ILASS-Americas 31st Annual Conference on Liquid Atomization and Spray Systems, May 2021

Planar SMD estimation with tomographic reconstruction of combined extinction and dual angle scattering measurements

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Abstract
The probability density function (PDF) of the drop size distributions in many sprays can be approximated by a log normal distribution. The log-normal distribution can be fully described with two parameters, the mean and variance of the distribution. Using a MIE electromagnetic field simulation, it was found that the scattering phase functions at two angles in an aerosol cloud, uniquely determine the mean and variance of the PDF of drop sizes within the cloud. The simulation was carried out for mean drop sizes ranging from 5 to 500 microns. Once the mean and variance of drop sizes is determined from the scattering phase functions, the SMD can estimated. A tomography system that measures the scattering phase function from a spray at two angles as well as the planar extinction has been developed and evaluated. The tomographic reconstruction of extinction and scattering at specific scattering angles provided the planar distribution of scattering phase function of the spray at the given scattering angles. The phase functions at the two angles were then used to find the SMD of the spray at that location. The uncertainty of conversion from the phase function to the SMD of the droplet was also analyzed theoretically from MIE field theory. The planar SMD system was calibrated with a known size glass beads that is floating on the water cell. The planar diffraction system was evaluated against a conventional diffraction system using the standard simplex atomizer. The SMD measured by the planar system agrees well with the measurements obtained with a conventional drop sizer.

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Introduction

The transfer of mass, momentum, energy, and species at any location in a spray is directly proportional to the surface area of drops at that location. One of the methods of estimating the surface areas is to directly measure the drop sizes in the spray. Drop size is one of key parameters in applications such as spray drying and coating of surfaces. For this reason, development or quality control process require quick and reliable tools to determine the drop sizes in the pharmaceutical and paint industry. Laser based instruments has been developed and commercialized, to measure drop sizes since they offer non-intrusive and spatially resolved measurements, compared to the physical probing.

The two major drop sizing equipment in commercial use are the Phase Doppler Anemometer (PDA) or interferometer [1-2] and the Laser Diffraction based dropsizer [3-4]. The PDA can measure simultaneously the drop sizes and velocities at a single point in a spray. Laser diffraction technique provides a line of sight measurements of drop size distribution in a spray. The diffraction instruments use Mie theory to estimate the drop size distribution from the scattering intensity measurements at one view angle.

A single point drop size measurement is generally not sufficient for characterization of nozzle because drop size varies significantly over the spray domain. Therefore, performing 2-D (for PDA) or 1-D scanning (for diffraction based instruments) is necessary to characterize the spray fully. However, 1-D and 2-D scanning can be time consuming and impractical in industrial settings. Therefore, planar techniques for drop sizing are desirable.

A few measurement techniques have been developed to estimate the planar drop sizes in a spray without the need for scanning. A LIF/Mie ratio technique has been used extensively to obtain planar drop size distribution [5–6]. The LIF/Mie uses the ratio of laser induced fluorescence and scattered light to estimate drop sizes. Flourescence signals from common fluids are generally weak. Therefore, the liquid is often doped with a fluorescence dye such as rhodamine [7] to increase the SNR of the measurements. Adding dye to the liquid is not desirable in the industrial testing processes. Another important issue with this technique is multiple scattering effects when the spray is dense. Multiple scattering causes redistribution in spatial intensity for scattering intensity as well as fluorescence emission, and scattering pattern for laser light and fluorescence emission is completely different because location of light source is not same, thus the ratio of fluorescence and scattering intensity would be biased in the SMD measurement.

Interferometric laser imaging (ILIDS), exploits the interference between light reflected from, and refracted through, individual drops in the forward-scatter region to estimate planar drop sizes [8-9]. The technique can be used for estimating drop sizes only in spatially sparse spray and sprays with large drop sizes. A planar drop size technique that uses polarization ratio of the scattered intensity has been reported in the past [10]. This technique is based on the fact that the scattered intensity roughly increases with the square of the drop diameter D, if the incident light is polarized perpendicular to the scattering plane, while it roughly increases with droplet diameter D when the incident beam is polarized parallel to the scattering plane. The technique has been used to estimate drop sizes in automotive injectors. However, this technique also suffers from multiple scattering effect for dense sprays.

Extinction tomography for spray has been developed [11-12] to estimate spatial distribution of the surface area of the drops in a plane. It was shown that planar extinction measurement on the spray field does not suffer from the multiple scattering effect [13], thus, the drop surface area measurement through extinction tomography is free from the multiple scattering effect even when the spray is optically dense. It may be feasible to use the extinction measurements to get planar drop size distribution if an additional scattering measurement are performed. The local scattering intensity may be used to estimate the scattering phase function which is directly related to the SMD of the droplet This is similar to the principle of the diffraction technique, however it is performed throughout the entire plane.

Based on the above, the motivation for this work is to develop a new planar drop sizing technique based on extinction and scattering tomography. The technique does not degrade from the multiple scattering effects for dense sprays, and it does not require fluorescent dyes, This implies that if the technique is shown to be feasible, it can be used for quality control, as well as for research and development of nozzles and injectors. In addition, the technique is evaluated using the simplex atomizer [14] which has been used to compare different drop sizers in the past [15]. sizes, for example A4, corresponding margin sizes will be different. The orientation of the entire paper should be in the portrait format.

Extinction/Scattering Tomography Algorithm

The extinction of laser light as it goes through a purely scattering medium as shown in Fig. 1.

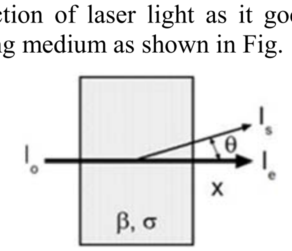

Figure 1. Laser extinction in a scattering medium

The intensity of the laser light after it passes through the path, I_e, is estimated from Beer's Lambert Law, and the off-axis scattering intensity, I_s, can be derived from the radiative transfer equation as:

$$\frac{dI_e}{ds} = -\beta \cdot I \quad \textbf{(1)}$$

$$\frac{dI_s}{dx} = -\beta \cdot I_s + \sigma \cdot I_o \cdot \exp(-\beta \cdot x) \cdot \int_{\Omega} \Phi(\theta) d\theta \quad \textbf{(2)}$$

where β and σ are the extinction and scattering coefficients of the scattering medium, respectively. The solution for the Eq. (1) results in Beer's Lambert law [16]. In Eq. 2, the first term on the right is attenuation through scattering medium, and the second term is production by the first order (single scattering) scattering of the extinction laser beam. The second term is not only dependent on the extinction and scattering coefficient, but also the scattering phase function $\Phi(\theta)$ of the scattering medium. From the MIE scattering theory the phase function, $\Phi(\theta)$, is directly related to the size of the droplet in the medium. In typical scattering medium such as water or fuel spray, the extinction coefficient is identical to the scattering coefficient, so the Eq. (2) can be simplified. An analytical solution for the differential equation (2) can be found from the method of separation of variables, and the solution is:

$$I_s = I_o \cdot \beta \cdot x \cdot \exp(-\beta \cdot x) \cdot \int_{\Omega} \Phi(\theta) \cdot d\Omega \quad \textbf{(3)}$$

The analytical solution, Eq. (3) was used in the tomography algorithm, and the eqn. (5) is derived from the solution. The planar drop sizing system measures path integrated (line-of-sight) extinction and scattering intensity, thus; local values can be obtained only through tomography technique that involves multi-paths and multi-view measurement and tomography algorithm. A simplified schematic of the tomography system is shown in Fig. 2.

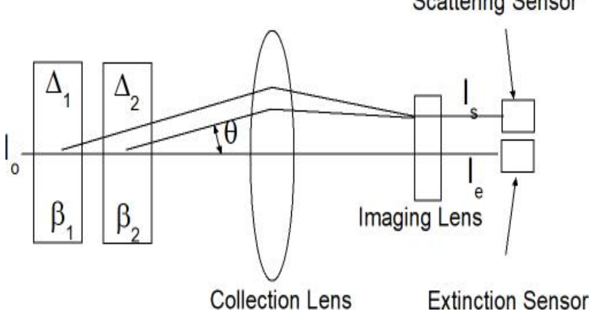

Figure 2. Schematic of simplified Extinction/Scattering Tomography system.

In the schematic, only two optical segments are displayed to show basic principle behind the algorithm.

$$-\log(\frac{I_e}{I_o}) = \beta_1 \cdot \Delta_1 + \beta_2 \cdot \Delta_2 \quad (4)$$

$$\frac{I_s}{I_o} = \beta_1 \cdot \Delta_1 \cdot \exp(-\beta_1 \cdot \Delta_1) \cdot \exp(-\beta_2 \cdot \Delta_2) \cdot \Phi_1(\theta) + \exp(-\beta_1 \cdot \Delta_1) \cdot \beta_2 \cdot \Delta_2 \cdot \exp(-\beta_2 \cdot \Delta_2) \cdot \Phi_2(\theta) \quad (5)$$

Eq. (4) is to be used to estimate local extinction coefficients (β_1, β_2), which is directly proportional to the surface area of the droplets (for drop sizes in the MIE scattering range). Extinction tomography [12] was first used to find the spatial distribution of the droplet surface area density. Once the local extinction coefficients are found from the extinction tomography system, Eq. (5) was used to find the local phase function of the droplets. In the tomography system, extinction and scattering intensity are measured along the parallel paths and multiple views to estimate independent extinction coefficients and scattering phase functions for all optical segments.

The Sauter Mean Diameter (SMD) is a statistical quantity for a group of particles, and it requires Probability Density Function (PDF) of drop size to accurately estimate its value. Most diffraction based drop sizers uses multiple phase function (scattering angles) measurement (32 or more sensors) to reconstruct the full PDF of the spray droplets distribution. The minimum number of phase function measurement would be 2 if the PDF of drop size is assumed to be lognormal distribution because two parameters (mean and variance) can fully describe the lognormal distribution. Using the MIE theory, a lookup table was created to estimate the SMD using two scattering phase angle measurements. In the present system, the scattering phase function at 0.36 degree and 0.63 degree were measured and used to tabulate relationship between the phase functions and SMDs. It is found that the SMD can be uniquely determined from the two phase function measurement for drop sizes within the range of 5 to 500 micron. The relationship between phase function and SMD for the two angles of 0l.36 and 0.63 degrees is shown in Fig. 3.

The phase function measurement requires a calibration process to relate the measurement to MIE scattering theory. Glass beads with a known drop size distribution were used to estimate optical efficiency of the linear arrays used for the measurements. The glass beads were floated in a water chamber that was agitated using a magnetic stirrer. A photograph of the water chamber and the magnetic stirrer is shown in Fig. 4. The floating cell has two clear window so that extinction and scattering intensity can be measured at the same time.

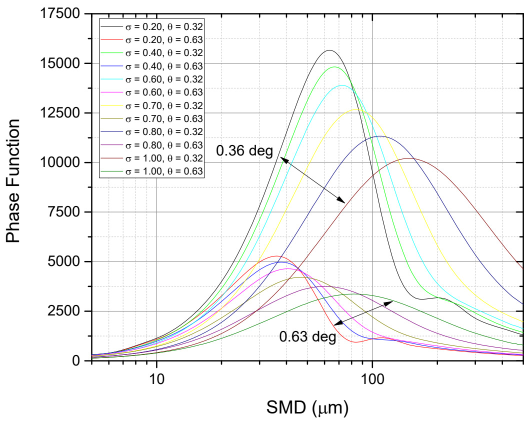

Figure 3. Relationship between Phase Function and SMD obtained from the Mie theory.

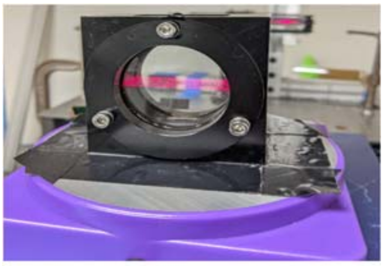

Figure 4. Photograph of the bead floating in a water cell.

Glass beads with 5 different sizes (42, 51, 69, 84 and 101 μm) were used to fit the measured phase function to the MIE theory prediction. For a given size of the glass bead, the phase function has to be constant regardless of the extinction levels in theory. The variation of measured phase function with the extinction from the glass beads is shown in Fig. 5.

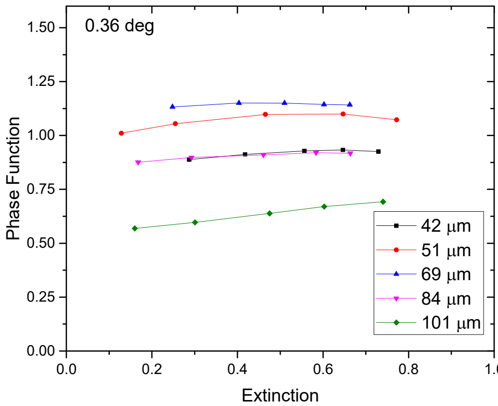

Figure 5. Phase function calibration with different extinction levels.

The overall changes in the phase function for extinction levels ranging from 0 to 0.80 is approximately 5 – 7 %. The exact reason for the change has not been identified. For the present set of measurements, the phase function values at an extinction level of 0.3 was used to convert the phase functions into drop sizes. Further validation is necessary to identify the exact cause of the change with respect to the extinction level. The calibration procedure was completed by fitting the measurements with the MIE theory. The actual scattering angles as well as scaling constants were found from the fitting procedure.

A sample result of the fitting procedure is shown in Fig. 6, and the fitting error is minimal.

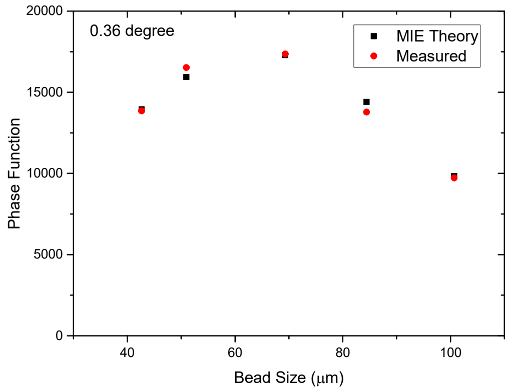

Figure 6. Measured phase function of glass beads and MIE theory.

Experimental results

All measurements were conducted on the simplex nozzle designated RS1 [15]. For these experiments, Mil C-7024 was used as the fluid and the injection pressure was 689 kPa. A photograph of the experimental arrangement is shown in Fig. 7.

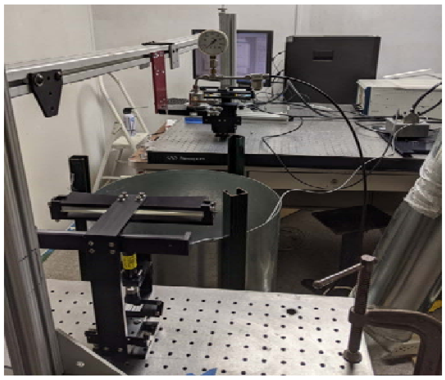

Figure 7. Photograph of the experimental arrangement.

The simplex nozzle was mounted on a rotating disk. The nozzle was rotated 6 times. The laser sheet from a fan beam laser was collimated and passed through the spray at an axial height of 50 mm. The extinction caused by the spray was measured at six view angles. The scattering intensity g at 0.36 degrees was obtained at three view angles and the scattering

intensity at 0.63 degrees was also captured at three view angles. The view angles were separated by 30 degrees.

The local surface area densities obtained from the measurements are shown in Fig. 8.

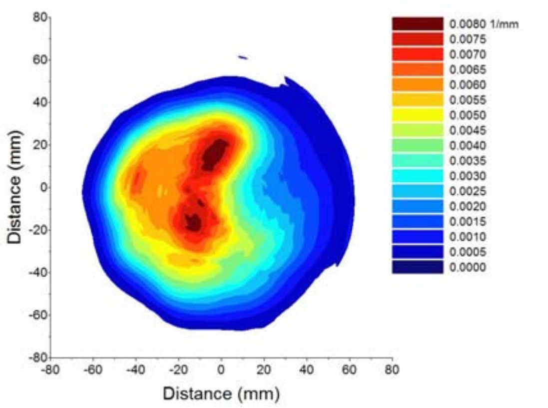

Figure 8. Local surface area densities within the spray.

The spray is not very uniform. There are two spots where the spray density is above the average value. The overall shape of the spray is symmetric. The spray angle (based on enclosing 90% of the surface area density) is 80 degrees. The spray patternation number [15] is 50%, which is high and indicates an asymmetric spray and not ideal for interlaboratory comparisons.

The mean extinction values along the radius of the spray is shown in Fig. 9.

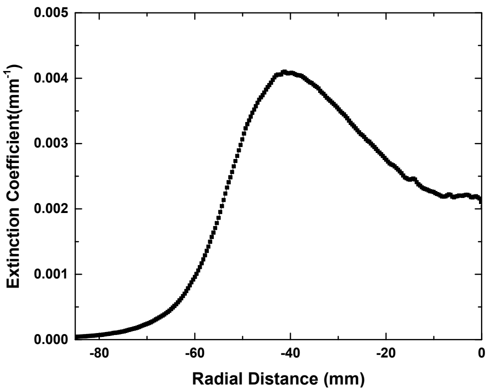

Figure 9. Radial profile of the mean extinction coefficient in the spray.

The mean extinction profile shows that the peak extinction occurs away from the center line of the spray. This behavior is representative of a hollow cone spray. However, the spray pattern is probably not developed fully due to the lack of atomizing air.

The radial profile of phase function at the two measurement angles are shown in Fig. 10. The radial profile of phase functions also shows that the peak value is not at the center of the spray. The peak value is almost at the same location as that seen in Fig. 9.

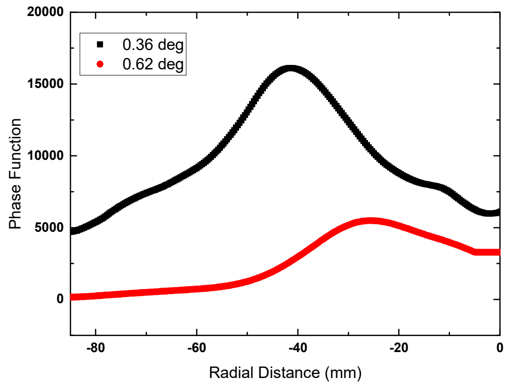

Figure 9. Radial profile of phase function at 0.36 and 0.63 degrees in the spray.

The radial profile of the SMD of the drops within the spray is shown in Fig. 10.

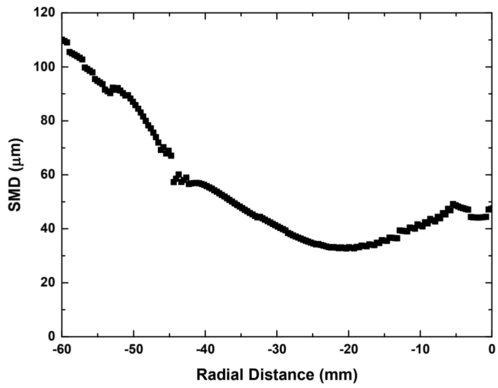

Figure 10. Radial profile of the SMD in the spray.

The SMD has a center line value of approximately 40 microns and increases to a value of 100 microns at the edges of the spray. Malvern measurements in the same spray provided a SMD of 50 microns through the spray centerline. However, the exact radial location of the measurement with regards to the contour map was not ascertained.

Conclusions

The following conclusions can be obtained from the present study

1. A combined extinction and scattering instrument was used to obtain the planar drop sizes with in a spray.
2. The measurements are consistent with those obtained with a diffraction based system

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