Chapter

Planar Drop-Sizing in Dense Fuel Sprays Using Advanced Laser Diagnostic Techniques

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Abstract

A reliable measurement of drop sizes and liquid fuel distribution in a spray is essential for best combustion efficiency and exhaust emission from I.C. engines. The droplet size and fuel distribution control air-fuel mixture formation and, hence, combustion characteristics. The chapter gives a concise summary of recent advances and developments in the LSD technique as a planar drop-sizing technique. The LSD technique relies on the principle that a ratio of planar laser-induced fluorescence (PLIF) and Mie signals is proportional to Sauter mean diameter (SMD). PLIF signal can also be used to determine the distribution of liquid in a spray. This makes LSD an attractive technique in dense spray characterization that can also provide liquid volume fraction distributions. A brief review of laser-based drop-sizing methods and working principle of LSD measurements are first discussed. Different approaches and limitations of the LSD technique are also summarized. Further, sources of error and ways to compensate these errors are explained in detail. Previous studies on LSD measurements in different fuel sprays of stationary combustion devices and I.C. engines are summarized. Finally, improvements in the LSD techniques are suggested, including structured laser illumination planar imaging (SLIPI) measurements, for reliable measurements in dense sprays.

Keywords: PLIF, Mie, LSD, liquid volume fraction, SLIPI

1. Introduction

Internal combustion (I.C.) engines are widely used in many applications including automobile, transport, power generation, etc. Delivery of liquid fuel in I.C engines is achieved by injecting liquid in the form of droplets into a combustion chamber, as in diesel or GDI engines, or into an intake manifold. It is recognized that atomization of liquid fuel and spray characteristics have critical impact on combustion processes and emission formation [1, 2]. **Figure 1** explains the role of spray characteristics in air-fuel mixture formation processes of a combustion engine. The liquid fuel is injected into a combustion chamber in the form of a spray. Fuel droplets evaporate due to available heat in the combustion chamber that controls the mixing of air and fuel and, hence, physical ignition delay. Vaporized fuel then mixes with the surrounding air to form a combustible air-fuel mixture and

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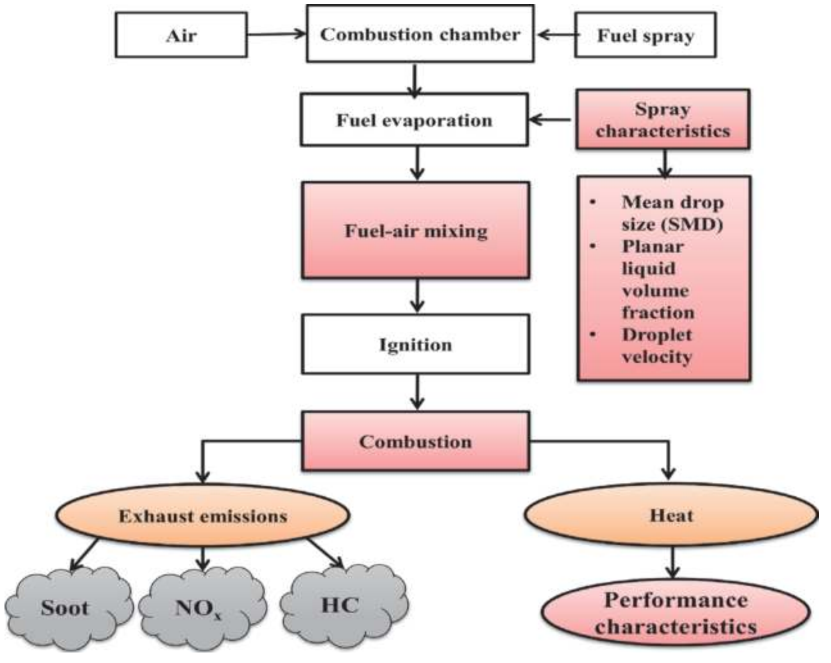

Figure 1.
Dependence of combustion performance on atomization characteristics of fuel spray.

initiate combustion reaction. Thus, distribution of liquid fuel droplets in the combustion chamber governs air-fuel mixture distribution and, thus, the temperature distribution. The combustion of fuel liberates heat and also produces undesirable exhaust gases as products. One of the exhaust gas emissions, nitrogen oxides (NO_x), is mainly formed due to high combustion temperature according to Zeldovich's mechanism [1]. Unburnt hydrocarbons and soot emissions are results of incomplete combustion of fuel. Soot and NO_x emissions can be controlled simultaneously with appropriate distribution of air-fuel mixture which is mainly governed by atomization of fuel and spray characteristics. Moreover, combustion efficiency is also controlled by the resultant distribution of air-fuel mixture [3]. Thus, various spray characteristics such as droplet size and its distribution, droplet velocity, and liquid volume fraction play an essential role in optimizing the combustion process along with minimum exhaust emissions.

Drop size and the distribution of liquid fuel (liquid volume fraction) in a spray have a considerable impact on the combustion efficiency. The Sauter mean diameter (SMD) is widely accepted as an average droplet size parameter in combustion applications that controls the evaporation rate [2, 4]. Therefore, a reliable measurement of drop sizes and liquid volume fraction is necessary for optimizing air-fuel mixture formation in a combustion process.

2. Laser-based drop sizing in sprays

Laser-based techniques provide high spatial and temporal resolution in measurement and are preferred due to their nonintrusive nature. Drop sizes of micrometric fuel droplets moving with high velocities can also be measured by using laser-based drop-sizing techniques. Various laser-based drop-sizing techniques have been used to measure drop sizes in a spray. Most of the drop-sizing techniques are point measurement techniques and are limited to spray regions where droplet number density is low. Laser sheet drop sizing (LSD) is a planar drop-sizing method that has capability to be used even in dense fuel sprays. Some of the advanced laser-based drop-sizing techniques are discussed below:

- Laser-diffraction-based drop size measurements
- Particle/Droplet Imaging Analysis (PDIA)
- Phase Doppler Interferometry (PDI)
- Interferometric laser imaging for droplet sizing (ILIDS)
- Laser sheet drop sizing (LSD)

2.1 Laser-diffraction-based drop size measurements

This is a commonly used technique and is also known as Malvern particle sizer. The technique is based on Fraunhofer diffraction of a monochromatic laser beam [5]. Line-of-sight drop-size measurements are obtained using forward scattering. Thus, spatial variations along the line-of-sight cannot be determined. The technique also suffers from laser beam extinction and multiple scattering [6]. These limitations lead to erroneous drop-size measurements in dense sprays [5–7].

2.2 Particle/droplet imaging analysis (PDIA)

PDIA is a microscopic shadowgraphy-based direct imaging technique [8–11]. The microscopic shadowgraphs are captured using a high resolution CCD camera coupled to a microscope [12, 13]. A long-distance microscope is used to probe into a very small field of view ($\sim 2 \times 2$ mm) with a pixel resolution of the order of a few microns per pixel. The microscopic images are analyzed using image processing tools to obtain statistically large number of droplets and mean drop size. The technique has a capability to consider nonspherical droplets and a presence of a number of droplets in a measurement volume [14, 15]. However, the technique is biased toward large size droplets as the resolution of the technique is diffraction-limited, and small droplets are neglected in the drop sizing [10, 14, 16, 17].

2.3 Phase Doppler interferometry (PDI)

PDI is an interferometry-based drop-sizing technique that uses Mie scattering theory to calculate drop size along with velocity at a point in a spray [5]. PDI is also known as Phase Doppler Anemometry (PDA) or Phase Doppler Particle Analyzer (PDPA). PDI is a widely accepted standard method in the spray diagnostics. However, single droplet occupancy, spherical droplets, and multiple scattering are some of the limitations of the PDI technique [5, 7, 18]. Therefore, drop sizing with PDI becomes questionable when spray is optically thick (optical density > 10) such as in non-evaporative, high-pressure diesel sprays. The state of art of PDI technique for drop-size measurement is well documented in the literature [7, 19].

2.4 Interferometric laser imaging for droplet sizing (ILIDS)

ILIDS is also known as interferometric particle imaging (IPI) or planar particle image analysis (PPIA) [20–23]. Glare points are formed due to interference of reflection and refraction on the droplet surface. The glare points are imaged out of focus to calculate drop size. In this technique, micron-ranged droplets can be imaged in a relatively large field of view. However, interference fringes tend to overlap when droplet number density is high. Therefore, this technique is limited in sparse sprays where droplet number density is low. A comprehensive review of ILIDS technique can be found in the literature [7, 24–26].

2.5 Laser sheet drop sizing (LSD)

Laser sheet drop sizing (LSD, also called as Planar Drop Sizing, LIF/Mie ratio technique) is a combination of planar laser-induced fluorescence (PLIF) and Mie scattering imaging that gives a distribution of SMD in a plane of the spray [27–32]. The PLIF signal is proportional to the volume of the droplet, whereas the scattering signal is proportional to the surface area of the droplet [27–30]. The ratio of these two signals is then proportional to SMD. Initially, the basic principle was explained and applied to non-evaporative diesel sprays [31]. The accuracy of the technique has been verified with established drop-sizing methods such as PDPA [30, 32] and diffraction-based drop sizing [6].

Table 1 lists various laser-based drop-sizing techniques along with the measurement principle and limitation of the technique. Except for LSD, these techniques are either point measurement techniques (PDIA or PDI or ILIDS) or line-of-sight (diffraction-based techniques). These techniques also have limitations in sprays with high droplet number density. A large number of droplets in a small volume affect the travel of laser light and signal through a spray. The LSD technique is an attractive drop-sizing technique that provides SMD and liquid volume fraction distribution in a plane. Moreover, the technique can also be used in dense sprays where droplet number density is high. A detailed discussion on LSD technique, principles, assumptions, and limitations is given in the following section.

3. Laser sheet drop sizing

The LSD technique is a combination of a signal based on volume of a droplet and a signal based on surface area of a droplet. When a droplet of diameter (D) is illuminated with a light of a wavelength λ, a relation between D and λ is given in terms of Mie parameter (X_m, Eq. 1). The Mie parameter (X_m) can be used to

Technique	Principle	Type of measurement	Important limitation (s)
Particle/Droplet Imaging Analysis (PDIA)	Microscopic shadowgraphy	Point measurement	Resolution is diffraction-limited
Phase Doppler Interferometry (PDI)	Interferometry	Point measurement	Single droplet occupancy in a measurement volume
ILIDS	Interferometry (glare-point separation)	Point measurement with large field of view	Can be applied only in sparse sprays
Diffraction	Interferometry	Line-of-sight measurement	Attenuation of laser beam in dense sprays
Laser sheet drop sizing	Intensity ratio	Planar measurement	Signal attenuation, laser extinction, and multiple scattering

Table 1.
Laser-based drop-sizing techniques used in spray diagnostics.

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estimate a relation between D and scattering intensity (I_s) [7, 26, 33]. It is observed that the scattering intensity is proportional to square of Mie parameter (X_m), i.e., $I_s \propto X_m^2$ for scattering angle of 90° for spherical droplets of diameter $D \geq 1\mu$m [7, 26, 33, 34]. This suggests that Mie scattering signal is proportional to the surface area of the droplet (Eq. 2).

$$X_m = \frac{\pi \cdot D}{\lambda} \tag{1}$$

$$I_s \propto D^2 \tag{2}$$

Laser-induced fluorescence signal is considered as volume-based signal. Rarely, Raman scattering signal can also be used for this purpose though the Raman signal is weak [35]. Laser-induced fluorescence (LIF) involves the excitation of liquid molecules by a laser followed by the detection of the subsequent emission of radiation from the liquid. Natural fluorescence of the liquid can be used if fluorophores are already present in the liquid. An external fluorophore, in the form of fluorescent dye, can be added in the liquid for generating PLIF signal. The radiation is necessarily inelastic and red-shifted according to Planck's law. The radiation can be distinguished from the incident laser wavelength using appropriate optical filters. The concentration of the dye is kept to a minimum to ensure low laser light absorption and all molecules of a droplet are equally illuminated. The linear regime of the PLIF signal with incident laser energy is ensured. Under these conditions, a relation between PLIF signal (I_f) and a droplet with diameter D can be expressed as

$$I_f \propto D^3 \tag{3}$$

The signal (PLIF or Mie signal) from each pixel of the CCD array is obtained from the total droplets present in the measurement volume. The measurement volume of the LSD technique is defined using field of view of the CCD camera and a thickness of the laser sheet. The LSD signal is obtained by dividing the LIF signal by the scattering signal (Eq. 4), when a statistically large number of droplets are present in the measurement volume.

$$\frac{I_f}{I_s} \propto \frac{\sum_i D_i^3}{\sum_i D_i^2} \propto SMD \tag{4}$$

A constant of proportionality (K) is introduced to get a quantitative SMD distribution in a plane.

$$SMD = K \cdot \frac{I_f}{I_s} \tag{5}$$

The constant of proportionality (K) can be calculated at a location using an independent drop-sizing method (PDIA, PDI, ILIDS). In the LSD measurement technique, the proportionality between a droplet diameter and Mie and PLIF signals is mainly responsible for reliable drop-sizing measurements. D^3 and D^2 proportionality is well documented in the literature. Le Gal et al. [36] reported that a low concentration (0.023 g/l) of p-terphenyl (PTP) in mineral spirit ensures the proportionality. Frackowiak et al. [37] reported that D^3 proportionality is ensured for the low dye concentration of 3-pentanone in n-heptane. Domann et al. [27] reported a similar observation for Rhodamine 6G in water droplets when the signal was captured at an angle of 90°. An increase in dye concentration deviates D^3

proportionality, mainly because of the absorption of light by the dye molecules. Domann et al. [27] further demonstrated that D^2 proportionality is respected at detection angle of 90°. Charalampous et al. [28] performed a numerical study to investigate D^3 and D^2 proportionality as a function of detection angle from 60 to 120° and various dye concentrations. The observations confirm D^3 proportionality at 90° detection angle with the lowest dye concentration. Further, it was suggested to use 60° detection angle instead of 90°, as Mie scattering fluctuations are minimum at 60° detection angle [28]. However, the use of 60° detection angle in Mie imaging may lead to Scheimpflug condition.

Assumptions made in the LSD technique are listed below [27, 28, 37, 38]:

1. Droplets are spherical and transparent.

2. The scattered photons undergo a single scattering event before reaching the detector.

3. Morphology-dependent resonances (MDR) in Mie and PLIF signals are neglected, or appropriate precautions are taken to avoid MDR [38].

4. The variation of fluorescence intensity with incident laser energy is in linear regime to ensure the non-saturated fluorescence signal.

5. Minimum dye concentration to avoid absorption.

6. Statistically large number of droplets are present in the measurement volume. This ensures drop size distribution in the independent drop-sizing technique is followed in the LSD technique at a location of the calibration.

7. The location of calibration must be accurately mapped in PLIF image, Mie image, and the independent drop-sizing technique.

8. The calibration constant K is constant over a range of drop sizes in the plane of the LSD measurements.

However, when LSD measurements are applied in real-life spray systems, these assumptions may lead to limitations of the technique.

- Mie scattering theory assumes that droplets are spherical. However, in the near-nozzle region, where the breakup of the liquid is in process, a large number of ligaments, liquid lumps, or nonspherical droplets are present. These nonspherical liquid droplets may lead to error in D^2 proportionality.

- It is assumed that the photon has undergone a single scattering event. This assumption may not be followed in the dense sprays where the droplet number density is high. The photons may undergo several scattering events leading to unreliable and unrealistic signals. This source of error is termed as multiple scattering or secondary emission. Therefore, LSD measurements may not provide reliable drop sizing in dense sprays.

- The quantitative SMD measurement in LSD technique further relies on an independent drop-sizing technique. An error involved in the independent drop sizing may propagate in the LSD measurements. Further, this dependence on the other drop-sizing technique adds additional cost to the LSD measurements.

- Laser extinction due to the scattering of the laser sheet and absorption of the laser sheet and signal attenuation may lead to error in the PLIF and Mie signals. These losses may lead to an error in the LSD measurements. The contribution of the error may be significant in dense sprays.

4. Approaches used in the LSD measurements

In the LSD technique, a combination of Mie and PLIF signals is used for droplet size measurements. Mie signals is elastic in nature (i.e., wavelength is the same as that of illumination), which helps to capture the Mie signal even without any optical filters. On the other hand, PLIF signals are red-shifted, thus inelastic in nature, which demands optical filters in PLIF imaging. For example, Rhodamine 6G dye is illuminated with 532 nm pulsed laser (green in color); it emits fluorescence signal in a window of 550–570 nm (orange in color). Thus, a band-pass filter is used to cover this window. Also, a notch filter can also be used to remove incident illumination of 532 nm.

There are two approaches for droplet sizing in the LSD technique. In the first approach, PLIF and Mie signals are acquired simultaneously, whereas the second approach relies on the sequential imaging of the signals. Averaged PLIF and Mie images are then obtained in both the approaches. The number of images used must be sufficiently large to ensure enough number of droplets in the measurement volume. This ensures that similar drop size distributions are observed in LSD measurement and the independent drop-sizing measurement at a location of the calibration.

4.1 Simultaneous imaging of PLIF and Mie signals

In simultaneous imaging, PLIF and Mie signals are obtained simultaneously using appropriate optical filters and two separate camera systems or by a single camera fitted with appropriate image-splitting optics. The two-camera method involves simultaneous and independent imaging of Mie and PLIF signals as shown in **Figure 2** [30–32, 35, 36, 39–41]. Both the cameras are focused on the same field of view that ensures pixel-to-pixel overlapping of the signals. The simultaneous imaging of the Mie and PLIF signals can also be obtained using a single camera system [35]. In this case, the CCD array of a single camera is used along with an image-splitting arrangement to acquire simultaneous PLIF and Mie signals. However, this reduces the resolution of the LSD measurements. Further, a weak fluorescence signal may be reduced due to additional image-splitting arrangement. The simultaneous imaging approach is widely used in literature to get SMD distribution, including time-resolved SMD measurements [30–32, 35, 36, 39–41]. However, in this approach, the cost of the measurement is high due to two cameras or image splitter. Moreover, pixel-to-pixel overlapping may be an additional problem in instantaneous imaging.

4.2 Sequential imaging of PLIF and Mie signals

It is also possible to use a single camera to record the fluorescence and elastic-light-scattering images in sequence [27, 42–49]. This approach provides reliable SMD measurements where there is reasonable confidence that the flow or spray

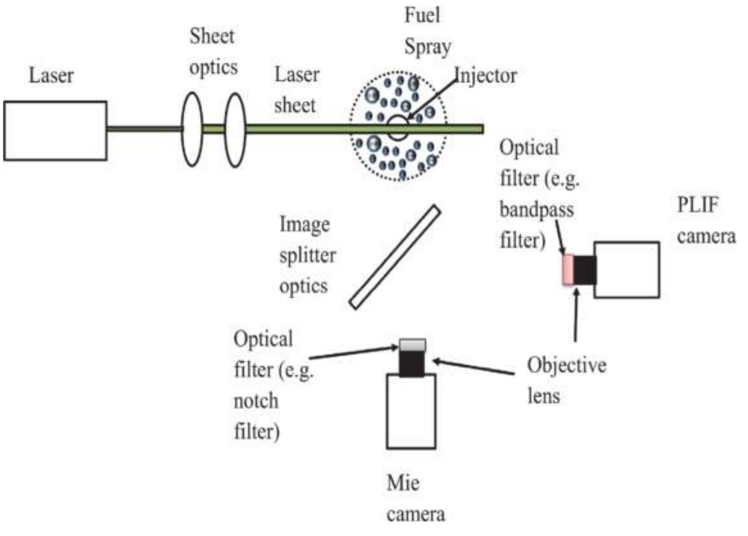

Figure 2.
Schematic representation of experimental setup for LSD measurements using simultaneous imaging of PLIF and Mie signals using two cameras.

characteristics do not change with time, steady spray [43, 44]. This approach is used in the literature, and it is observed that results are consistent with SMD measurements from Phase Doppler Interferometry (PDI) [43–46].

Both simultaneous and sequential imaging have been widely used in the literature. However, it is necessary to compare the approaches with other independent drop-sizing techniques under a controlled environment to evaluate the reliability of the SMD measurements.

5. Sources of error in the LSD measurements

The Mie and PLIF signals suffer various losses due to interactions between spray droplets and the laser sheet. These losses affect signal-to-noise ratio (SNR) and the accuracy of the measurements. The losses can be categorized into three types, namely, laser extinction, signal attenuation, and multiple scattering. These sources of error in the LSD measurements are discussed in the following subsections.

5.1 Laser extinction and signal attenuation

The energy of the incident laser sheet is reduced as the laser sheet travels through the spray due to scattering by the droplets and as a part of the energy is absorbed by the droplets. This loss in the incident laser sheet reduces Mie and PLIF signals. The loss in the incident laser sheet due to scattering and the absorption by the medium is termed as laser sheet extinction loss [5, 18, 50, 51]. The laser extinction loss is observed in both Mie and PLIF signals [18]. The contribution of laser sheet extinction can be different in Mie and PLIF signals which may lead to error in SMD measurements of the LSD technique. The laser extinction loss leads to asymmetry in the images [18]. **Figure 3** shows SLIPI-PLIF image of an airblast spray for GLR of 4 when the laser sheet is traveling from left to right. It is expected that the spray is symmetrical about the spray axis [18]. However, a weak PLIF signal is observed on the right side due to loss in the incident laser sheet (laser extinction).

The PLIF and Mie signals travel from the plane of the laser sheet to the detector through ensembles of spray droplets. The spray droplets may absorb these signals

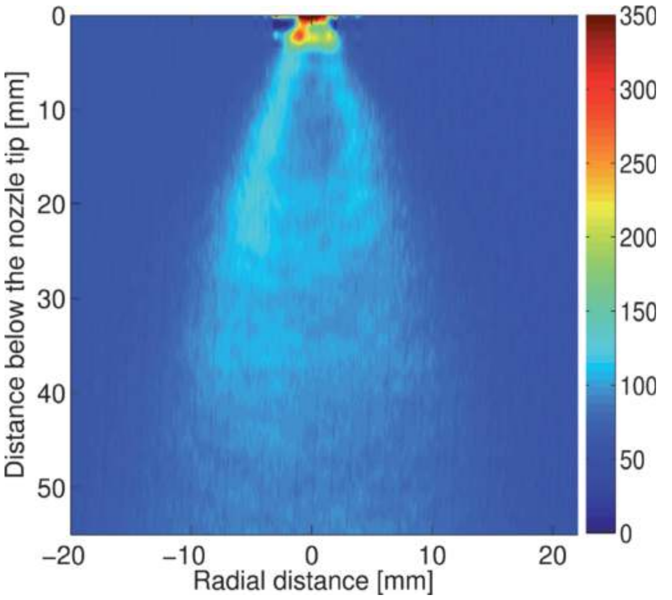

Figure 3.
Averaged SLIPI-PLIF signal in airblast spray at gas-to-liquid mass ratio (GLR) of 4 [49]. The intensity of signal is skewed due to various losses.

due to the overlapping of emission and absorption spectra of the liquid. This loss is termed as auto-absorption or self-absorption or re-absorption of the signal [52]. Auto-absorption is primarily observed in PLIF imaging. The laser sheet absorption and PLIF signal attenuation are mainly controlled by a dye concentration [52]. High dye concentration can increase the absorption and auto-absorption losses which will lead to deviations in D^3 proportionality [38].

5.2 Multiple scattering

The LSD technique assumes single scattering event of photons. However, many photons reaching the CCD camera are scattered more than once in a spray with high droplet number density. This phenomenon is referred to as multiple scattering or secondary emission. When a laser light interacts with a spray, a photon may follow

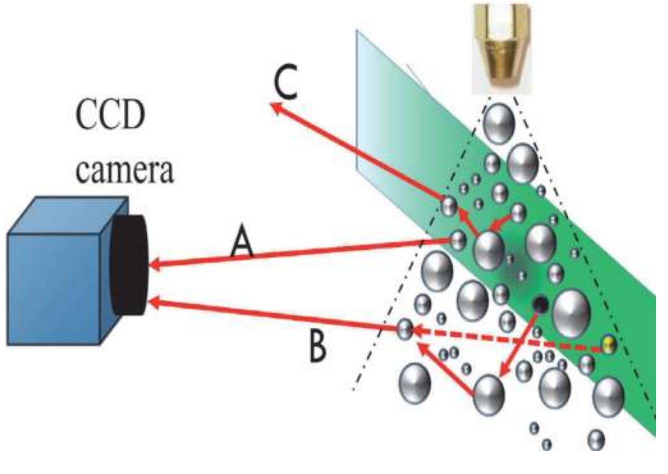

Figure 4.
An illustration of possible scattering events in a spray with laser sheet imaging. (A) Single scattering event; (B) multiple scattering that provides incorrect information about a droplet; (C) multiple scattering that results in the loss of the signals.

several paths before it reaches a CCD camera. **Figure 4** shows an illustration of possible scattering events in a spray with laser sheet imaging. Condition A explains a single scattering event. The laser light interacts with a droplet and reaches the CCD camera without interacting with any other droplet. This is the most ideal

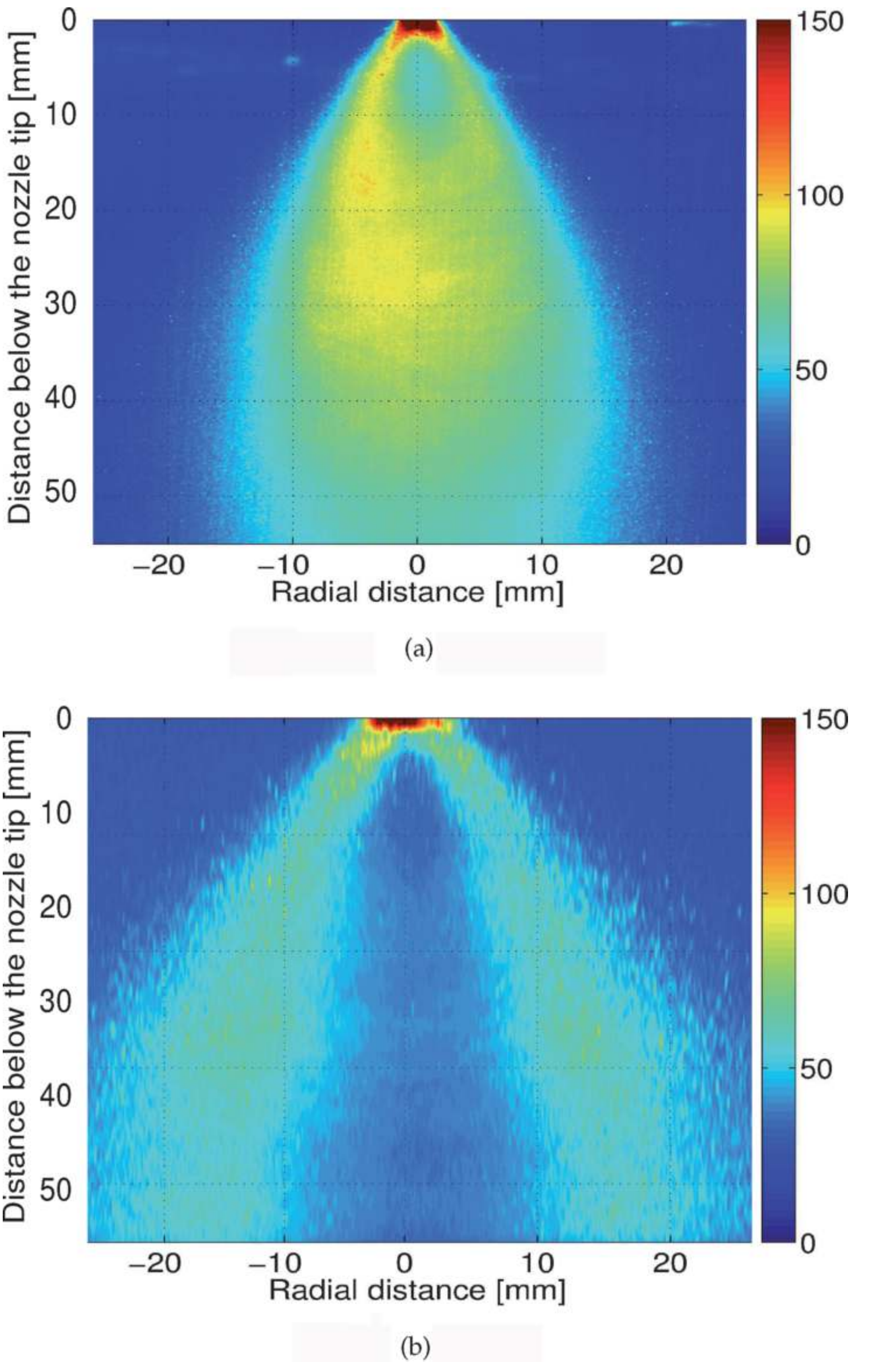

Figure 5.
A comparison of conventional and SLIPI-PLIF signals of airblast sprays at GLR 1. Conventional PLIF image shows a solid cone spray due to multiple scattering, whereas a hollow cone is observed in SLIPI-PLIF imaging [53]. The laser sheet travels from left to right. (a) Conventional PLIF signal. (b) SLIPI-PLIF signal.

condition in the LSD measurement for reliable drop sizing. In Condition B, a photon starts traveling from a droplet illuminated with laser light. However, the photon interacts with several other droplets before its detection by the CCD camera sensor. This path causes misinterpretation of a false droplet (a yellow droplet with a dashed line). Condition C shows a path of a photon that interacted with a droplet; however, the photon is not recorded on the camera sensor leading to a loss in the signal. Conditions B and C are considered as multiple scattering, which may lead to error in the drop sizing of the LSD measurements. In the case of PLIF imaging, multiple scattered photons (path B) may induce additional errors due to absorption of the photon and reemission of the fluorescence signal. This suggests that the contribution of multiple scattering in Mie signal and PLIF signal may be different due to the absorption of the multiple scattering signal by the dye in the PLIF imaging. The unwanted multiple scattered photons lead to a blurred image or reduction in resolution of the image. Structured laser illumination planar imaging (SLIPI) technique is used to reduce multiple scattering in planar spray imaging. Conventional and SLIPI-PLIF signals of the airblast spray are compared for GLR 1 in **Figure 5**. The conventional imaging showed a solid cone spray as shown in **Figure 5a**. On the other hand, a hollow cone spray is observed in the SLIPI imaging (**Figure 5b**). The change in the spray geometry of the airblast spray was attributed to the presence of multiple scattering in the PLIF signal [53]. A similar observation was made by Linne [18]. It was observed that the conventional Mie image of a hollow cone spray shows the presence of liquid along the axis of the spray due to multiple scattering. Thus, the contribution of multiple scattering is significant in both Mie and PLIF signals [18].

Most of the LSD measurements neglect the contribution of the multiple scattering. Berrocal et al. [54–56]conducted Monte Carlo simulations to study the contribution of multiple scattering in a hollow cone spray with OD < 1, i.e., an optically dilute spray. It was reported that the contribution of multiple scattering is significantly high ($\sim$76%), even in the optically dilute spray. Payri et al. [57] observed that LSD could be applied only at small particle concentrations where loss due to multiple scattering is low. At higher particle concentrations, loss due to multiple scattering is significant that reduces the accuracy of the LSD measurements. In few studies, it is assumed that the contribution of multiple scattering may be similar in Mie and PLIF signals, and it will be canceled while ratioing the signals. However, the contribution of multiple scattering may be different in Mie and PLIF signals. Mishra et al. [40] reported that multiple scattering has a significant impact on LSD technique even in optically dilute sprays (OD$\sim$1). Therefore, the contribution of multiple scattering may lead to unreliable drop-sizing measurements.

6. Methods to reduce errors in the LSD measurements

Many attempts have been made to compensate for the losses in the laser sheet imaging. Talley et al. [58] proposed a correction for laser extinction using counter-propagating laser sheets. Koh et al. [59] corrected signal attenuation using the geometric mean value of the intensities obtained using two cameras. The loss in the fluorescence signal due to auto-absorption of the fluorescence signal and absorption of the laser sheet can be corrected using Beer–Lambert law [52]. Abu-Gharbieh et al. [60] proposed a numerical approach to compensate for a loss in a laser sheet due to scattering. Brown et al. [61] attempted to reduce multiple scattering by scanning the spray with a narrow laser beam, instead of a laser sheet. They observed that the results were consistent with Phase Doppler Anemometry measurements. However, this method involves a long measurement time. A planar technique, structured laser illumination planar imaging (SLIPI), reduces the contribution of multiple scattering in a planar imaging [62–66]. The SLIPI technique reduces the effect of multiple scattering in Mie and PLIF imaging which can be used in dense sprays to get more accurate measurements of droplet diameter, spray structure, liquid volume fraction, and temperature [62, 63, 66, 67].

A spatially modulated laser sheet is used in the SLIPI technique to reduce multiple scattering in PLIF and Mie signals. The spatial modulation of the structured laser sheet is obtained by using a Ronchi grating. Three spatially modulated sub-images (I_1, I_2, and I_3) are acquired at the period of one-third of the modulation [62–66]. The SLIPI image is calculated using modulated images with Eq. (6).

$$I_{SLIPI} = \frac{\sqrt{2}}{3} \cdot \left[(I_1 - I_2)^2 + (I_2 - I_3)^2 + (I_3 - I_1)^2\right]^{1/2} \tag{6}$$

SLIPI signals require corrections for laser extinction and signal attenuation for reliable measurements. Various losses in the laser sheet and the signals pose difficulties in extracting reliable quantitative information from these techniques. Loss in Mie and PLIF signals due to scattering of the laser sheet can be compensated using Beer–Lambert law as explained by Abu-Gharbieh et al. [60]. Similarly, the loss in the fluorescence signal due to absorption of the laser sheet and auto-absorption of the fluorescence signal can be corrected using Beer–Lambert law [52]. Thus, the SLIPI signal needs to be corrected further for losses due to laser sheet extinction and signal attenuation. Recently, this methodology is used to improve LSD measurements in dense sprays. More details on the methodology can be found in [53, 68].

7. Applications and limitations of the LSD technique

The LSD technique is well established in the spray diagnostics. The method has been used in many spray systems, including fuel sprays that include ensembled SMD measurements and time-resolved SMD measurements. The LSD measurements have been performed using both simultaneous and sequential imaging of the Mie and PLIF signals. The various sprays are studied at evaporative and non-evaporative conditions using the LSD technique [36, 43, 44, 69–72].

Yeh et al. [31, 73, 74] developed LSD technique using simultaneous imaging of the Mie and PLIF signals of transient diesel sprays at non-evaporative conditions. Sankar et al. [32, 75] termed the technique as optical patternator and applied it to study the spray characteristics of continuous pressure atomizer. They compared SMD measurements from the LSD technique with PDPA measurement and found a good agreement. It was noted that the technique is ideal for dense spray applications compared to that of the PDPA. A similar observation was reported by Le Gal et al. [36]. In this study, the LSD was applied to study a small pressure-swirl spray and a full size industrial air-spray injector. The SMD measurements from the LSD technique were compared with PDPA measurements, and good agreement was observed. These studies employed simultaneous imaging of PLIF and Mie signals. Zelina et al. [43, 44] showed that LSD measurements could be performed by recording Mie and PLIF signals in a sequence for a steady-state continuous spray. The SMD distribution of a prefilming airblast atomizer was studied in this work. A good agreement between SMD measurements of LSD and PDPA measurements was observed with the sequential imaging. Jermy et al. further used sequential imaging of the Mie and PLIF signals [76] to study a dense cooling spray of water. Park et al. [77] argued that sequential imaging cannot be applied to the transient spray, as the images are not taken simultaneously. Hence, they used the simultaneous imaging approach to get the time-resolved SMD distribution of a swirl-type GDI spray. The D^3 and D^2 proportionality was verified using a droplet generator.

Domann et al. [30] performed planar SMD measurement in a spray generated by a pressure-swirl atomizer in a liquid-fueled burner at isothermal conditions. An assumption that the calibration constant is independent of a droplet diameter was analyzed. They found that the assumption was incorrect and can lead to sizing errors up to 30%. The discrepancies between LSD and PDA measurements were observed in dilute spray regions. These discrepancies were attributed to the increased statistical uncertainty of the LSD measurements due to the limited sampling period. It was suggested to acquire a large number of Mie and PLIF images to get reliable drop sizing in dilute sprays. Zimmer and Ikeda [78] performed LSD measurements to study droplet clusters in an industrial gun-type burner. In this study, the calibration constant (K) was calculated along a line in the image of the ratio of PLIF and Mie signals and PDA measurements, instead of calculating the K at a point. It was observed that the use of a single constant for calibration underestimates the small droplets. Stojkovic and Sick [79] reported relative SMD measurements of an automotive hollow-cone, transient spray of isooctane with bidirectional laser sheet illumination in a real engine cylinder head. LSD measurements were performed to study an air-assisted fuel injector in a constant volume chamber and an optical engine [47, 48]. The sequential imaging approach has been adopted in these works. Mie and PLIF signals were over separate injection events to obtain transient development of the ensemble averaged spray. Anand et al. [42] reported time-resolved quantitative SMD distributions of PFI sprays from two-hole and four-hole plate-type injectors using the sequential imaging. In this work, calibration constant (K) was determined using granulometry with an accuracy of $\pm$20%. Deshmukh and Ravikrishna [80] adopted the sequential imaging approach to study high-pressure transient diesel sprays of straight vegetable oils under high pressure conditions. In this work, K was calculated at the edge of the spray using PDIA technique. Kannaiyan et al. [6] performed simultaneous LSD measurements in liquid-centered swirl coaxial (LCSC) injector. They argued that the use of point measurement techniques such as PDI may be difficult to calculate K, as exact mapping of a small measurement volume ($\sim$500μm) in a LSD image of the pixel resolution of the order of micrometer is difficult. On the other hand, a measurement diameter of around 10 mm in a line-of-sight measurement technique will be easy for the calibration. They suggested the use of a line-of-sight measurement over point measurement for the calibration. The SMD measurements were compared with that from diffraction-based method, and good agreement was reported. They observed that the use of line-of-sight measurement technique was more reliable, which ensures exact mapping of the calibration location in the independent drop sizing and PLIF and Mie images. Most of the researchers used PLIF signal as a volume-dependent signal. Malarski et al. [35] suggested using Raman scattering signal as an alternative to the PLIF signal. However, a weak Raman signal leads to low signal-to-noise ratio (SNR), which might cause an error in LSD measurements, particularly in dilute sprays. Pastor et al. [46] compared the influence of natural fluorescence and doped fluorescence on LSD measurements. Natural fluorescence gives a weak PLIF signal that may lead to erroneous drop sizing in dilute sprays. Recently, Mishra et al. [81] demonstrated that the three-dimensional distribution of SMD can be obtained using SLIPI-LSD method. Koegl et al. [71] studied DISI multi-hole gasoline sprays of biofuels, ethanol, and butanol in a constant volume chamber using the SLIPI-LSD measurements. The measurements were carried out at reactive and engine-relevant conditions using simultaneous approach of the LSD measurements. They observed larger spray tip penetration and bigger droplet SMD in butanol sprays than those of ethanol sprays, which was attributed to reduced atomization in butanol sprays due to lower evaporation rate and higher surface tension and viscosity of butanol fuel. Kapusta [70] adopted simultaneous approach of LSD measurements to study SMD distributions of urea-water solution (UWS) sprays for after-treatment devices in diesel engines. SLIPI technique was used to mitigate multiple scattering in Mie and PLIF signals.

Overall, sequential and simultaneous imaging approaches are employed in many continuous and transient sprays. It is also possible to get time-resolved SMD measurements using sequential imaging. The LSD measurements are well established at non-evaporative conditions. At evaporative conditions, it is expected that the loss due to laser extinction, signal attenuation, and multiple scattering will be less important than that at non-evaporative conditions due to low droplet number density. However, extensive studies, e.g., studies on the effect of evaporation rate on the calibration constant and dye selection, etc., are required to establish LSD measurements in evaporative conditions.

8. Summary

Laser sheet drop sizing is an attractive technique that can be used in dense fuel sprays. The LSD technique provides planar SMD and liquid volume fraction distributions in a spray plane. However, the technique suffers from various sources of error due to multiple scattering, laser extinction due to scattering and absorption of the laser sheet, and auto-absorption of the PLIF signal. These sources may lead to significant errors in the LSD measurements, especially in dense sprays due to high droplet number density. Further, the contribution of the sources in Mie and PLIF signals might be different, which may lead to error in SMD measurements. Therefore, it is essential to reduce the contribution of these sources of error to obtain reliable planar SMD and liquid volume fraction distributions using the LSD technique in dense sprays.

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Abbreviations

CCD	charge-coupled device
Conv. LSD	conventional LSD measurements
GLR	gas-to-liquid mass ratio
ILIDS	interferometric laser imaging for droplet sizing
K	constant of proportionality in the LSD technique
LSD	laser sheet drop sizing
MDR	morphology-dependent resonances
OD	optical depth (−)
PDA	Phase Doppler Anemometry
PDI	Phase Doppler Interferometry
PDIA	Particle/Droplet Imaging Analysis
PDPA	Phase Doppler Particle Analyzer
PLIF	planar laser-induced fluorescence
SLIPI	structured laser illumination and planar imaging

SLIPI-LSD	SLIPI-LSD measurements
SMD	Sauter mean diameter
SNR	signal-to-noise ratio
ΔP	gauge pressure of the atomizing gas (Pa)
λ	wavelength of illumination (nm)
I_1, I_2, and I_3	SLIPI sub-images
I_f	fluorescence intensity
I_s	scattering intensity
X_m	Mie parameter

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