Multiple scattering suppression for correct light transmission measurements through the ECN Spray G running with ethanol

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Abstract

In this work, transmission measurements combined with high-speed imaging are performed using four different optical methods. Those methods are characterised by various types of illumination and filtering strategy: 1) a diffuse light without filtering, 2) a collimated homogeneous laser beam without filtering, 3) a collimated laser beam with structured illumination filtering, 4) a collimated laser beam and Fourier filtering filtering prior to detection. This study shows that the detection of multiple light scattering differs significantly between each method, leading to various optical depths, OD, deduced from the Beer-Lambert law. The spray events are generated by the ECN Spray G injector (from the Engine Combustion Network) running with ethanol and imaged, here, between 0.25 ms to 1.00 ms after liquid injection. The images are averaged over 60 injections in order to to obtain statistical images of the OD and to increase the range of the measured optical depth. It has been observed that Method 4) is reaching higher OD than the other methods, demonstrating an efficient suppression of multiple light scattering. It is also seen that Method 3), involving the use of structured illumination, provides efficient results but of slightly lower OD than method 4). Finally, without any filtering, Method 2) is reliable when $OD < 1$ and Method 1) is not reliable for correct transmission measurements.

Introduction

To reach the requirements of carbon emission reduction, global energy consumption must be optimized. Nowadays, the injection of liquid fuel still remains predominant in automotive internal combustion engines [7]. Direct fuel injection is currently being modified for replacing the use of conventional petrol fuels by electrofuels. Those are generated by capturing carbon dioxide or carbon monoxide, together with hydrogen obtained from sustainable electricity sources. Electrofuels (e-fuels) includes butanol and other alcohols [17, 18, 8]. Optimizing the combustion of e-fuels, requires to verify 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 [2, 16]. The characterization of the liquid phase of Gasoline Direct Injection (GDI) sprays has been recently performed using Shadowgraphy [14], Mie-scattering, [13]; as well as Structured Laser Illumination Planar Imaging (SLIPI) [20], Two-photon LIF planar imaging [1] and soft X-ray imaging [9]. Those last techniques are used to significantly suppress the detection of multiple light scattering, allowing to obtain 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.

In this work, high-speed transmission measurement is performed using different optical methods in order to quantify the optical depth of the ECN Spray G running with ethanol. By definition, the optical depth, OD, is defined through the Beer-Lambert law such as:

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

where I_i and I_f are the incident and 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 the scatting 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. Thus, OD equals the ratio between the total length and the mean free path length:

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

Thus, the optical depth defines the averaged number of scattering events that statistically occurred when crossing the spray. Thus, 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 dominate 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 [6]. In this study, this effect is investigated on the ECN Spray G by means of four optical methods with results that are compared. Those methods are based on the use of diffused illumination, collimated illumination, Structured Illumination filtering and Fourier filtering.

Experimental set-ups

The experiments were performed by injecting ethanol at 200 bar with the ECN spray G injector. The spray was formed within atmospheric conditions and was recorded at different times using a Photron Nova S16 high-speed camera running at 16 000 fps and 0.7 μs exposure time. All optical methods are using a CW laser (Spectra-Physics Millennia Prime) emitting light at at 532 nm. Photons crossing the spray were collected from an objective lens of 10 cm diameter with a focal distance of f=300 mm and a F# of 2.8. The optical setups of each method are depicted in Fig.1 and consist of forming a homogeneous and large collimated beam reaching 12 cm diameter. This diameter optimize the detection by the objective lens. In parrallel to the collimated illumination, the first method shown in Fig.1A, is based on a diffusive illumination. This was tested by adding a diffusive screen. In the two last methods, two filtering strategies have been applied:

- The first filtering strategy is called structured light illumination. In this approach, a modulation of the light intensity is implemented by using a Diffractive Object Element (DOE), acting like an optimized Ronchi grating. While ballistic photons are perfectly preserving this modulation, photons that are scattered multiple times are loosing this modulation contribution and diffuse the recorded image. The contribution of this non-modulated intensity can be suppressed by means of image post-processing. This was firstly demonstrated in 2008 using a light sheet crossing a spray (SLIPI) [3, 12, 4]. The final image based on structured illumination is generated by recording three modulated images where the phase of the sinusoidal modulation of the intensity is shifted by $2\pi/3$. This is experimentally done by vertically and accurately displacing the DOE. The final image of light intensity I_{SI} is finally obtained using the following equation:

$$I_{SI} = \frac{\sqrt{2}}{3}\sqrt{[I_{2\pi} - I_{2\pi/3}]^2 + [I_{2\pi} - I_{4\pi/3}]^2 + [I_{2\pi/3} - I_{4\pi/3}]^2} \tag{3}$$

- The second filtering strategy consists of preserving the direction of the incident collimated beam, as photon propagations are randomized in other directions due to multiple scattering events. This is done by using Fourier spatial filtering by inserting a small iris diaphragm placed at the center of the focal plane of the imaging lens. [21, 19].

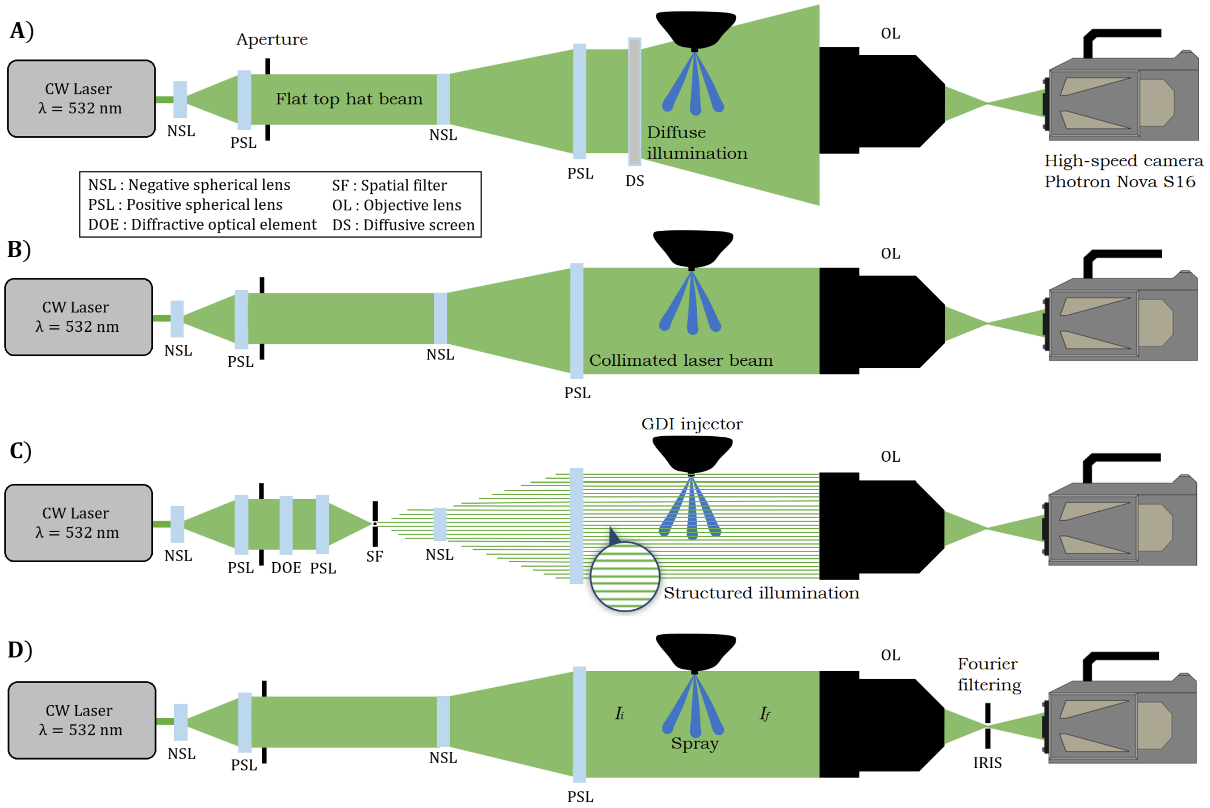

Figure 1. Description of the optical setups used for high-speed spray imaging, in order to deduce the OD of the spray region. The setups involve: A) a diffused incident light, B) a collimated laser beam, C) a collimated structured laser illuminations and D) a collimated laser beam with Fourier filtering.

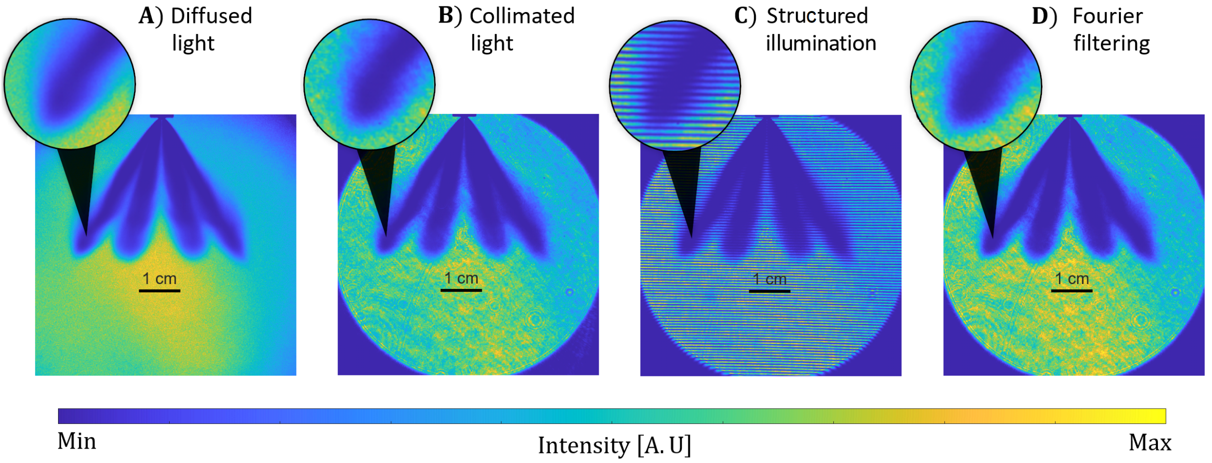

Figure 2. Example of raw images using the optical setups presented in Fig.1 with A) diffused light, B) collimated light, C) collimated light and structured illumination and D) collimated light and Fourier filtering.

To characterize and analyze the effect of multiple light scattering detection during OD measurements in sprays, four different measurement Methods have been implemented:

- A) Method 1 : Using diffuse illumination.
- B) Method 2 : Using a collimated laser beam.
- C) Method 3 : Using a collimated laser beam with structured illumination.
- D) Method 4 : Using a collimated laser beam with Fourier filtering prior to detection.

The optical set-ups for each method applied in this study are shown in Fig.1. An example of the images obtained by each method is presented in Fig.2. The structured beam used in Method 3 and shown in Fig.2C, has a spatially modulated period equal to 0.84 mm. The Fourier filter used in Method 4, has an iris diaphragm of 2.8 mm diameter prior to photon detection.

Results and Discussion

The OD measured with the optical Methods are presented in Fig.3, for four injections in a time ranging between 0 to 1 ms. During each recording, the spray was imaged with the same high-speed frame rate and exposure time of the camera. To obtain OD data that are statistically comparable, images have been averaged over 60 injections. The images of the incident light intensity I_i are the images recorded just before the injection of the spray. In addition, the variations of the incident laser intensity have been quantified and corrected using an area located on the upper side of the images; where no droplets are present. Those approaches were providing reliable quantitative data that are comparable between each other.

At 0.25 ms, spray formation is occurring and the optical depth is measured on the periphery of the liquid jet injections. It should be noted that OD is not reachable in the central part of each jet -shown in white- due to the presence of larger and non-spherical liquid bodies which are under breakup events. This is creating a variety of liquid structures that are very close from each other, involving the effect of *"dependent scattering"*. In this case, the reduction of the incident light is not related to the cross-sections of independent droplets. Thus, the Beer-Lambert law is not applicable under those conditions, which occur during spray formation. Instead, the Beer-Lambert law is applicable in regions containing the spherical micrometric droplets that are positioned sufficiently far from each others, applying *"independent scattering"*.

An averaged optical depth, $\bar{OD}$, has been calculated within a part of the spray region located at the bottom right of the spray. This area is identical for each method and corresponds to the magnification (x3 zoom) shown in Fig.3.

At 0.44 ms, the $\bar{OD}$ is high as this time remains close from the start of injection. When comparing each approach, $\bar{OD} \sim$ 2.70 is obtained with Method 1 and 2, while higher optical depths are obtained with Method 3 and 4 with $\bar{OD} \sim$ 4.00. During the transition from 0.44 ms to 0.94 ms it is seen that $\bar{OD}$ is reducing by a factor of ~1.5. When comparing the results in between each Method, it is observed that the lowest averaged optical depth is constantly obtained with Method 1, leading to significant issues of using a diffused light illumination. In contrast, the highest optical depth is obtained with Method 4, demonstrating the most efficient and reliable transmission measurements when combining a collimated laser beam with Fourier filtering.

It has been demonstrated in the past that structured illumination is highly efficient for the suppression of multiple light scattering through spray systems for both planar (SLIPI) [3, 12] and transmission imaging (SLITI) [11]. However, it is seen in Fig.3 that Method 3, based on structured illumination, does not provide an optical depth as high as Fourier filtering. This can be explain by the fact that for transmission measurements, single light scattering must also be suppressed. As the objective is located at 81.5 cm from the spray and has a 300 mm focal distance, it results to a depth of field of a few centimetres. In the depth of field, the modulation from single light scattering remains well imaged. Thus the single light scattering contribution from the depth of field is not suppressed, explaining why the transmitted intensity I_f, detected with the setup of Method 3, does not only correspond to the ballistic light.

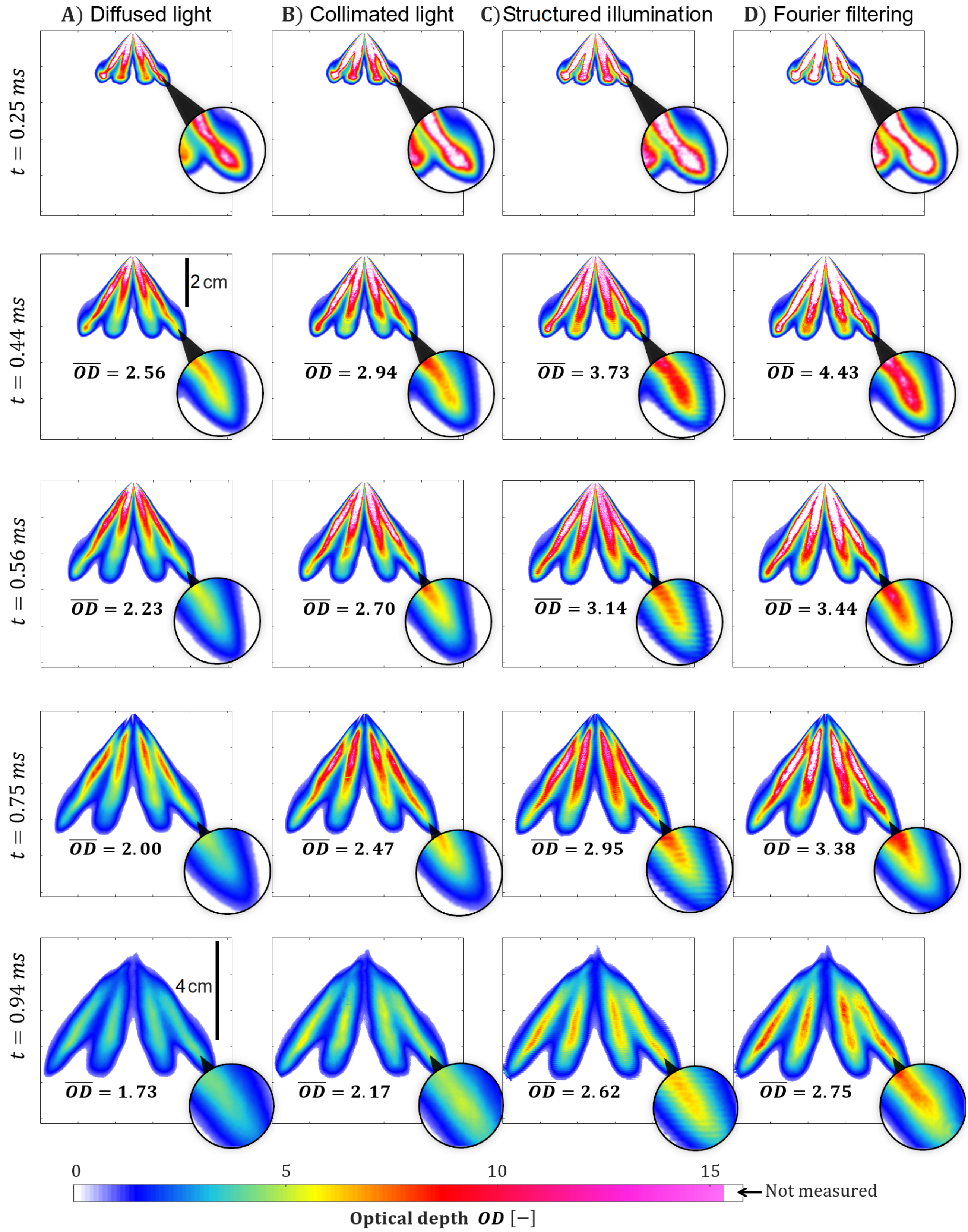

Figure 3. Optical depth measurement of the ECN spray G imaged at different time after the injection of ethanol. A spherical area is magnified by a x3 zoom of a disc where the averaged optical depth has been calculated within the spray region. Each A), B), C) and D) case corresponds to the recording of the spray respectively using the Methods described in Fig.1. The white area within the spray corresponds to situations where the signal was really low due to the presence of large liquid bodies related to primary breakups.

Note that when SLITI was applied in [11], the transmitted light was projected on a screen which was imaged. In this case only the ballistic light was preserving the modulation, leading to a more accurate measurement of the OD. It can also be noted that the combination of structured illumination and Fourier filtering (SIF) has demonstrated the highest contrast that can be reached when imaging through turbid media of $OD = 10$ [5].

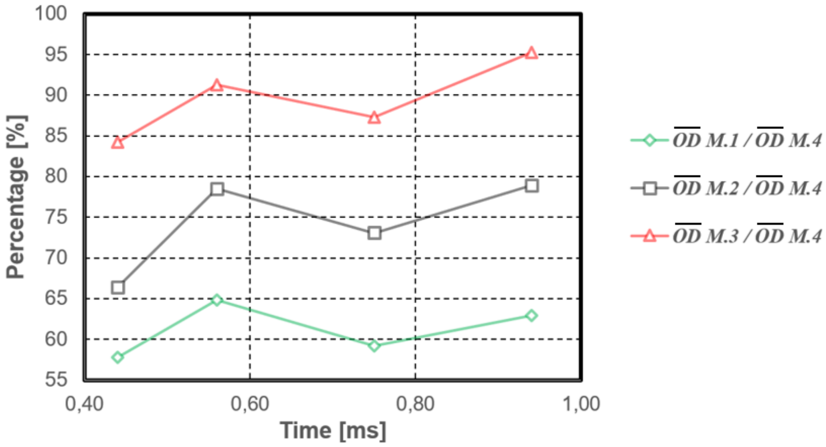

Figure 4. Comparison of the averaged optical depths shown in Fig. 3. As Method 4 provides the highest value of $\bar{OD}$, this data divides the $\bar{OD}$ from Method 1, 2 and 3. This plots, shown in percentage, quantifies the variations of the measurements between the three first optical approaches.

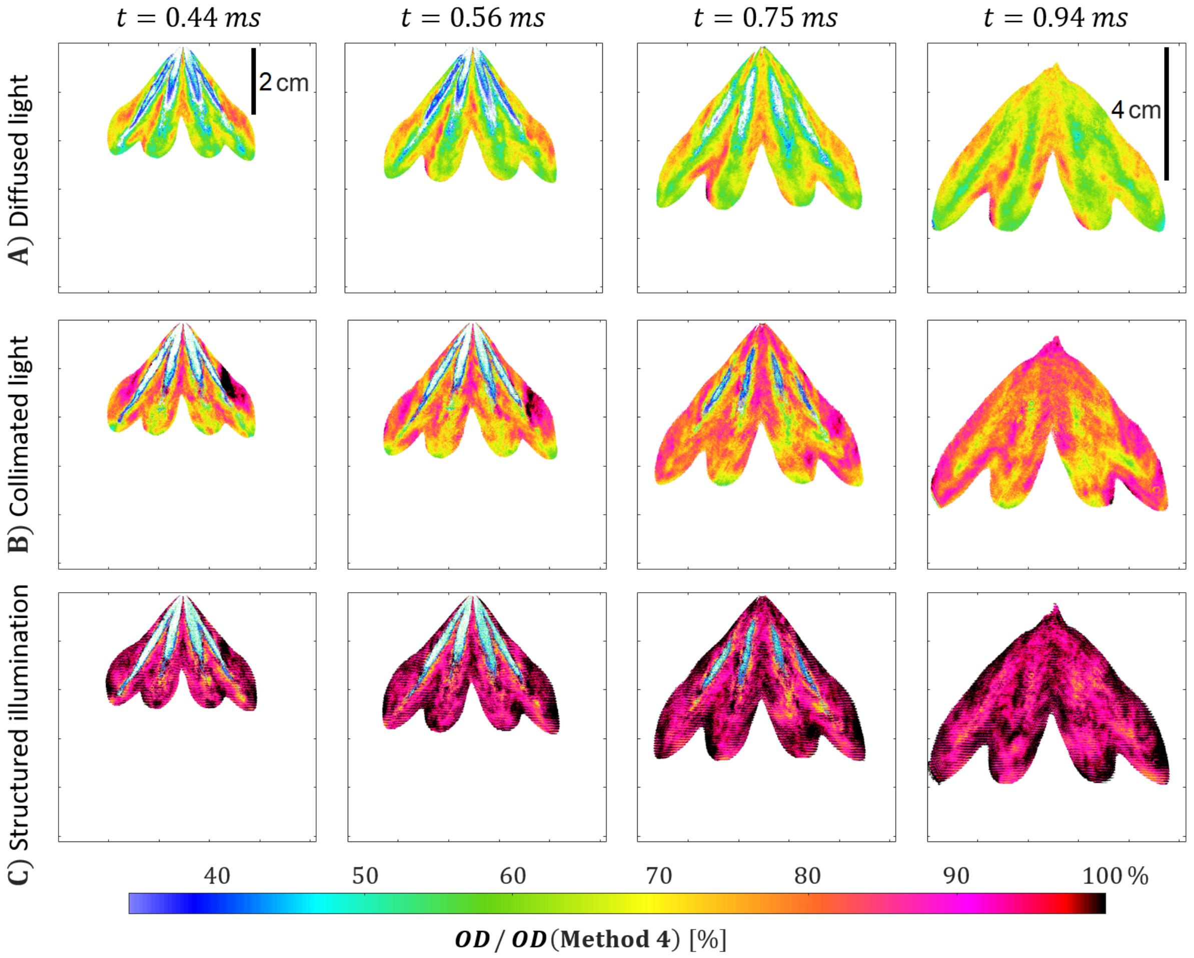

Figure 5. A) Ratio of OD measurement using A) Diffused light, B) Collimated light and C) Structured illumination by the OD measurement using Fourier filtering over time.

To quantify the $\bar{OD}$ variations, shown in Fig. 3, between the three first Methods and Method 4 (which gives the most efficient results), the percentage is calculated and shown in the plots of Fig. 4. For Method 1 results are in between 55% and 65%, for Method 2 they are in between 65% and 80%, and for Method 3 they are in between 85% and 95%. Large errors occurs in Method 1 and 2 as the contribution of multiple light scattering is not suppressed. Thus Method 1 and Method 2 loose their reliability at $\bar{OD}$ > 1. The errors are the largest when using diffuse light illumination. When the optical depth reduces, such as during the late time after the start of injection, the differences with Method 1 are reducing. This is the case at 0.94 ms, with a comparison reaching 94% with the use of structured illumination. Similar calculations of the percentage of $\bar{OD}$ are given in Fig. 5 in 2D when considering the images from Fig. 3. Once again it is observable that the use of diffuse light does not provide any correct $\bar{OD}$, the use of a collimated beam provides better results at late injection time and close to the edges of the spray. Finally structured illumination shows mainly above 90% of similarities with $\bar{OD}$ results obtained with Fourier filtering .

Conclusions

The results from this study highlight the effect of multiple light scattering on quantitative measurements of the optical depth, based on transmission detection. The error induced by the detected intensity of the scattered light is estimated by comparing the measured OD from different optical Methods. Note that some of the setups used here were similar to the ones used in other recent study characterizing the same injector [10, 15]. Thus, it can be deduced that some corrections would be needed in those works that are also related to the Engine Combustion Network, due to an underestimation of the extinction coefficient. It is found in this study that higher and more accurate OD have been obtained in 2D using Fourier filtering imaging. To further evaluate how the extinction coefficient can be measured correctly, some Monte Carlo simulations of the problem can be implemented as demonstrated in [15]. Finally, it is observed that OD measurement using a collimated light beam, without any filtering, must be corrected when $OD > 1$. As a diffused light illumination includes various incident directions through the spray, it increases the detection of single light scattering which remains problematic even at low OD.

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