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Single-Shot SLIPI-LIF/Mie Ratio for Droplet Sizing in DISI-Sprays

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Abstract

This paper reports on the first realization of two-phase SLIPI (Structured Laser Illumination Planar Imaging) in combination with LIF/Mie ratio imaging for a single shot mapping of relative SMD (Sauter Mean Diameter) in a transient fuel spray. The technique is applied to a non-combusting multi-jet DISI (direct-injection spark-ignition) spray of ethanol fuel injected into an optically accessible constant volume chamber. The organic dye Eosin is added to the fuel as a laser-induced fluorescence (LIF) tracer when illuminated by the 532nm laser sheet. It is found that SLIPI produces more reliable relative SMD distributions in comparison to the conventional LIF/Mie-approach. Multiple scattered light is suppressed by the SLIPI technique and the background spray plumes and artifacts behind the illuminated plane are successfully suppressed. The single-shot SLIPI images give a clear insight into the highly turbulent liquid spray structure and provide reliable information on the spatial droplet distribution.

1. Introduction

The 2D-LIF/Mie droplet sizing technique has been applied over more than two decades for the determination of droplet sizes in terms of SMD (Sauter Mean Diameter) [1]. However, the conventional approach suffers from multiple light scattering effects in optically dense sprays, which may introduce large systematic uncertainties. SLIPI is a measurement technique capable of successfully suppressing most of these effects, providing more reliable SMD data [2,3]. This has recently been demonstrated for a steady laboratory hollow-cone (HC) water spray [3]. In addition, non-calibrated SLIPI-LIF/Mie imaging has already been performed in Diesel sprays [4]. However, those previous SLIPI measurements were all based on averaged imaging using a 3-phase SLIPI-approach. To acquire single-shot SLIPI images, Kristensson et. al have recently reported a two-pulse SLIPI technique capable of temporally freezing the rapidly occurring processes in the near nozzle region of an HC spray [5]. The technique is based on using two spatially modulated light sheets having same spatial frequency but of opposite phase. Thus, a SLIPI image can be deduced from the absolute value of the intensity difference between the two-phase mismatched sub-images. Here, the LIF/Mie ratio imaging along with two-pulse SLIPI-approach is introduced for single-shot visualization of droplet sizing. It enables qualitative single-shot SLIPI-LIF/Mie droplet sizing for realistic transient DISI (direct-injection spark-ignition) engine sprays. The acquired 2D-droplet distributions on single-shot basis provides much deeper insight into the turbulence of the spray formation process in comparison to average measurements.

In this study, the atomization and evaporation behaviour of multi-jet DISI-sprays are investigated at 16 MPa injection pressure and full engine load conditions in an optical injection chamber. The spray structure is visualized in terms of relative SMD distributions for single shot sprays, which is compared to the results of averaged SLIPI imaging and conventional measurements.

2. Imaging Technique

SLIPI is an imaging technique for suppressing multiply scattered light in optically dense sprays initially based on using three individual images of structured light with different phases. In contrast to a common light sheet imaging, the incident light sheet follows, with SLIPI, a sinusoidal pattern. When illuminating the spray, the light scatters and thus, the singly scattered photons keep the modulated signature, however, the multiply scattered photons will lose the coded pattern. For averaged SLIPI-imaging three intensity-modulated images (sub-images) - corresponding to the phases 0°, 120° and 240° - are recorded. The SLIPI image can be created after taking the root mean square of the differences of the modulated images, described mathematically as:

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

where $I_S(x,y)$, is intensity corresponding the resulting SLIPI image and similarly I_0, I_{120} and I_{240} represents the three sub-images. Due to the requirement of a minimum of three sub-images to keep full image resolutions without any artifacts, it becomes very challenging for single-shot imaging as shown in [2]. Therefore, SLIPI has been mostly used for averaged imaging and the technique assumes that for each averaged sub-image the spray structure is statistically the same. A complete description of 3-phase SLIPI can be found in [3].

For the two-phase SLIPI the final image is created from only two sub-images using a high spatial frequency on the incident modulation and by adequately post-processing the images in the Fourier domain to remove residual lines. The resulting image is therefore extracted as:

$$I_S = \frac{\sqrt{2}}{2} \cdot \sqrt{\left(I_0 - I_{180}\right)^2} + \text{Fourier post-processing} \tag{2}$$

A detailed description of 2-phase SLIPI can be found in [6].

The SMD of spray droplets can be measured by division of simultaneous acquired LIF and Mie (LIF/Mie ratio) images. It is based on the assumption that the LIF and Mie signals from droplets are proportional to the droplet volume (d^3) and to their surface area (d^2), respectively. The necessary conditions for technique to work: (i) The spray droplets must be spherical.The spray evaporation rate must be adequate slow in order to avoid fluoresence from the gas phase. Furthermore, all photons which are reaching the camera should only be scattered once before detection. If these conditions are fulfilled, the SMD of a droplet cloud for each camera pixel is equal to:

$$SMD = \frac{\sum_0^\infty D_i^3}{\sum_0^\infty D_i^2} = \frac{S_{LIF}}{S_{Mie}} \cdot \frac{K_{LIF}}{K_{Mie}} \tag{3}$$

Where, S_{LIF} and S_{Mie} are LIF and Mie signals, while K_{LIF} and K_{Mie} are constants from experimental components such as signal collection angle, detector response, laser power and dye concentration. However, several experimental and theoretical studies have shown that the cubic and square dependence of droplet diameters on the LIF and Mie signals respectively is not practically valid [7-12]. It is found that due to an increase in dye concentration the molecular absorption changes the exponent for the fluorescence from three to two. Also, the droplet size distribution influences the proportionality exponent of the LIF signal intensity averaged on an ensemble of droplets.

3. Experimental Setup

The two-pulse SLIPI setup consists of an optically accessible constant volume chamber, an optical arrangement for a modulated light sheet and a detection unit including two scientific sCMOS cameras (LaVision), see Figure 1. The spray chamber is operated at 0.2 MPa and 298K representing high load engine operation. The fuel temperature is set to 298K and the injection pressure is set to 16 MPa. The injection duration is kept constant at 1.8 ms. A 5-hole DISI-injector (BOSCH) was utilized, where one cone is centrally separated from the others allowing unrestricted optical access. For the LIF measurements an organic luminescence dye Eosin (Kingscote Chemicals, USA) of which 0.5 vol.-% is added to fuel.

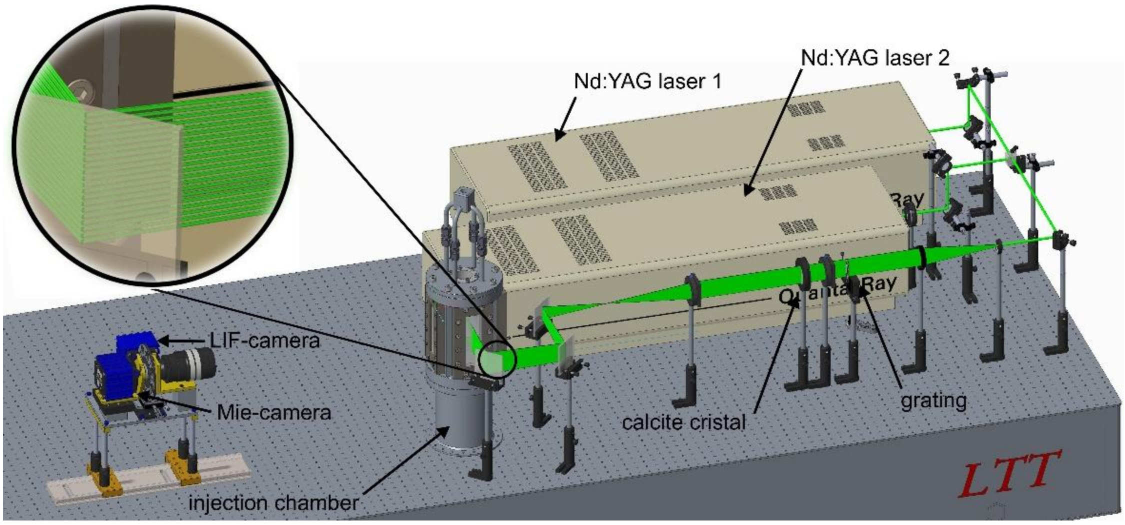

Figure 1. Illustration of the two-pulse SLIPI-LIF/Mie experimental setup

The fuel spray is visualized by structured illumination using two pulsed 532 nm Nd:YAG lasers (laser 1: Quanta Ray and laser 2: Quantel Brilliant). The structured light sheet is formed by a square Ronchi grating (4 line-pairs/mm), which is focused in the measurement plane inside the chamber. The laser sheets have a height of 90 mm and a thickness of 500 µm, the laser fluence for the two lasers was matched. The sub-images of the LIF- and Mie-signal are shown in Figure 2. The modulation in the spray is still visible, which can be better seen in the respective close-up photograph (right side).

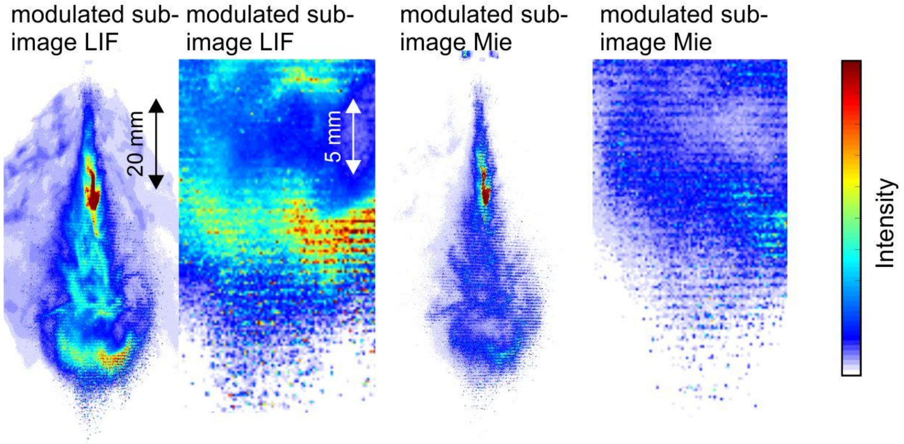

Figure 2: Modulated LIF and Mie sub-images with close-up photograph for a single shot at 2300 µs after ESOI

In order to record single shot images, the light sheet has to be shifted spatially by 180°. The shifting of the two phases is performed with a calcite crystal based on its polarization dependent double refraction properties. The thickness and the orientation of the optical axes of the crystal determine the shift between the two phases. Laser 1 produces s-polarized pulses, while laser 2 p–polarized pulses.
Mie scattering simulations showed, that the intensity difference of a droplet distribution (5-20µm, [13]) between p and s polarisation is roughly constant. This circumstances is considered by a intensity correction during post processing. The time-shift between the two lasers is 0.75 µs enabling a quasi-simultaneous spray visualization.

The propagation and evaporation of the spray is analysed simultaneously by Mie and LIF imaging. The in-house designed camera system combines both sCMOS cameras with one objective allowing for a similar imaging scale. A 70/30 cube beam splitter is used to optimize the LIF/Mie signal, which is placed behind the objective. When the injected fuel is illuminated, the broadband emission of the LIF signal occurs between 500 nm and 620 nm. The two signals are separated by appropriate filters directly mounted just in front of the cameras chips. The LIF emission is detected by using a 532 nm (17nm FWHM) notch filter in order to exclude the excitation laser light and the Mie scattering signal is detected by using a 532 nm (1 nm FWHM) short pass filter. Both sCMOS cameras are operated in a double shutter mode to capture both pulses (phase shifts) with a short time delay.

4. Results

Single shot images of SLIPI and conventional detection are shown for the LIF-signal, the Mie-signal and the LIF/Mie ratio in Figure 3**.** The acquisition time is set to 2300 µs after ESOI. At this point in time, the spray is fully developed in size and the nozzle has been closed shortly before. The modulated light sheet enters the spray from the left side and illuminates it along its central plume axis. Based on the modulated sub-images, the conventional and the SLIPI images of the LIF- and Mie- signal are extracted and shown. In comparison to the conventional image, the SLIPI images have a significantly improved clarity because of the suppression of multiply scattered light, revealing vortex structures and single droplet clouds. This improvement in signal-to-background (background representing scattered light of the spray cones in the background) is essential for an accurate determination of the SMD in the subsequent post-processing steps.

When comparing the LIF and the Mie images obtained using SLIPI it is noticed that a strong signal occurs in the spray front in both cases, although the Mie image gives an additional strong signal in the tail. The conventional Mie/LIF-ratio features signals that are not in the image plane and the outer spray cone is not clearly distinguishable from the background. Here, the largest signal occurs at the spray front as well.

The signal of the SLIPI LIF/Mie-ratio shows the largest intensities at the spray edges and on the edges of the vortices. A large eddy is visible behind the spray front.

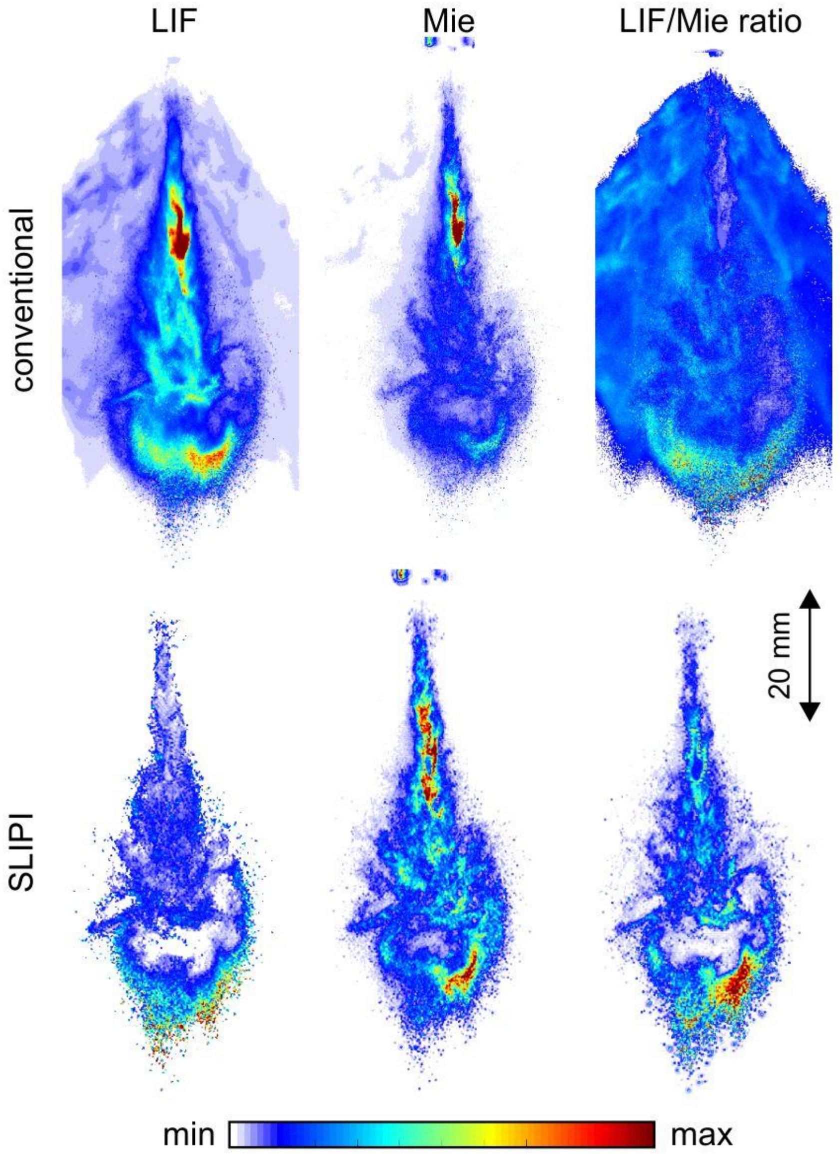

Figure 3. Comparison of SLIPI and conventional single shot images of LIF, Mie and LIF/Mie ratio at 2300 µs after ESOI

The drag forces at the spray front support collision of the fuel droplets accompanied with droplet coalescence. This leads to larger droplets at the spray front which is typical for DISI-sprays [13, 14]. The droplets with lower kinetic energy are pushed away from the spray axis and form the outer region [14]. The single shot SLIPI LIF/Mie ratio shows the same behaviour. The pulsating spray motion in combination with the existing vortices at the spray front lead to a low LIF/Mie ratio in the centre of the eddy. Also evaporation of fuel is ongoing, which may lead to locally low LIF/Mie signals in this spray region.

The low LIF/Mie ratio in the tail of the spray of both the conventional and the SLIPI-images is not physical. This low LIF/Mie ratio is caused by the destuction of the line structure due to the presence of large irregular liquid elements. However, in the conventional LIF image a high signal is visible due to these large non-spheric structures. However, the LIF/Mie ratio for planar droplet sizing is only applicable for spherical droplets.

Five example single shot images and the calculated standard deviation (determined from 100 images) are shown in Figure 4 in terms of the LIF/Mie ratio. It can be seen that the maximum penetration of the spray within one measurement row is comparable, but the spray front is not symmetric and it is characterized by large spatial variations of the droplet distibution appearing from shot-to-shot. Large-scale vortices appear especially at the spray front, generated by large droplets with high droplet momentum. The cyclic spray fluctuations are generated by the turbulent, instationary nozzle flow and by the spray-induced turbulence leading to distinct axial pulsations as well as radial bending of the spray. The cyclic variations are also visualized by the standard deviation of the LIF/Mie ratio, which can only be calculated for the 2-pulse SLIPI technique for which single shot SLIPI-images are available. LIF/Mie ratio shows large variation especially at the spray front as the strongest turbulent droplet dispersion occurs there due to the large vortices. Since the largest droplets appear at the spray front as well showing spatial variation from shot to shot, this also contributes to the large standard deviation of the LIF/Mie ratio. Even two distinct spray tips are visible due to the different spray bending appearing from shot to shot.

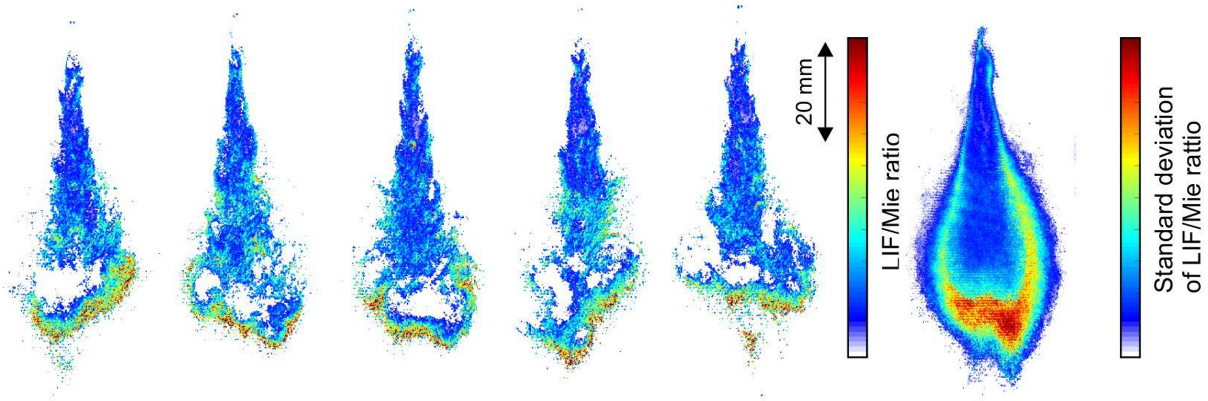

Figure 4: Comparison of five single shot images and standard deviation of the LIF/Mie ratio at 2300 µs after ESOI

In Figure 5 the relative LIF/Mie signal of 100 images of the averaged three-phase SLIPI and the averaged two-phase SLIPI single-shot is compared.

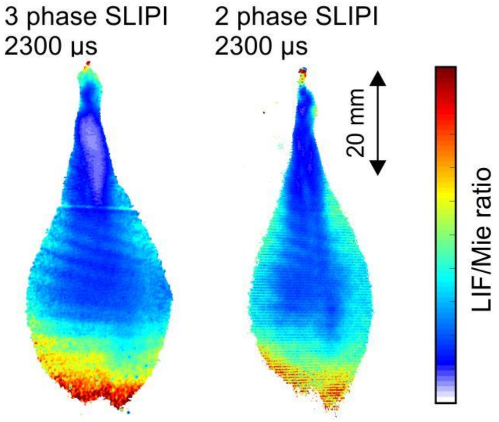

Figure 5: Averaged LIF/Mie ratio (100 images) of E100 at 2300 µs after ESOI

In general, the average images show strong LIF/Mie-signal at the spray front, indicating large droplets. Additionally, at the spray edges on the right and left of the plume larger droplets can be detected. This signal is attributed to strong spray fluctuations and occasionally occurring larger droplets (see also Figure 4). It can be seen that the averaged LIF/Mie-ratios of the two SLIPI techniques are very similar. The turbulent spray fluctuations and cyclic variation appear blurred in the averaged image, making it difficult to accurately interpret and draw conclusions from the data. The two-phase SLIPI technique offers great advantages in capturing the highly turbulent motion, which is clearly necessary for understanding the properties of dense fuel sprays. The average images will form a basis for a SMD calibration by future phase-Doppler anemometry (PDA) measurements. In future studies also the capability of the new single-shot SLIPI technique will be analyzed for various ambient conditions and different points in time.

5. Conclusions

The two-phase SLIPI technique for single-shot LIF/Mie droplet sizing was introduced allowing for the measurement of the relative SMD in DISI fuel sprays. The technique offers great advantages in spray analysis, thanks to the suppression of the effects from the multiply scattered light and to single-shot capability of the technique. The LIF/Mie-ratio of the E100 spray at 2300 µs after ESOI shows larger droplets at the spray tip and the lateral edges of the spray front. The highly turbulent spray motion with large eddies at the spray front can be clearly visualized in single shot images and the standard deviation in terms of the LIF/Mie ratio. The large vortices lead to small LIF/Mie ratios within the centre of the eddies representing smaller droplets. The average images will be used for a SMD calibration using data from future PDA measurements. In subsequent studies the capability of the new single-shot SLIPI technique will also be analyzed at various ambient conditions and for different times after injection start.

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Nomenclature

SLIPI	Structured Laser Illumination Planar Imaging
SMD	Sauter Mean Diameter
LIF	Laser Induced Fluorescence
Mie	Mie scattering
DISI	Direct Injection Direct Ignition
ESOI	Electrical Start Of Injection

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