3D tomographic reconstruction of Spray G after multiple light scattering suppression using Fourier filtering

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Abstract

In this work, we compare transmission measurements combined with high-speed imaging and tomographic reconstruction. A common measurement technique to observe spray propagation and air-fuel mixing is Diffuse Backlight Illumination (DBI). When applying light transmission measurements with DBI, DBI is prone to detecting multi-scattered photons and therefore strongly underestimates the optical depths (*OD*), deduced from the Beer-Lambert law. We showed in previous studies that an experimental setup with a collimated light source and Fourier filtering prior to detection, provides efficient results, reaching higher *OD* than other methods, and demonstrating a suitable suppression of multiple light scattering. We are using this method to measure the spray evolution of an ECN Spray G injector at ambient conditions, with iso-octane, and compare them to DBI measurements with the same optical receiver setup. The images are averaged over 60 injections in order to obtain statistical images of the *OD* and to increase the range of the measured optical depth. The investigated ECN Spray G injector is mounted in a rotation system, allowing an exact and reproducible rotation of the spray. The spray event is detected at 36 viewing angles. An interpolation of the sinogram reduces the angle step size to 1 degree. The *OD* from different angles is tomographically reconstructed by the method of Filtered Back Projection (FBP). We use this to compare the different measurement techniques and estimate the error generated by multi-scattering. Results show major differences in the voxel and time-resolved extinction coefficient data. The OD of the $35\ mm$ plane differs up to a factor of approximately 5.

Keywords

Spray G, Tomography, High-Speed, Liquid Distribution

Introduction

To reach the requirements of carbon emission reduction, global energy consumption must be optimized. Used in direct-injection spark-ignition and diesel combustion engines, the liquid fuel direct injection still remains predominant in automotive internal combustion engines. Direct fuel injection is currently being modified to replace the use of conventional petrol fuels with synthetic fuels, also called e-fuels, and is already investigated [4, 6, 12]. Those synthetic fuels are generated by capturing carbon dioxide or carbon monoxide, together with hydrogen obtained from sustainable electricity sources. Optimizing the combustion of e-fuels requires verifying the performance of an injector in producing transient spray systems that efficiently transit from liquid to gas. Thus, there is a need for detailed quantitative imaging of the cloud of micrometric droplets at different times after injection. The optical diagnostics used for imaging transient sprays must be adapted depending on the density and the level of optical depth [1, 11]. The characterization of the liquid phase of Gasoline Direct Injection (GDI) sprays has been recently performed using Shadowgraphy [9], Mie-scattering, [8]; as well as Structured Laser Illumination Planar Imaging (SLIPI) [15], Two-photon LIF planar imaging [3] and soft X-ray imaging [5]. Two-photon LIF and X-ray imaging are used to significantly suppress the detection of multiple light scattering, generating reliable quantitative data of the imaged GDI spray; such as the droplet sizing, the presence of non-spherical liquid structures, and the liquid volume fraction respectively. Often, DBI setups are used to quantify the projected liquid volume of a spray. However, this is not feasible without detailed consideration of multiple and single light scattering effects [10]. In this work, high-speed transmission measurements are performed using the two different optical methods DBI and Collimated Illumination Fourier Filtering (CIFF) in order to quantify the optical depth of the ECN Spray G running with iso-octane. By definition, the optical depth, OD, is defined through the Beer-Lambert law such as:

$$\frac{I_i}{I_f} = e^{-N\sigma_e L} \quad with \quad \mu_e = N\sigma_e \quad and \quad OD = N\sigma_e L \tag{1}$$

where I_i are the incident and I_f the final light intensities, N is the number density of droplets (in $\#/mm^3$), σ_e is the extinction cross-section of the droplets (in mm^2), L is the path length through the spray (in mm) and μ_e is the extinction coefficient (in mm^-1), which is equal to the sum of scattering μ_s and absorption μ_a coefficients. The distance of light propagation between two scattering and/or absorption events corresponds to the free path length l_f. The mean free path length $\bar{l_f}$, which is the average distance between two light-droplet interactions, is inversely proportional to the extinction coefficient. The OD equals the ratio between the total length and the mean free path length:

$$\bar{l_f} = \frac{1}{\mu_e} \quad and \quad OD = \frac{L}{\bar{l_f}} = L\mu_e \tag{2}$$

Thus, the optical depth defines the averaged number of scattering events that statistically occurred when crossing the spray. A regime where the ballistic light is dominating corresponds to $OD < 1$; the contribution of single scattering together with the start of multiple light scattering dominates in the range of $1 < OD < 2$; finally, multiple light scattering is dominating at $OD > 2$. The detection of photons that have been scattered both a single time and multiple times leads to a higher transmitted light intensity and, thus, a significant underestimation of OD [2]. Furthermore, if the incident light is not collimated, single scattered light, which is radiated at a certain angle, can be detected. Depending on the radiation angle and the optical path lengths this effect can induce a high error in the OD, and further calculations e.g. the projected liquid volume [10].

Previous studies showed, that CIFF is very suitable to suppress multi-scattering detection and even superior to structured illumination [14]. Therefore in this study, the effect of light scattering is further investigated by means of the two optical methods CIFF and the often used DBI. Moreover, by measuring 37 viewing angles of the spray, we tomographically reconstruct the extinction coefficients and compare them. Similar investigations have already been done with structured illumination transmission imaging at less dense water sprays [7]. The reconstruction of Spray G enables a detailed investigation of the spray patterns and differentiates liquid distribution, allowing good comparison with common measurement techniques.

Experimental setup

We perform the experiments by injecting iso-octane with the ECN Spray G injector. A fuel system regulates the fuel pressure of 200 bar. The experiments are performed in atmospheric conditions. The injector is mounted in a motorized rotational system. This allows a precise rotation of the whole injector with an angle resolution of 0.0123°. To gain time-resolved data, a Photron Nova S16 high-speed camera recording at $16\ kHz$ and $0.7\ \mu s$ exposure time is used. Both methods use the same camera lens with an aperture of $10\ cm$, a focal distance of $f = 300\ mm$, and an $F\# = 2.8$. The distance between the spray center and the lens is $81.5\ cm$ and the distance between the lens and the camera chip is $6\ cm$. The two optical setups are illustrated in Fig. 1. Above is the DBI and below is the CIFF setup depicted.

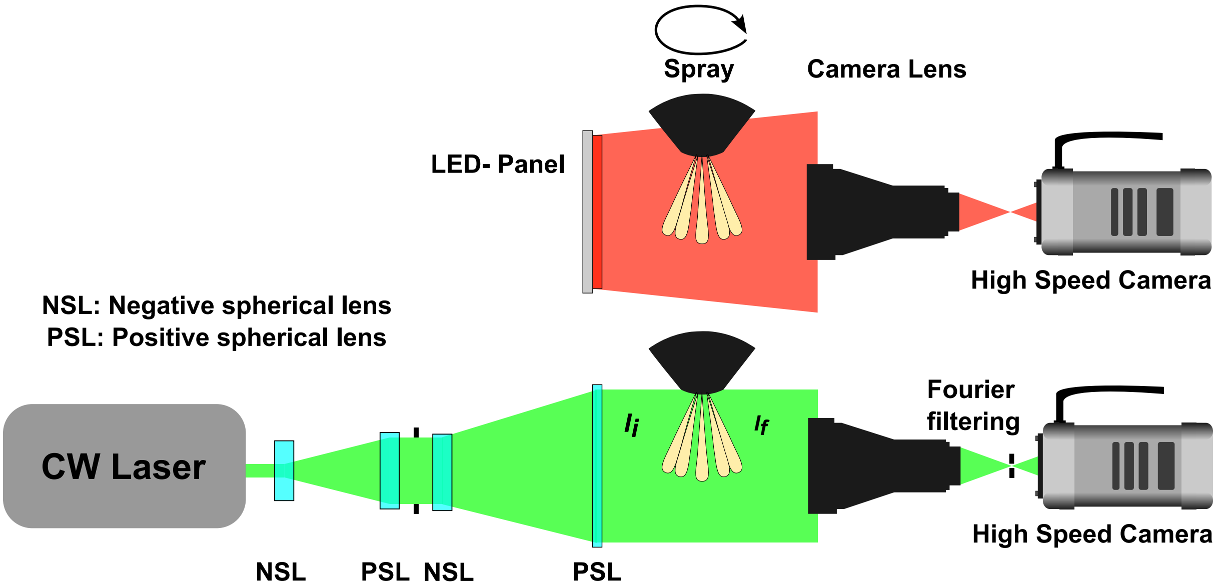

Figure 1. Experimental setups used for high-speed spray imaging. At the top DBI setup with a LED panel as a light source. At the bottom a CIFF setup using a collimated laser beam with Fourier filtering.

The DBI setup uses an LED panel with a wavelength of $635\ nm$ as a light source. The panel has been studied in previous work and has the characteristics of a Lambert emitter at radiation angles > 20° [10]. It is similar to the setup of Westlye et al. [17]. The transmitted light is collected by the camera lens and displayed on the sensor.

CIFF uses a CW laser (Spectra-Physics Millennia Prime) emitting light at 532 nm. The optics behind the laser aperture are chosen to form a homogeneous, large, and collimated beam reaching 12 cm in diameter. The diameter optimizes the detection by the camera lens. Further, a filtering strategy is applied to preserve the direction of the incident collimated beam, as photon propagations are randomized in other directions due to multiple scattering events. This is done by inserting a small iris diaphragm in the Fourier plane, the center of the focal plane of the imaging lens. [13, 16]. The Fourier filter allows only collimated light to reach the sensor, which in this setup can be used to filter for ballistic light.

Results and discussion

OD measurements of CIFF transmission are shown in Fig. 2 at timings between $62.5\ \mu s$ and $1000\ \mu s$ after the visual start of injection (vSoI). The last frame before the end of the injection is at $687.5\ \mu s$ (image 11 in Fig. 2). To gain statistically comparable OD, 60 injections have been recorded with the same frame rate at each viewing angle. The incident light intensity is calculated with five images prior to injection for every spray event. As presented in the work of Stiti et al. [14] the CIFF method shows very high OD, because of the insensitivity to multiple light scattering.

A drawback of the technique is, that at higher droplet densities light can not surpass the spray anymore. Literature shows, that a combination of structured illumination and Fourier filtering has demonstrated the highest contrast that can be reached when imaging through turbid media [2]. For this reason, the data is not calculated at an $OD > 10$, due to the density of the spray and the lack of final light intensity I_f detected. This is also illustrated in Fig. 2, where the spray center is shown white. Therefore a quantification at spray depths, where $OD > 10$, is not possible with light extinction. At the beginning of the injection, most of the spray is still in this region, and only spray edges can be detected. At ongoing injection, the spray is more separated and diluted. Nevertheless, the measured OD is still very high after the injector closing, even at $1000\ \mu s$ after vSoI, $OD > 5$ can be detected at ambient conditions. The white areas in the spray center are also shown in Fig. 3, where the DBI and CIFF methods are compared at $687.5\ \mu s$ after vSoI. Here the difference between DBI and CIFF is visible. The maximum OD measured by DBI here is only 3.3. The deviation between the methods is particularly large in dense spray regions. This is consistent with the explanation that in volumes with a high number of droplets, the chance of multiple scattering effects increases exponentially. Thus, at high densities, DBI greatly underestimates the OD because of detected multi-scattering increasing the final light intensities. At lower spray densities this error is reduced. This is also in good agreement with previous work, where we simulated the error of DBI for this injector [10].

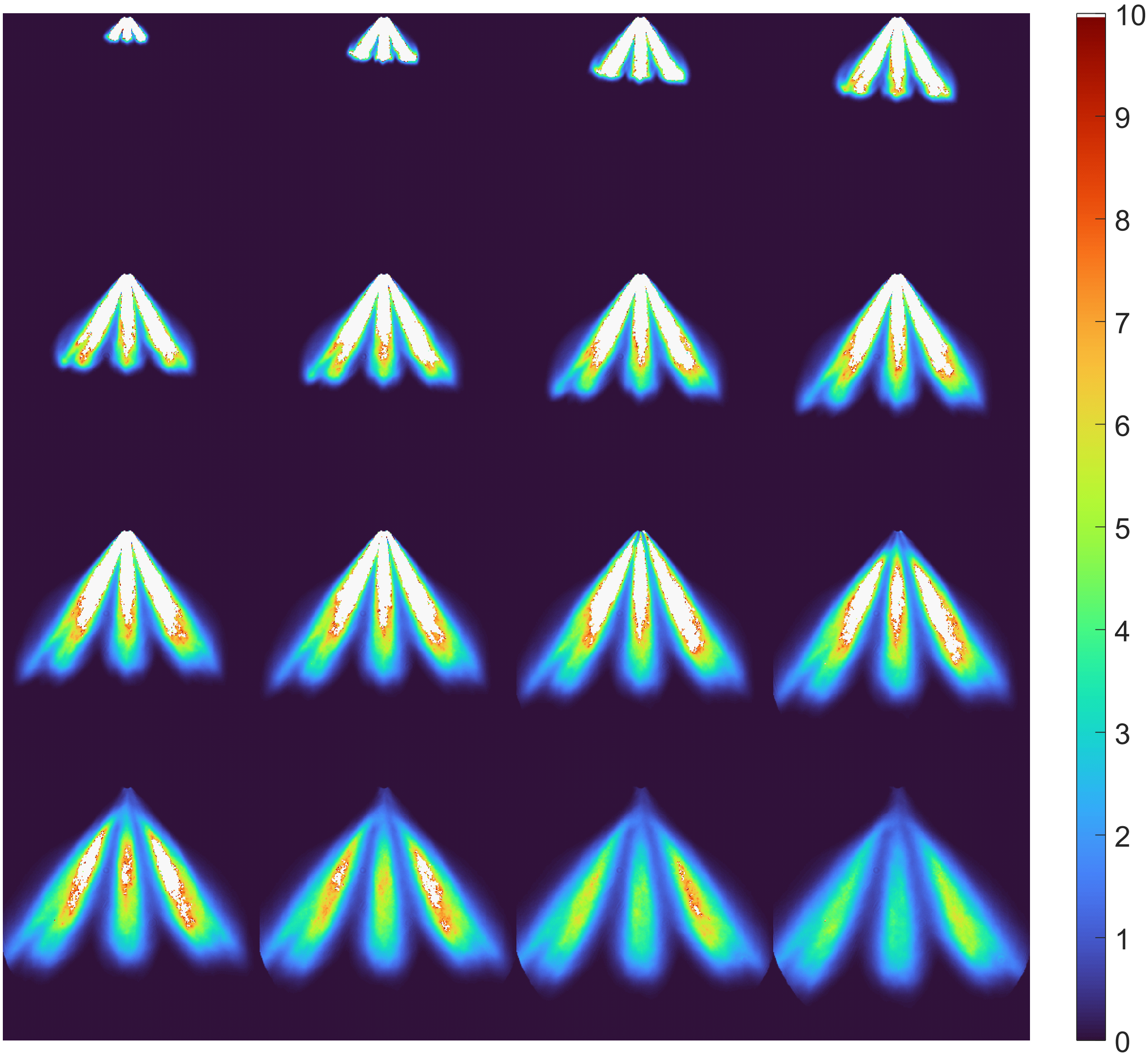

Figure 2. CIFF images of OD from $62.5\mu s - 1000\mu s$ after vSoI.

At 35 mm along the spray propagation direction, the density is low enough for a quantitative comparison. The 35 mm line is also shown in Fig. 3. The results of this line are plotted in Fig. 4. The overall macroscopic spray

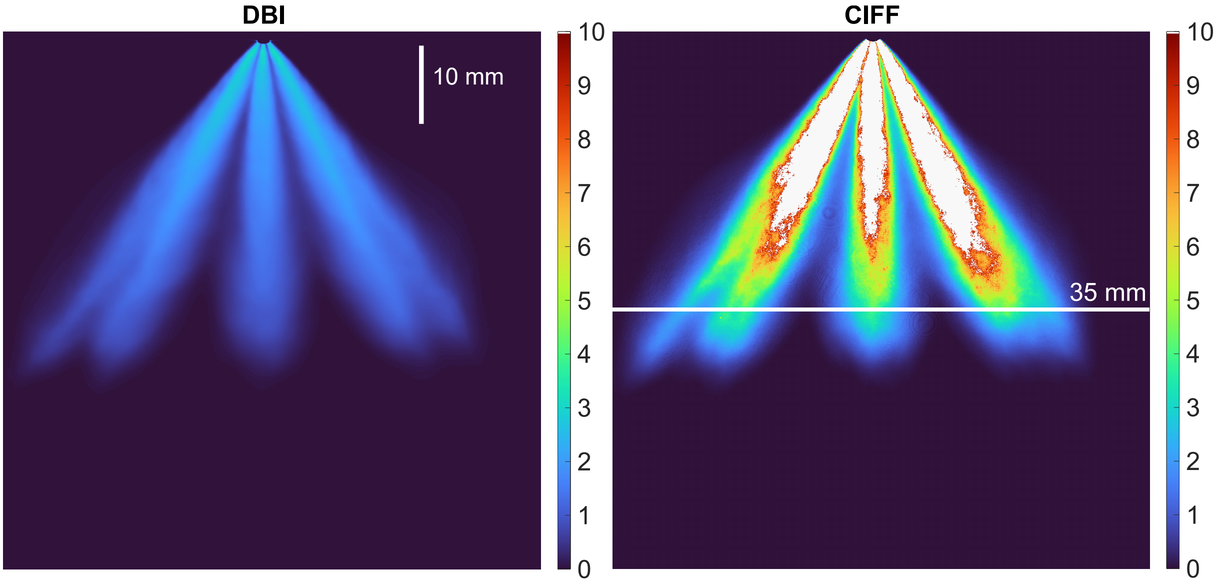

Figure 3. Comparison of OD images with a DBI setup (left) and a CIFF setup (right). A 35 mm distance line is drawn in white.

geometry is preserved, showing the same trend for both techniques. The OD measured by DBI is < 1 in most of the spray plumes. According to the regime classification from equation (2) ballistic light is dominating. The CIFF measurement shows that this is not true. Here, an OD of ≈ 4.5 is reached in the center of the plume. This means that multiple light scattering is dominating, highlighting the strong underestimation of the OD by DBI. We can see, that without consideration of single and multiple scattering DBI is not suitable for quantitative.

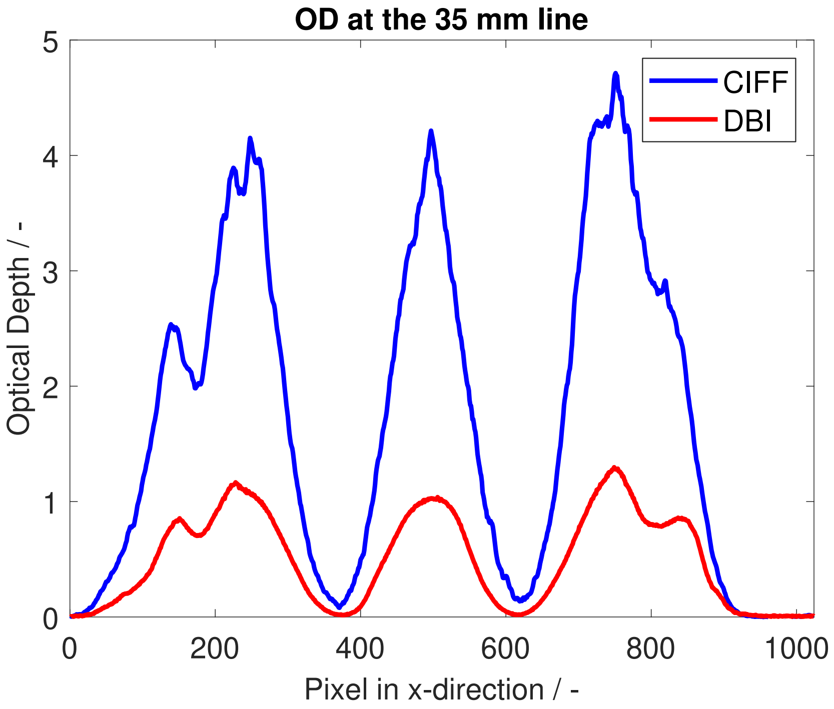

Figure 4. OD of DBI and CIFF at 35 mm distance to the nozzle tip.

To gain more detailed information on the scattering effects for the different methods, the injector is rotated 180° in 5° steps. For every viewing angle, the experiments are repeated, as shown before. With data of the spray from different angles, we can reconstruct every y-pixel plane, resulting in a completely time-resolved 3D measurement of the spray, by the method of Filtered Back Projection (FBP). We hereby receive a dataset of 1024x1024x1024 voxels for each timestep. The sinograms are interpolated, increasing the angular resolution to 1°. This reduces reconstruction artifacts. Moreover, we use a Hamming filter in the frequency domain with a scaling factor of 0.5. This is necessary to decrease reconstruction noise in the CIFF. In order to maintain the comparability we reconstruct each method with the same parameters.

Results of the tomography are shown in Fig. 5, representing the reconstructed spray planes at a $35\ mm$ distance to the nozzle tip at different time steps, allowing a detailed comparison at suitable spray densities. It must be noted, that the color bar is multiplied by a factor of 5 for CIFF. Both spray targets are quite similar taking into account the scaling factor. The factor was derived by the results shown in Fig. 4. In Fig. 5 every spray plume is well distinguishable. At $625\ \mu s$ the distribution of the extinction coefficient μ_e looks similar between the methods, but the spray distribution measured by DBI is not as concentrated as measured with CIFF. While the reconstructed spray on the left is wider, the plumes on the right are more directed and focused. Assuming uniform droplet sizes in the center of the jets, where evaporation at these conditions is smaller, CIFF shows a higher OD and therefore higher liquid mass along the plume axes. A reason for this is, that with increasing OD the scattering error increases exponentially [2]. Thus, the multiple scattering also reduces the OD sensitivity, which is shown in the wider spray density distribution of DBI inside the spray plumes. Differences further increase at $750\ \mu s$ where the max μ_e remains approximately the same for DBI, while the μ_e of CIFF is still rising. This trend is additionally developed at $875\ \mu s$, where the μ_e measured by DBI is already decreasing compared to the max μ_e in CIFF. It can be noticed, that at $1000\ \mu s$ the spray target is collapsing. This spray timing is recorded well after the closing of the nozzle. Therefore, the impulse of the liquid is lower, and the surrounding pressure pushes the plumes to the spray center. Because CIFF highlights the spray features through an increase of contrast, the effect of the collapse is better observable with it. We can already see a change in the spray pattern at $875\ \mu s.$ The described effect shows, that even macroscopic spray properties can be influenced by the detection of multiple light scattering. To estimate the impact of this, further investigations have to be done. The results show that light extinction measurements must be performed with consideration of the detection of single and multi-scattered light.

A full 3D tomography is illustrated in Fig. 6 for $687.5\ \mu s$ after vSoI. It shows the reconstruction with angular data of CIFF. The color bar of the extinction coefficient μ_e of the tomography is between 0.2 and 2 mm^{-1}. In the front right quarter, the spray was sliced. The data shows, that reconstruction with CIFF transmission measurements, allows detailed insights into the spray structure. Dense spray regions can be recognized at the center of each jet near the nozzle. This behavior is comparable to the literature [7, 5]. The dense spray regions could not be detected with DBI transmission. It must be mentioned, that quantification of this area is not applicable, because of the OD sensitivity of CIFF and very high values here, which is already discussed in Fig. 2 and Fig. 3.

Conclusion

In this work, the influence of single and multiple light scattering on quantitative measurements, based on light transmission is investigated. We compare the OD detected by the two measurement techniques DBI, using a diffuse light source, and CIFF, filtering collimated light in the Fourier plane. CIFF has been recognized as the most promising method in previous work [14]. For the experiments, we use an ECN Spray G injector with iso-octane at ambient conditions. The light transmission measurements show, that the detected OD varies strongly between both techniques. CIFF transmission measurements enable the detection of the OD while suppressing multi-scattering effects. At a 35 mm distance to the nozzle tip, the OD differs by a factor of approximately 4. The difference is particularly strong at high spray densities. Additionally, we mount the injector in a rotational system, allowing observation of the spray events at defined 5° angle steps. This enables a tomographic reconstruction of the spray, by Filtered Back Projection for both measurement techniques. We compare the reconstructed extinction coefficient of the spray for the two techniques in the 35 mm plane. Because of its high sensitivity, CIFF captures the extinction coefficient even in higher-density regions. The extinction coefficient is increased by a factor of > 5. The results of the time-resolved data are also influenced by the measurement technique. Finally, also the detected liquid distribution differs, showing higher gradients for CIFF. A complete CIFF tomographic 3D reconstruction result is shown at the end of the injection. High liquid densities can be observed in the spray jet centers, which was not possible previously.

Results of this work show, that quantitative transmission measurements are not viable without consideration of single and multiple light scattering. Outcomes are heavily influenced by these effects and can lead to a strong underestimation of the OD. The measurement technique CIFF coupled with a tomographic reconstruction method provides high suppression of these scattering behavior, enabling a reliable quantification of macroscopic sprays. This procedure allows an evaluation of spray targets and mixture formation, in areas where measurement techniques like x-ray absorption are not suitable anymore.

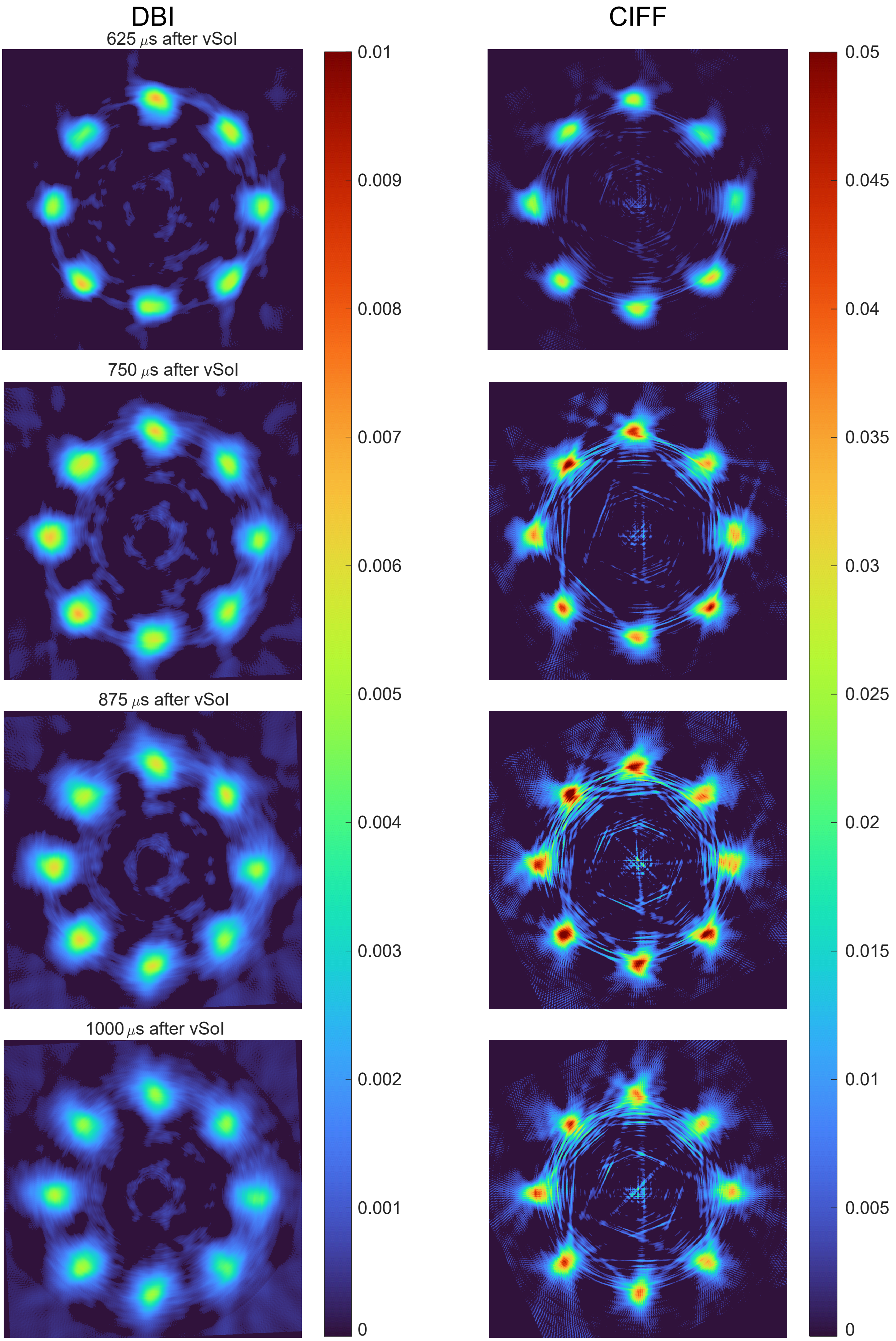

Figure 5. Extinction coefficient μ_e at 35 mm down the nozzle tip at different times for DBI (left) and CIFF (right).

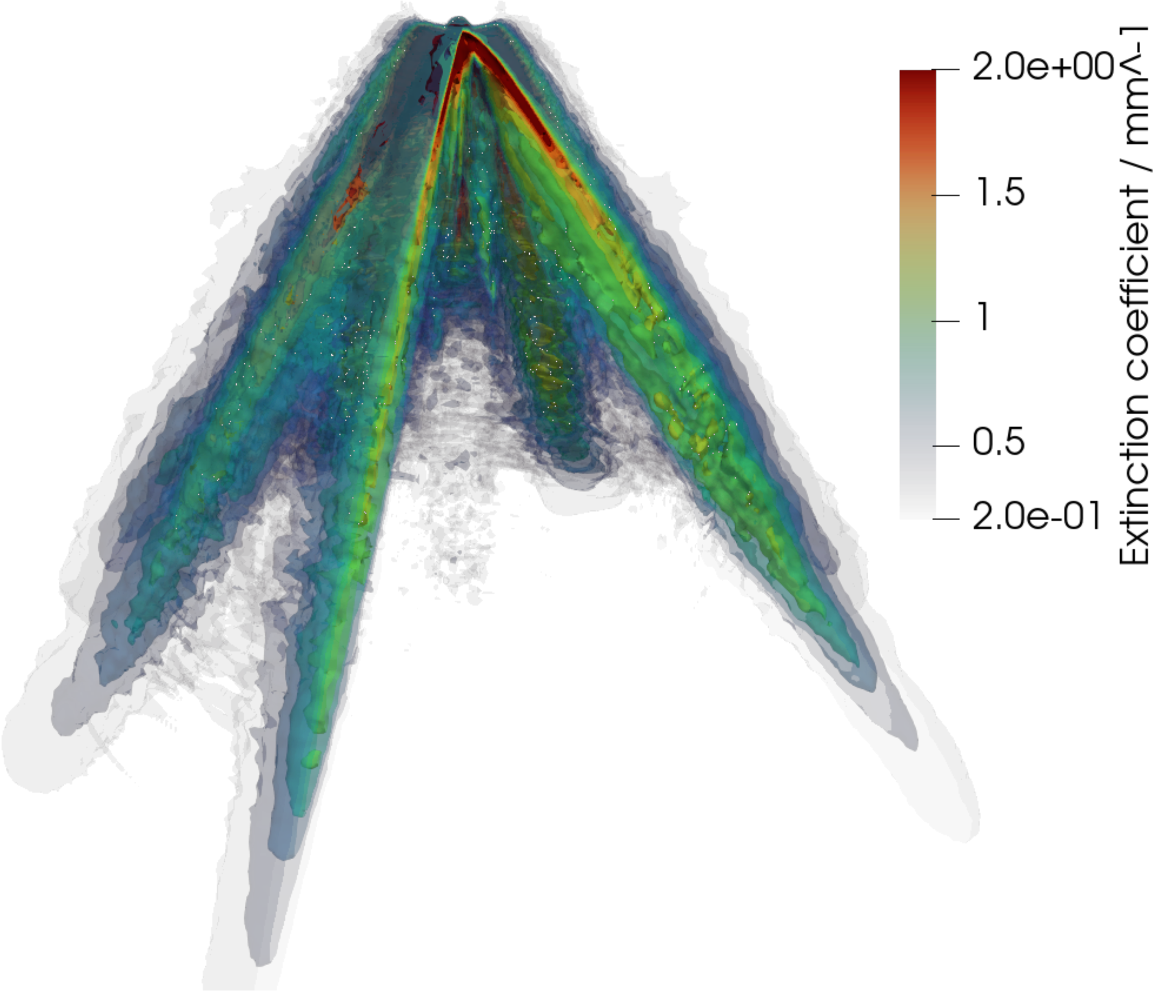

Figure 6. Tomographic reconstruction of SprayG at $687.5\ \mu s$ after vSol with CIFF.

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Nomenclature

DBI	Diffuse Back Illumination
CIFF	Collimated Illumination Fourier Filtering
GDI	Gasoline Direct Injection
SLIPI	Structured Laser Illumination Planar Imaging
LIF	Laser Induced Fluorescence
ECN	Engine Combustion Network
vSoI	visual Start of Injection
FBP	Filtered Back Projection
OD	optical depth [-]
I_i	incident light intensity [-]
I_f	final light intensity [-]
N	number density of droplets [$\frac{1}{mm^3}$]
σ_e	extinction scattering cross-section [mm^2]
L	path length through spray [mm]
μ_e	extinction coefficient [mm^{-1}]
$\bar{l}_f$	mean free path length

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