra et al. "Application of SLIPI-based techniques for droplet size, concentration, and liquid volume fraction mapping in sprays". In: *Applied Sciences (Switzerland)* 10.4 (Feb. 2020). ISSN: 20763417. DOI: 10.3390/app10041369.