Laser Sheet Dropsizing of DI Sprays under Various Conditions Calibrated Using PDI

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Abstract

It is time consuming for phase Doppler interferometry (PDI) to get the diameter distribution of a plane of the spray though it is quite precise. Laser sheet dropsizing (LSD) is a new laser technique which is based on a planar laser-induced fluorescence (PLIF) and Mie-scattering images originated from a cloud of droplets in a spray. LSD technique could obtain the Sauter mean diameter (SMD) across the spray region simultaneously and quickly by the ratio of the LIF signal to the Mie scattering signal. However, the precision of LSD technique is highly dependent on the calibration. The objective of this paper is to combine these two techniques so as to verify the accuracy of the calibration coefficient K of LSD technique in a wide range of injection pressures and fuel temperatures. Since the LSD technique produces a spatial distribution result while the PDI generates a single-point measurement result with temporal resolution, two comparison methods for the calibration of the coefficient K were conducted. Data conversion between the drop size results of these two measurement techniques were implemented in this paper. The drop size results of PDI and LSD techniques were in a good agreement. After the calibration, the spray SMD distribution can be thoroughly investigated by LSD technique with good temporal and spatial resolutions.

Introduction

As a non-intrusive instrument, phase Doppler interferometry (PDI) has been developed and utilized for in-situ spray drop size measurement and investigation on spray characteristics in spark-ignition direct-injection (SIDI) engines during last two decades. Bachalo et. al. developed PDI for simultaneous measurements of spray drop size and velocity [1]. Presser et. al. obtained the axial and radial droplet size and velocity distributions in a swirl-stabilized, pressure-atomized kerosene spray [2]. Tang et. al. used PDI to measure the droplet size, axial velocity and concentration of an electrostatic spray [3]. Ahmed et. al., combined laser Doppler anomematry (LDA) and PDI to understand the detailed structure of the transient spray near the nozzle of a SIDI engine [4].

However, the phase doppler technique is a point-wise measurement technique which measures the diameter and velocity of an individual spherical particle with temporal resolution at high data rates. Thus, it is quite time consuming for PDI to measure the diameter distribution of a whole plane of the spray. Moreover, the droplet information from different positions of the spray could not be measured by PDI simultaneously. The cyclic fluctuation of the drop size across the spray region could not be captured by PDI.

Laser sheet dropsizing (LSD) is a new laser technique which is based on a planar laser-induced fluorescence (PLIF) and Mie-scattering images captured from a mass of droplets in a spray. LSD technique could obtain the SMD from different positions of the spray simultaneously with high efficiency by taking the ratio of LIF signal to Mie scattering signal. A huge mount of the drop size information from a spray plane which PDI cannot capture could be collected by LSD. The cyclic fluctuation of drop size from the sequential of pulsing sprays can be detected by LSD. However, the precision of LSD technique is highly dependent on the calibration.

The objective of this paper is to combine these two techniques so as to get the precise K coefficient of LSD in a wide range of injection pressures and fuel temperatures. Since the LSD technique produces a spatial distribution result while the PDI generates a single-point measurement result with temporal resolution, two comparison methods for the calibration of the coefficient K were conducted by either converting the PDI results to the LSD data presentation or converting the LSD results to the PDI data presentation. The coefficients from the both calibration methods agree to each other with a negligible difference.

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Laser Diagnostic Techniques

1) PDI technique

PDI is a nonintrusive measurement technique based on measuring the Doppler signal scattered by a particle as it crosses the probe volume formed by the intersection of the laser beams. It has been successfully used in a wide variety of situations for in-situ measurements of particle size and velocity [5]. The principles and applications of PDI measurements were reviewed by Bachalo [6].

2) LSD technique

The principle of the LSD technique relies on the assumption that the fluorescence intensity emitted by the fluorescent dye is proportional to the volume (d^3) of the droplet and that the scattered light intensity is proportional to its surface area (d^2) [7]. The fluorescence and scattered light intensities from droplets are measured simultaneously during the illumination of a spray with a laser sheet. As a consequence, the ratio of the two intensity distribution on an illuminated plane of a spray is proportional to the SMD and can be estimated, according to

$$\frac{i_f}{i_s} = K \cdot SMD \tag{1}$$

where i_f and i_s are the signal of fluorescence and scattered light intensities respectively; and K is the calibration coefficient, which is usually obtained from calibration experiments.

The calibration coefficient K is not a constant value parameter, but it is a function of the SMD for the typical SIDI engine sprays, as shown in Figure 1 [8]. The dotted curve is a polynomial fit on the calibration values. Simultaneous Laser-induced-exciplex-fluorescence/Mie-scattering (LIEF/MIE) techniques, which had been proven to improve the accuracy of the evaporating sprays, were used in this study [8]. Two calibration methods were conducted for the data analysis and comparison.

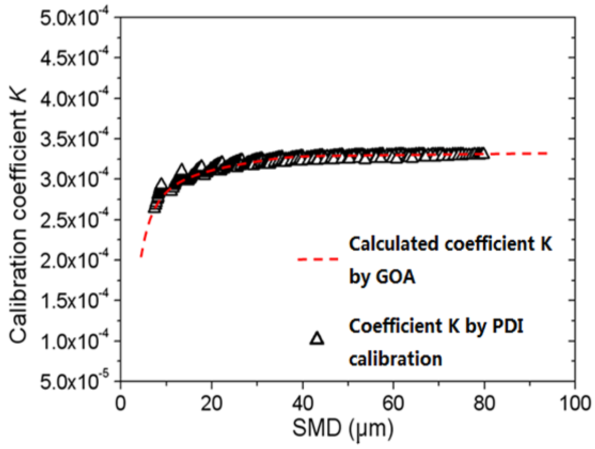


Figure 1 Values of calibration coefficient K versus SMD.

Experimental setup

Figure 2 shows the experimental setup for PDI and LSD tests. The droplet sizes of a multi-hole SIDI injector spray were measured in a constant volume chamber with full-optical access. The multi-hole SIDI injector was installed vertically on the top of the constant volume chamber. Four quartz windows were equipped on the four sides of the chamber for optical access. Two of them were located with a relative angle of 150° so that the PDI transmitter and receiver pointed to each window can obtain a clear burst signal of a droplet. Another two quartz windows were set at an angle of 90° so as to obtain planar scattered light and fluorescent light signals from a cross-section of the spray illuminated by a laser sheet formed by a Nd:YAG laser at 266 nm wavelength. Both MIE and LIEF images were captured simultaneously using an Image-Doubler, which was mounted in front of a 12-bit CCD camera with a 1376×1024 resolution. Since the direct fluorescence signals were too weak to be detected, an image intensifier unit was fitted on the camera. The centerline wavelength/band-width for Mie-scattering filter is still 266/10 nm, while for the fluorescence filter is 289/10 nm. The more detailed information of facilities and post-processing can be found in references [8], [9], [10].

A piston type accumulator along with nitrogen supply system was utilized to provide the desired fuel pressure from 2 MPa to 10 MPa. The fuel temperature control system and heat exchanger system were used to regulate the fuel temperature from 20 °C to 60 °C.

The setup of PDI system is shown in Table 1. A commercial two-component Phase Doppler Interferometry system (PDI-200 MD, Artium® Technologies, Inc.) was used in this study. A three-directional traverse system was utilized to move the PDI transmitter and receiver simultaneously in three directions (X, Y, Z) to scan through different positions of the spray.

Table 1 Phase Doppler Interferometry specifications

Parameters	Value
Laser type	Diode-pumped solid state Nd: YAG laser
Laser beams wavelength	532 nm (green)
Two laser beams separation	60.6 mm
Beam diameter	1.05 mm
PDI transmitter focal length	500 mm
PDI receiver focal length	500 mm
Interference fringe spacing	4.4 μm
Beam waist	322.6 μm
Collection angle	30°
Measurement diameter range	1.2 – 182 μm
Slit aperture of receiver	50, 100 μm

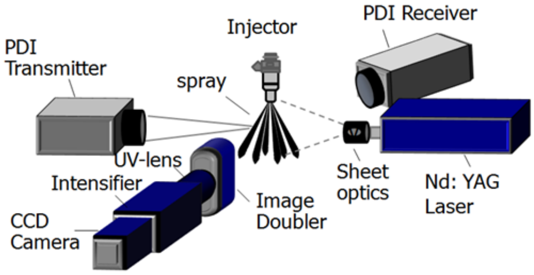


Figure 2 Experimental setup schematic for PDI and LSD systems.

Experimental conditions and positions

For the LSD technique, the selected exciplex mixture needs to have similar properties with actual fuel and the tracers need to co-evaporate with the base fuel. The fluorobenzene (FB)/diethylmethylamine (DEMA)/n-hexane exciplex system was selected in this study since it has shown good co-evaporation based on components measurement of an evaporating droplet and the crosstalk is low [11]. In FB/DEMA/n-hexane system, FB is the monomer (M), DEMA is the exciplex forming component and (G) n-hexane is the base fuel. According to the previous studies, the concentration of DEMA and FB used in this study were the constant with volume percentage of 9% and 2%, respectively [8]. With carefully chose fluorescence tracer and corresponding concentration, the fluorescence intensity is proportional to the d^3 while scattered light intensity is proportional to d^2 as it was evaluated theoretically by Domann et al. [12] and geometrical optics approximation (GOA) method[8].

In this study, the injection pressure was varied from 2 MPa to 10 MPa. The fuel temperature was changed from 20 °C to 60 °C. The test conditions were described in Table 2.

Figure 3 depicts the position of the drop size measurement by both PDI and LSD techniques. The drop size measurement by PDI was implemented at 40 mm, 50 mm and 60 mm downstream of the injector tip through the center of one spray plume. The drop size measurement by LSD was conducted using a laser sheet which passed through the center of the spray plume and the axis of the injector to obtain planar scattered light and fluorescent light signals. The laser sheet images were taken at different times from 1.0 ms to 5.0 ms after the start of injection (SOI) with 50 μs time step while the PDI collection time was from 0 ms to 15 ms after SOI. The SOI is defined as the start of driver logic signal. By acquiring 50 images for each test condition at each time-step, the drop size data was statistically sufficient.

For the reasonable calibration of the coefficient K and SMD comparison, the results of LSD measurement at the same measuring volume with that of the PDI technique (about 0.16 mm^3) were selected and analyzed statistically. Namely, the pixel numbers of the laser sheet imaging were carefully selected to keep the same spatial resolution between LSD and PDI.

Table 2 Experimental conditions

Conditions	Values
Injection pressure (MPa)	2, 10
Fuel temperature (°C)	25, 60
Back pressure (kPa)	100
Ambient temperature (°C)	25
Fuel types	N-hexane

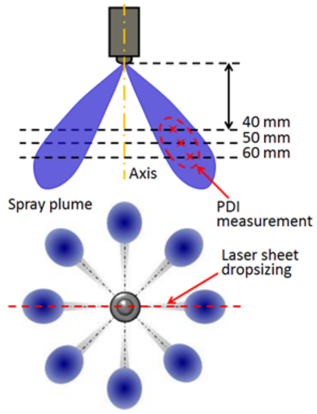


Figure 3 Measurement positions.

Results and Discussion

1) Measurement results of spray drop size by PDI

For each test condition listed in Table 2, three hundred injections at each measurement location were conducted and at least 10,000 validated counts were collected by the PDI instrument. The collection time window was set from 0 to 15 ms after the start of logical signal. To ensure data reliability, 60% validation rate of the PDI data was chosen in the experiments [13], [14].

The experimental results such as drop size distribution and droplet diameter versus time are shown in Figure 4(a) and (b) respectively. From the drop size distribution, mean diameter such as SMD could be calculated to compare with LSD measurements.

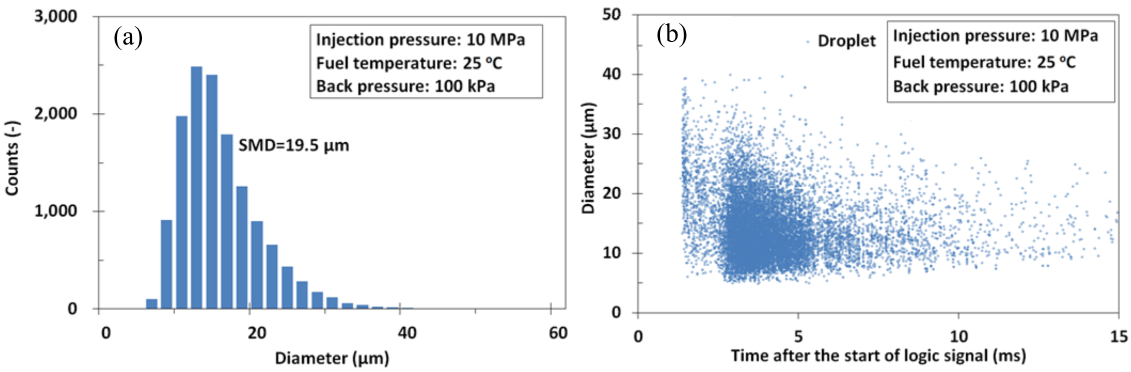


Figure 4(a) and (b) One of the PDI experimental results (drop size distribution and drop size versus time).

2) Two methods of data conversion between PDI and LSD

Since LSD is a technique to provide a snapshot of the spatial distribution while PDI is a point-wise measurement technique, the conversion between the results of these two measurements is necessary.

a) Method one -- temporal resolution based

Figure 5 illustrates the method of the data conversion from the LSD way to the PDI way. The calibration location of the coefficient K was selected at the center of the spray plume, the same as PDI measurement. PDI measured the droplet diameter versus time at each pulse of the spray as shown in Figure 5. The PDI data in a narrow time window (Δt =30 μs) at a series of time steps (50μs apart) were calculated to correspond to the high-speed sequential images of the LSD measurement, as illustrated in Figure 5. The ratio of LIEF/MIE was obtained from the fluorescence and scattered light signals from sprays at the position of PDI measurement point and a sequence of SMDs were calculated at every time step. For the same time steps as LSD measurement, the SMD of all droplets present in a narrow time period (Δt =30 μs) were calculated by PDI measurement results. Therefore, at every image collecting moment, dividing the ratio of LIEF/MIE by the value of K derived the value of SMD_{LSD} by the following equation (2),

$$SMD_{LSD} = \frac{i_f/i_s}{K} \tag{2}$$

where K was looked up from Figure 1 as a function of SMD from PDI measurement.

Figure 6 describes the comparison results for the first method between PDI and LSD at 50 mm downstream the injector tip. For every time step, SMD values from both PDI and LSD are almost identical and the trend of SMD versus time is almost superimposed in Figure 6.

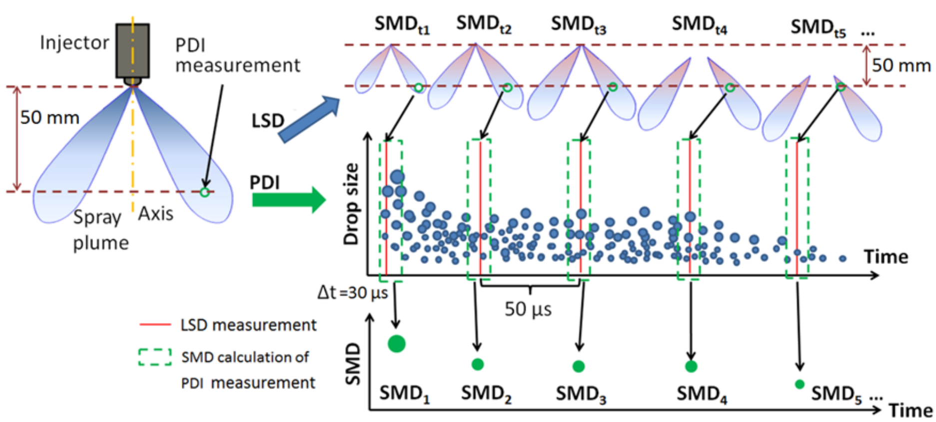


Figure 5 Schematic diagram for the first method of data conversion between PDI and LSD.

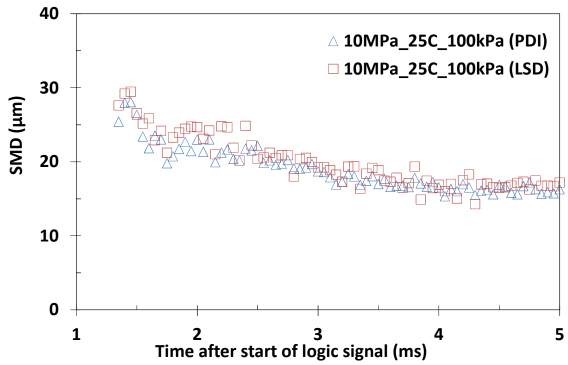


Figure 6 The results of the first method between PDI and LSD.

b) Method two -- time ensemble averaged

In method two, the SMD data of all droplets present in a large time period (5 ms) were calculated using the PDI data as shown in Figure 7. Within the same time period, the fluorescence and scattered light signals from all sequential sprays at the position of PDI measurement point were integrated to calculate the ratio of LIEF/MIE. Therefore, in order to compare the SMD data between PDI and LSD, the SMD was calculated as the ensemble average through the time period (5 ms) based on PDI measurement results, and then the similar ensemble averaged ratio of LIEF/MIE of the LSD measurement was derived from the integrated fluorescence and scattered light signals for all the time steps. Furthermore, the ensemble averaged SMD from LSD data was obtained by dividing the ratio of LIEF/MIE by the value of K.

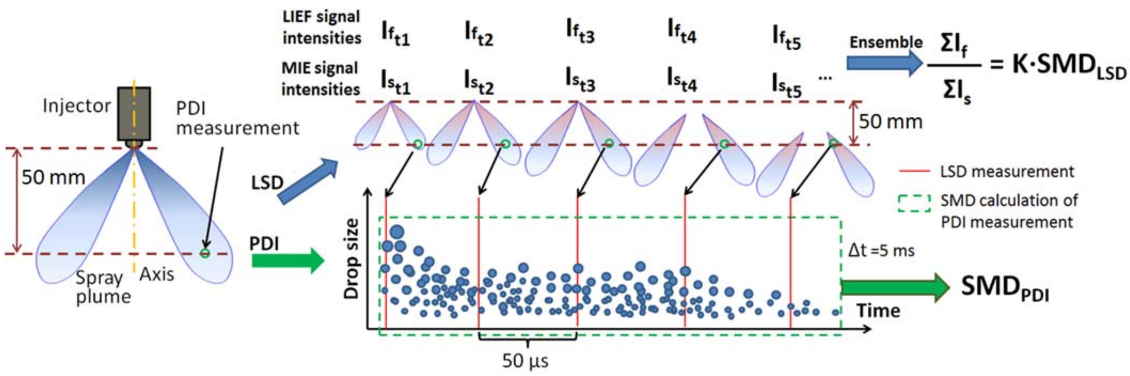


Figure 7 Schematic diagram for the second method of data conversion between PDI and LSD.

Figure 8 shows the comparison of the method two between PDI and LSD at 50 mm downstream the injector tip. For each condition, SMD between PDI and LSD are close to each other and the magnitude deviations of SMD are 5% and 10% respectively in Figure 8.

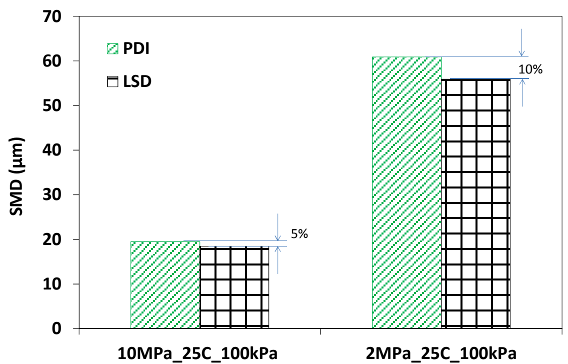


Figure 8 The results of the second method between PDI and LSD.

3) LSD application in different positions of the spray

Figure 9(a) and (b) describe the comparison results of the first and second calibration methods between PDI and LSD for different distances (40 mm and 60 mm) downstream the injector tip. The results between PDI and LSD show a reasonable agreement with some discrepancies. The drop sizes measured by LSD are slightly smaller than the PDI measurements. Based on the results comparison in method two, the difference between PDI results and LSD results increases with the augment of the distance from the injector tip. For each condition, SMD values between PDI and LSD are similar and the maximum difference of SMD is 5%. Therefore, the calibration coefficient K in Figure 1 is suitable for the different axis positions of the spray.

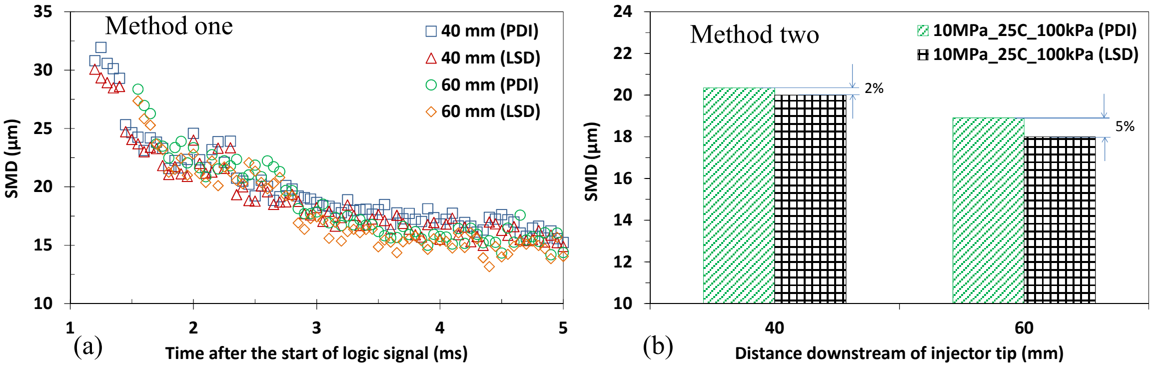


Figure 9(a) and (b) Comparison results of the first and second calibration methods between PDI and LSD at different distances downstream the injector tip.

4) LSD applications in different conditions of the spray

Figure 10(a) and (b) show the comparison results of the first and second calibration methods between PDI and LSD for different test conditions. A good agreement between the two techniques was demonstrated under a relatively large range of the conditions. As the injection pressure decreases, the difference between PDI results and LSD results increases. However, the fuel temperature variation has negligible influence on the results from two techniques. For all the test conditions, the maximum difference of SMD results from PDI and LSD is about 10% in Figure 10(b). Thus, the calibration coefficient K in Figure 1 is appropriate for the different conditions of the spray such as various injection pressures and fuel temperatures.

Figure 11 indicates the comparisons between LIEF/MIE and PDI, which provides an assessment of the error associated with LSD technique. The maximum deviation is about 15%.

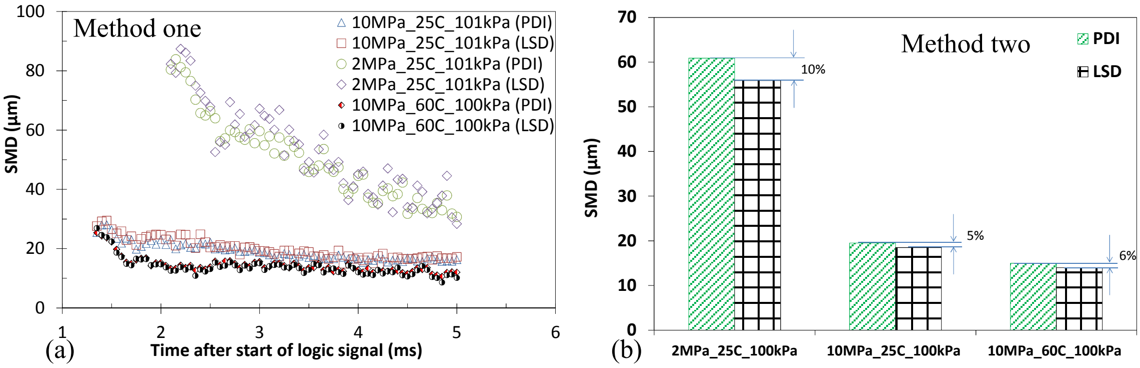


Figure 10(a) and (b) Comparison results of the first and second calibration methods between PDI and LSD at 50 mm downstream the injector tip.

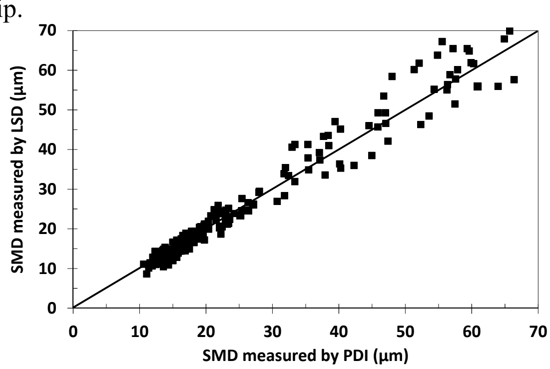


Figure 11 Comparison results of the first and second calibration methods between PDI and LSD at different positions of the spray and at different conditions.

5）Drop size distribution measured by LSD in different time after start of logic signal

Because of the multiple scattering problems in dense sprays near the injector tip, the drop size measurement by LSD in the near field of the injector tip cannot be trustable. Only the LSD data at the positions of the spray below 30 mm downstream the injector tip were considered as valid results. Figures 12 and 13 present the two dimensional SMD distribution measured at different times after the SOI, for the two injection pressures respectively. At low injection pressure (2 MPa), all SMD values of the spray were larger than 25 µm. SMD values reached to 60 µm near the center of the spray plume, while SMD values were around 30 µm at the edges of the spray. With the increase of the distance downstream the injector tip, the SMD values remains unchanged. The trend of SMD variation at low injection pressure was almost the same as that in high pressure (10 MPa), but the average SMD was around 20 µm, as shown in Figure 13. SMD values in the center of the spray plume were larger than those at the edge of the spray. SMD values of the whole spray decrease with longer delay time after the SOI, especially at the tail of the spray plume.

Therefore, the spray microscopic characteristics such as drop size can be quickly investigated by LSD technique based with both temporal and spatial resolutions.

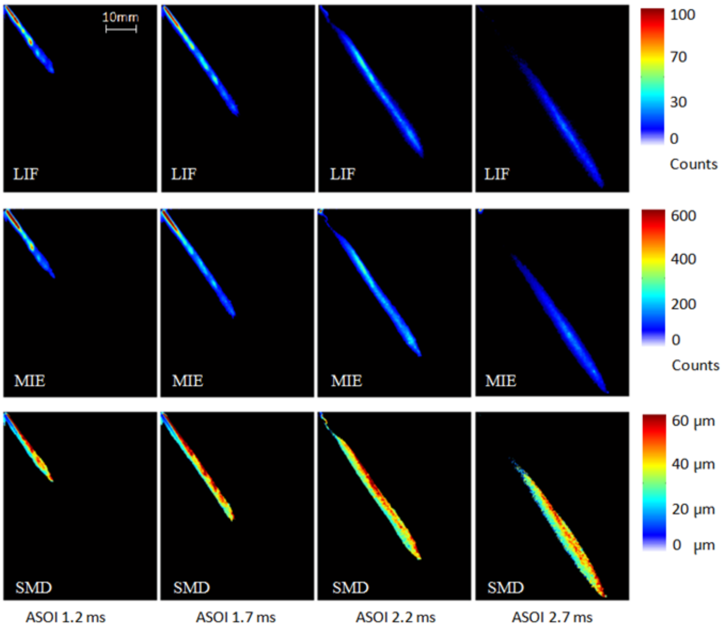


Figure 12 Drop size distribution measured by LSD in different times after SOI (Injection pressure 2 MPa, back pressure 100 kPa, fuel temperature 25°C).

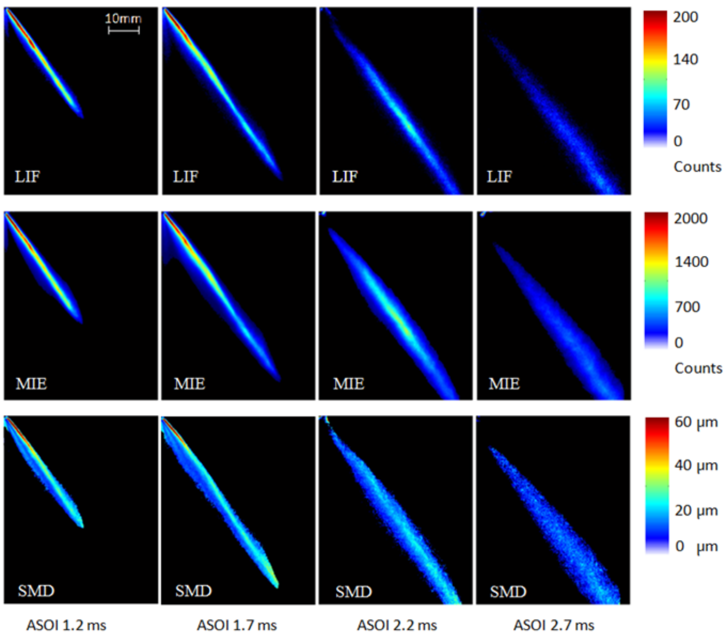
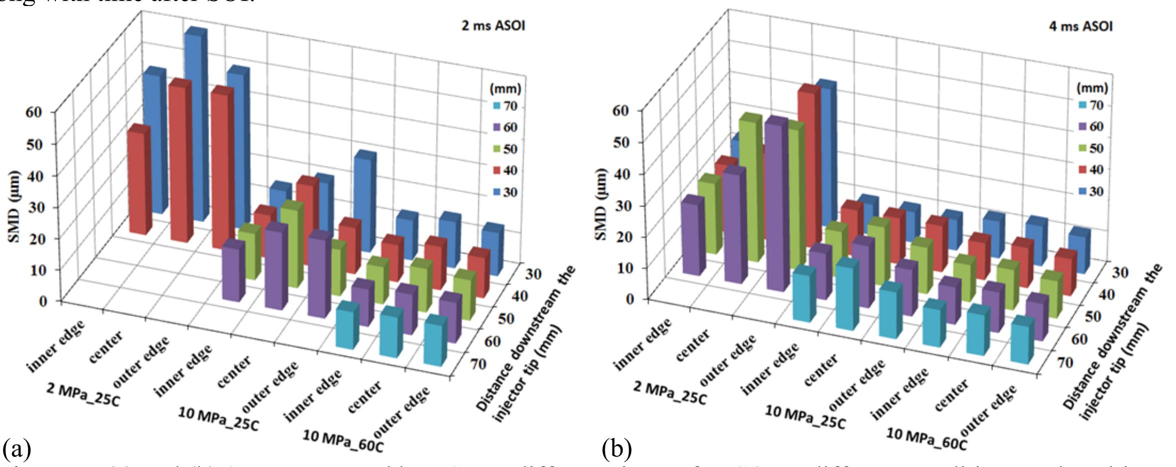


Figure 13 Drop size distribution measured by LSD in different times after SOI (Injection pressure 10 MPa, back pressure 100 kPa, fuel temperature 25°C).

Figure 14(a) and (b) show the SMD measured by LSD at 2 ms and 4 ms after the SOI respectively. The

SMD data was taken from various axial and radial positions of the spray for various injection conditions. In general, the drop size reduces with the injection pressure. At 2 MPa injection pressure condition, the SMD at the outer edge of the spray plume is larger than that of the inner edge. At 10MPa injection pressure and 25 °C fuel temperature, the SMD at the center of spray plume is larger than that on both sides of the spray edge. For the higher fuel temperature of 60 °C, the SMD seemed to be uniform across the spray plume. The SMD decreases along with time after SOI.



(a) (b)

Figure 14(a) and (b) SMD measured by LSD at different times after SOI at different conditions and positions

Summary and Conclusions

The drop sizes of a SIDI multi-hole injector spray were measured and investigated by means of PDI and LSD techniques in this paper. Two techniques were compared to varify the accuracy of the calibration coefficient K for the LSD method in a wide range of injection pressure and fuel temperature conditions. The results of PDI measurement and LSD measurement were also compared at different axial locations of the spray. The conclusions are as follows:

(1) Two methods were used for the calibration of the coefficient K on temporal resolution base and time ensemble average base. Data comparisons between the drop size results of these two measurement techniques show good agreement.

(2) The drop size results of PDI and LSD at different axial locations of the spray were in a good consistency. The calibration coefficient K is suitable for LSD technique to measure the drop size at the main spray region.

(3) The calibration coefficient K is appropriate for the different conditions of the spray such as various injection pressures and fuel temperatures. The maximum measurement error is about 15%.

(4) The spray microscopic characteristics such as drop size can be quickly investigated using LSD technique with good temporal and spatial resolutions.

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