Analysis of the SLIPI technique for multiple scattering suppression in planar imaging of fuel sprays

E. Berrocal*, E. Kristensson, D. Sedarsky and M. Linne§
Department of Combustion Physics, Lund Institute of Technology, Lund, Sweden
§Department of Applied Mechanics, Chalmers University, Gothenburg, Sweden

Abstract

Structured **L**aser **I**llumination **P**lanar **I**maging (SLIPI) is a new laser sheet based diagnostic able to significantly increase the contrast of spray images by removing the multiple scattering noise contribution. The technique has been recently developed and applied to the study of a conventional hollow-cone water spray, where the transmission through the near-field spray was 26%. In such condition, it has been shown that 44% of the total optical signal, corresponding to multiply scattered photons, could be removed. In order to now employ the technique to more challenging sprays, such as air-blast atomizer and Diesel sprays, where the transmission can be reduced down to ~0.25%, further investigations and refinements of the approach are required. This article focuses on the analysis, optimization and application of SLIPI for fuel sprays by means of a modern 3-dimensional computational model. The simulation is performed via a validated Monte Carlo code in association with a ray-tracing approach, to simulate the propagation of the incident laser radiation through the spray and the collection optics respectively. This computational work aims to quantify the amount of multiple light scattering detected by both the conventional Mie laser sheet imaging and the SLIPI technique. Results are compared for two hollow-cone fuel sprays of different transmission and droplet size properties. In the first spray the laser transmission, at λ = 532 nm, is 5% in the dense region and 27% in the dilute region, with a droplet size distribution ranging from 8 to 68 μm. The second spray is assumed to be more highly atomized, with a transmission of only 0.17% in the dense region and 7.5% in the dilute region, and with a droplets size distribution ranging from 4 to 34 μm. From these numerical calculations, it is observed that the resultant SLIPI signal tends to be closer from the pure single scattering signal when reducing the spatial period of the incident modulated light. We demonstrate here that the technique should be able to suppress an unwanted light contribution up to 91%, of the light intensity detected in the conventional planar imaging.

Introduction

One of the most commonly used techniques for two-dimensional analysis of a spray is the whole-field detection technique known as planar laser imaging or laser sheet imaging. Depending on the scattering and detection process involved, velocity vectors can be found with Particle Image Velocimetry [1] and Particle Tracking Velocimetry [2], liquid volume fraction determined through Planar Laser Induce Fluorescence [3-4], and droplet sizes estimated using Planar Drop Sizing [5] or droplet lasing [6]. Although these techniques use different approaches and properties of light scattering, they are all based on the single scattering approximation; they all assume that the detected photons have experienced only one scattering event prior to arrival at the detector. This assumption remains valid when the droplet number density is low (e.g. in the dilute spray) and when total photon path length within the spray is short (e.g. on spray peripheries). However, in the dense spray region and/or inside the spray, a large amount of multiple light scattering makes the single scattering assumption invalid. Multiple scattering blurs the recorded images as well as introducing uncertainty and ambiguity to the detected signal. These effects lead ultimately to errors on the measurement. While the number of papers related to light attenuation and multiple scattering in planar imaging of sprays has increased over the last decades [7-11], there have been no straightforward corrective solutions other than the recent development of Structured Laser Illumination Planar Imaging [12-13]. SLIPI is based on using an incident laser sheet which is spatially modulated along the vertical direction. The principle consists in recording three successive images, while vertically shifting the light modulation by one third of a period between exposures. If the three images are directly added, a conventional planar image of the spray is obtained. However, by adequately post-processing the three images, the similar features between images can be suppressed while the unique features which are preserved by the sinusoidal modulation are retained. This process acts, in effect, as a filter which mitigates the intensity contribution induced by multiple scattering (global blurring effect) from the single light scattering (optical signal originating from the laser sheet). In fact, the sinusoidal modulation provides a "finger print" or a signature of

*Corresponding author, edouard.berrocal@forbrf.lth.se

the incident plane of light. Photons which are multiply scattered lose this signature while the singly scattered light preserves it. Finally, post-processing consists of extracting the data containing the original "finger print". Figure 1 describes the technique with related equations used for the image post-processing. Previous results [13] have shown that the technique effectively reduces noise contributions from the multiply scattered light by removing up to 44% of the total detected intensity. The technique was applied to a hollow-cone water spray, where the minimum transmission was 26%. In order to apply the diagnostic to more challenging sprays, where the transmission is reduced to 0.25% - 5% (corresponding to the intermediate single-to-multiple scattering regime) further investigation and improvement of the technique is required. In this article, we analyze the SLIPI technique by means of a numerical model. The propagation of the laser radiation through the spray is simulated using a Monte Carlo (MC) code validated in previous work [14], while the photon transport through the collecting lens to the CCD array is performed via a ray tracing approach. The final aim of the article is to compare the results from the conventional Mie laser sheet imaging with the SLIPI results and to estimate the applicability of the technique to dense fuel sprays.

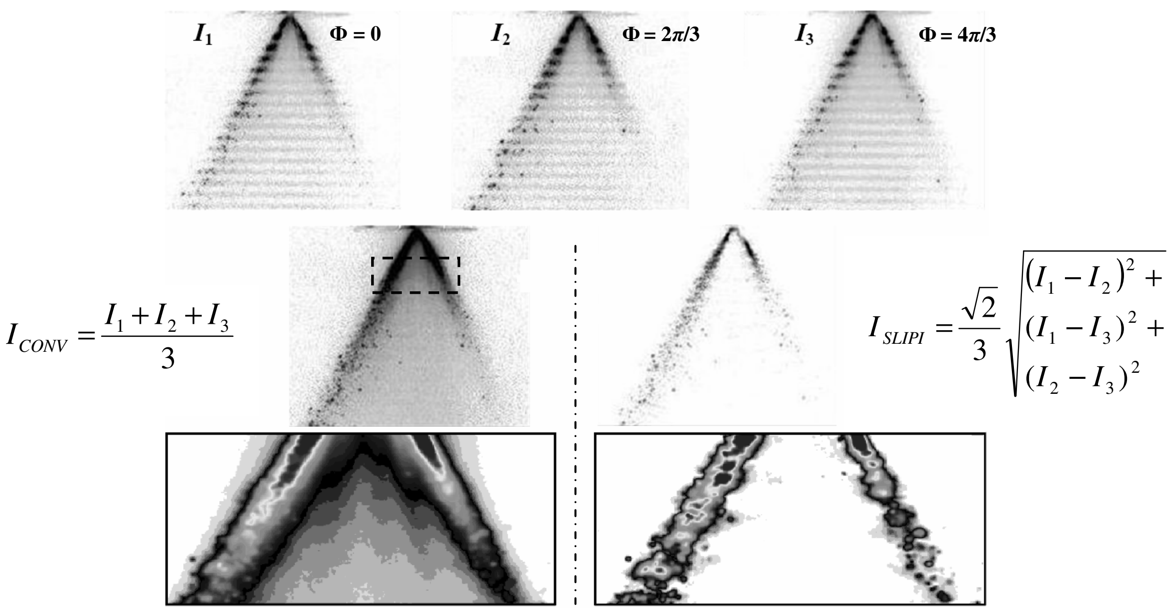

Figure 1. Illustration of the SLIPI technique: 3 successive images are taken successively using a spatially modulated laser sheet. In each of these images, the spray is illuminated differently by vertically shifting the phase (Φ) of the modulation (in I_1 $\Phi_0 = 0$, in I_2 $\Phi_0 = 2\pi/3$ and in I_3 $\Phi_0 = 4\pi/3$). When summing up the three images, a conventional planar image is obtained. However, when summing up of the absolute value of the pair-wise differences between the images, the SLIPI image is formed. In this new image, all light intensity contribution which did not represent the incident sinusoidal modulation is suppressed. This suppressed intensity corresponds mostly, for spray planar imaging, to the multiply scattered light.

Description of the Monte Carlo simulation

The radiative transfer theory is a theoretical model for the transport of photons through a scattering medium like spray systems. The method ignores the behavior of the component wave amplitudes and phases, and treats photons as point particles. The theory is based on the central Radiative Transfer Equation (RTE):

$$\frac{1}{c}\frac{\partial I(\vec{r},\vec{s},t)}{\partial t} = -\mu_e I(\vec{r},\vec{s},t) + \mu_s \int_{4\pi} f(\vec{s}\,',\vec{s}) I(\vec{r},\vec{s},t) d\Omega' \quad (1)$$

$$\text{with} \quad \mu_e I(\vec{r},\vec{s},t) = \mu_s I(\vec{r},\vec{s},t) + \mu_a I(\vec{r},\vec{s},t) \quad (2)$$

where t is time, c is the speed of the light, f is the scattering phase function and μ_e, μ_s, and μ_a are the respective extinction, scattering and absorption coefficients. The RTE describe the change of radiance along a line of sight. This radiance variation corresponds to the loss of radiance due to the extinction of the incident light, plus the amount of radiance that is scattered from all other directions $\vec{s}\,'$ into the incident direction $\vec{s}$. Although the RTE is applicable for a wide range of turbid media, analytical solutions are only available in rather simple circumstances, where assumption and simplification are introduced to reduce the equation to a more tractable form. Since there are no analytical solutions available to the transport equation for most laser diagnostics, numerical techniques have been developed and utilized. At present, the Monte Carlo (MC) technique is the most versatile approach to solve the RTE in complex 3-dimensional structures. Over the last twenty years, the technique has been extensively applied for light propagation through skin tissues [15] and more recently for spray diagnostics [10-11]. In the MC approach, each photon enters the medium containing scattering and absorbing centres (droplets) with an initial direction, and each photon is tracked as it travels through the medium. The photon trajectory is governed by probability density functions defined beforehand: the probability that a photon is scattered, the probability that it is absorbed and the probability to follow a new direction of propagation after a scattering event. The free path length l before each light-droplet interaction is derived from the Beer-Lambert law and calculated as a function of the extinction coefficient using a random number ξ uniformly distributed between 0 and 1: $l = -\ln(\xi)/\mu_e$. At each interaction with a particle, photons can be either absorbed or scattered depending on the medium albedo. In the MC technique, the scattering events are assumed independent of each other [16]. This assumption requires a distance between particles of greater than three times the radius [16]. After each scattering event, the photon's direction is selected with a random number and the Cumulative Probability Density Function (CPDF) calculated here from the appropriate Lorenz-Mie phase function $f(\theta_s)$. The polar scattering angle θ_s defined between 0 and π is found from the inverse of the CPDF of f by θ_s = CPDF$^{-1}(\xi)$ (where ξ is a random number between 0 and 1). The azimuthal scattering angle φ_s is uniformly distributed between 0 and 2π. When a new propagation direction is defined, the position of the next scattering point is re-calculated and the process repeated until the photon is either absorbed or exits the medium. The total number of photons depends on the accuracy desired and on the detector characteristics. The final propagation direction, position, number of scatters, and the total path length are calculated at the end of each photon's journey. If the detection conditions are satisfied (e.g. the photon lies within the detector field and its trajectory is within the acceptance angle), these data are recorded. The process is repeated for a large number of photons in order to reach acceptable statistics. In fact, the exact solution of the RTE would be obtained by sending an infinite number of photons.

Two hollow-cone fuel sprays are investigated here. Due to the inhomogeneous, polydisperse nature of atomized sprays, the scattering medium must be decomposed into a large number of elementary volumes assumed homogeneous. In the present model, these elementary volumes are cubic cells of constant size as seen in Fig. 2. The dimension of the cells is 300 μm side and their respective scattering properties are provided Fig. 3 (a) and (b). Both sprays are assumed to be symmetric and the full 3-dimensional structure is constructed by rotating the data around the central vertical axis. The dimensions of the full simulated volume are 22 mm X 22 mm X 15 mm.

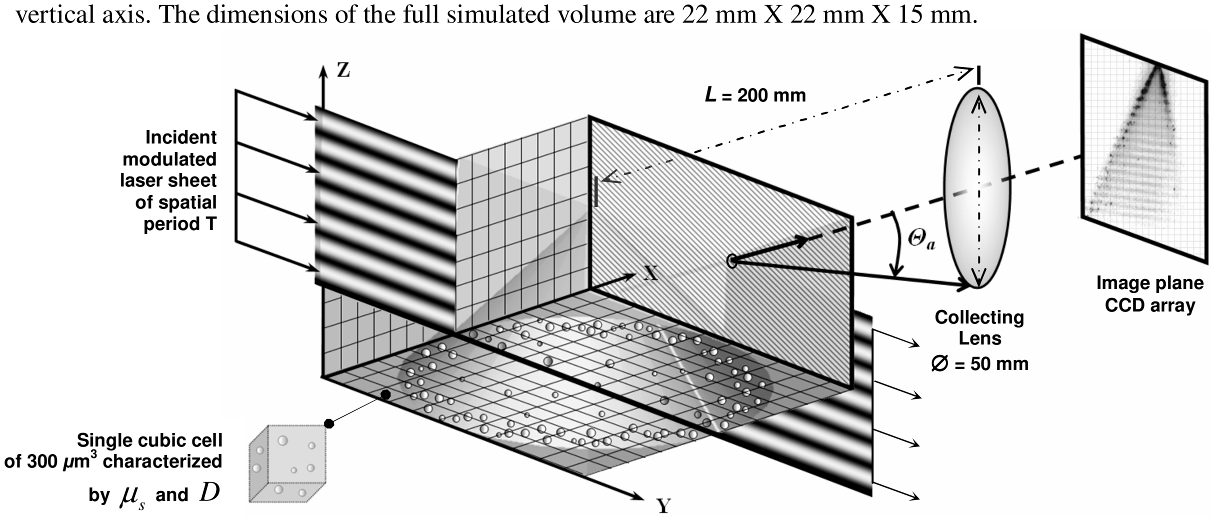

Figure 2. Illustration of the simulation: A modulated laser sheet enters a 3D scattering medium (22 mm X 22 mm X 15 mm) representing a hollow-cone fuel spray. The scattering/optical properties of the spray are defined using homogeneous cubic cells, allowing simulation of the scattering inhomogeneities in the spray. Photon transport through the spray is performed via MC simulation. The photons detected by the collecting lens are selected and an image of the laser sheet is reconstructed using a ray-tracing approach.

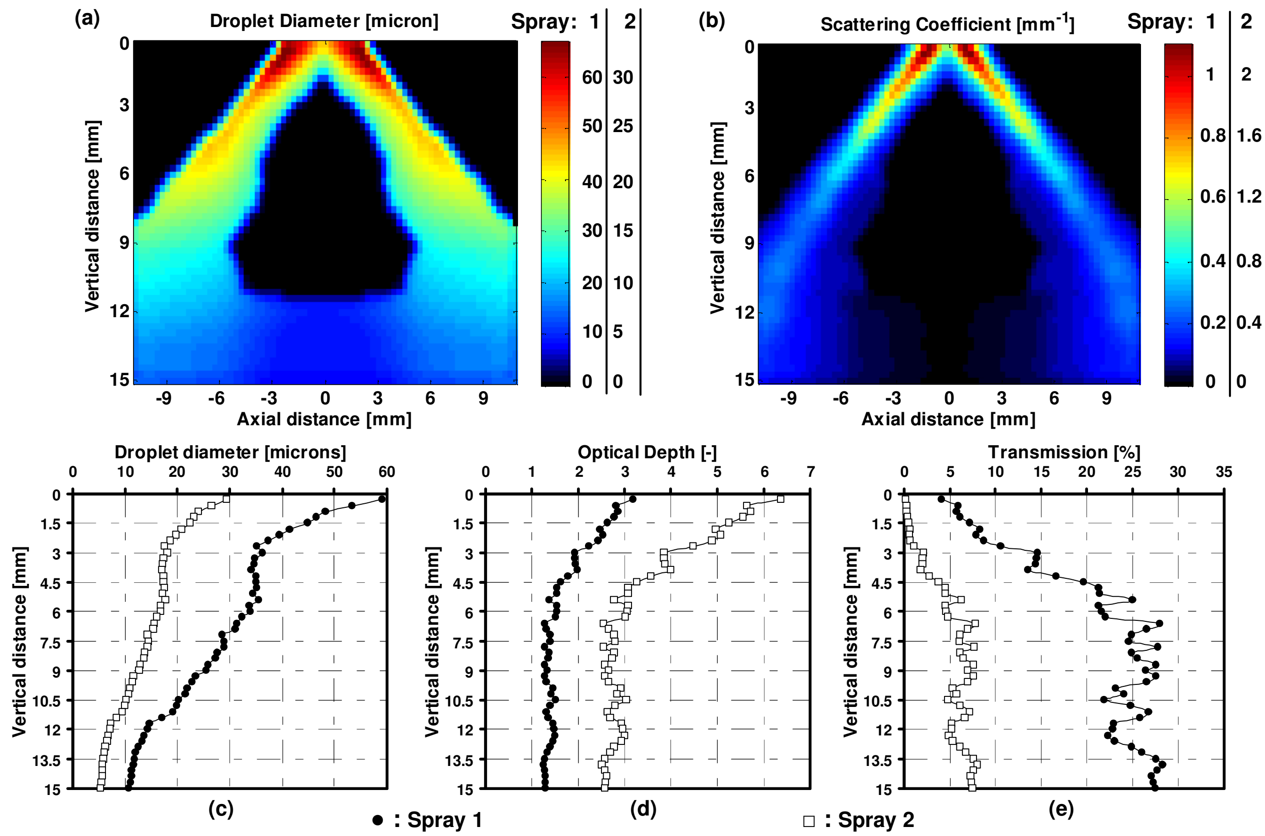

Figure 3. Illustration of the input data used for the Monte Carlo simulation. Two sprays have been considered: In Spray 1 the optical depth ranges from OD = 1.25 to OD = 3 with droplet diameters 8 μm < D < 68 μm; whereas, in Spray 2, the optical density is assumed twice as much (2.5 <OD < 6) and the droplets twice as small (4 μm < D < 34 μm). The droplet size and scattering coefficient distributions in the central plane are shown in (a) and (b) respectively; whereas the resultant transmission and optical depth are given in (d) and (e).

The synthesized laser sheet (1 mm wide and 22 mm high) crosses the spray through its centre. Two sinusoidal modulation patterns are tested and compared. In the first case, the period of the modulation is T = 2 mm, while in the second case the period of the modulation is twice as small. The wavelength of the laser radiation is 532 nm. The droplets are assumed spherical (Lorenz-Mie scattering theory) and non-absorbing ($\mu_s = \mu_e$) with a refractive index of n = 1.4+0.0i. The droplet size distribution, which governs the scattering process occurring at each scattering event, and the scattering coefficient distribution, which governs the probability for each photon-droplet interaction, are presented Fig. 3 (a) and (b) respectively. These data are given for the two sprays: In the second spray, droplets are assumed to be twice as small but with a scattering coefficient which is twice as large as in the first spray. All photons reaching the collecting lens (50 mm diameter), situated 200 mm from the laser sheet, are recorded and the laser sheet image is reconstructed using a ray tracing approach. Such a configuration corresponds to a detection acceptance angle of Θ_a = 7.25° (see Fig.2). Finally, a total of 2 billion photons are launched for generating each of the single images I_1, I_2 and I_3 required for the SLIPI technique.

Results and discussion

Figure 4 shows a detailed comparison between the conventional and the SLIPI technique for Spray 1 and Spray 2. Simulations are performed for two different intensity modulations of the incident laser sheet. In one case the vertical period of the modulation is set to T = 2 mm, while in the other case this period is reduced to T = 1 mm. The laser sheet enters the spray from the left side. In order to highlight the effectiveness of the method, the SLIPI results are also compared with the "pure" single scattering signal. Finally, quantitative data are provided by plotting the scattered light intensity profile along the horizontal axis located 3mm below the nozzle tip (as indicated with an arrow on each image).

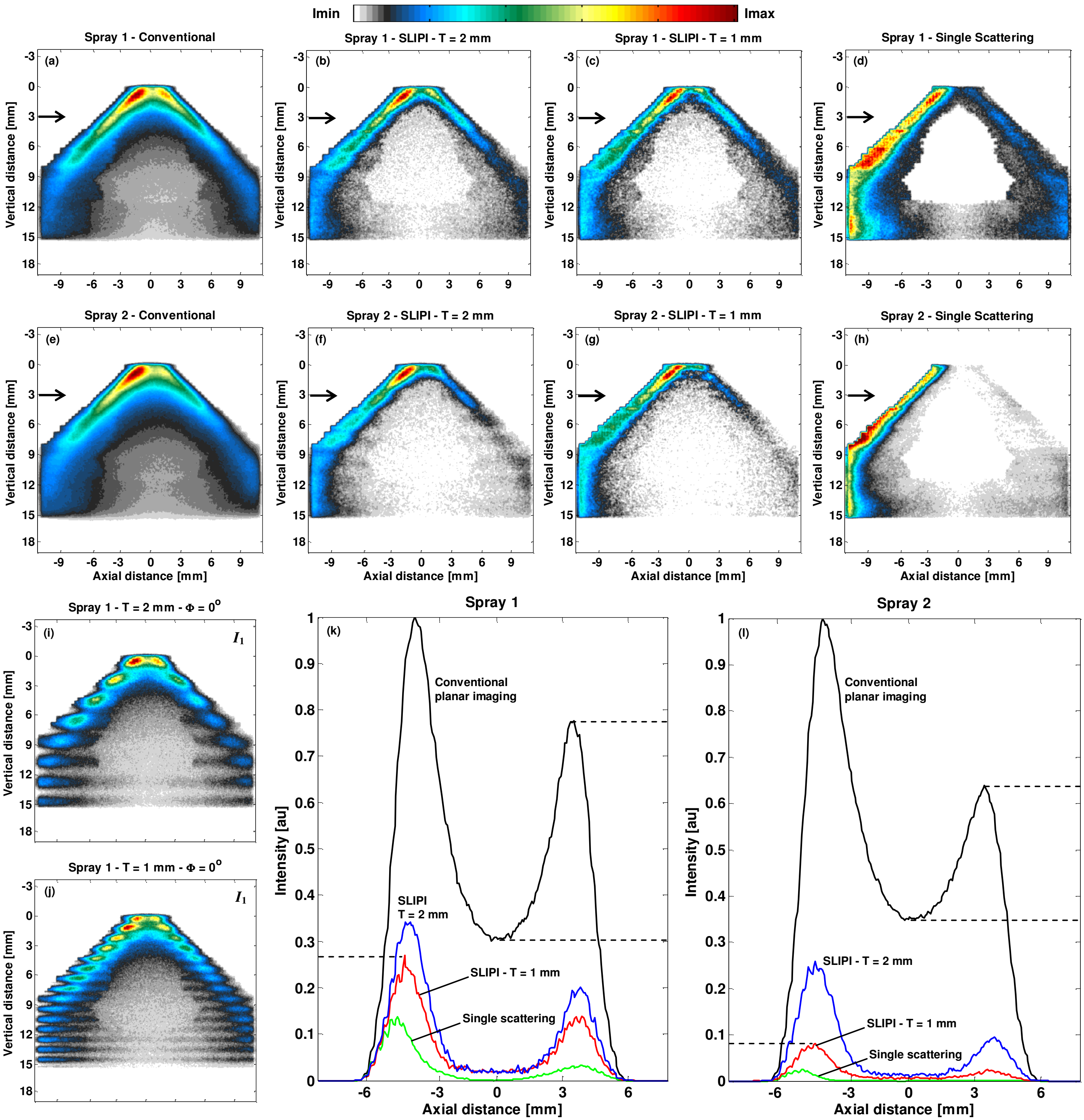

Figure 4. Comparison between conventional planar Mie imaging and SLIPI for Spray 1 and Spray 2. The single light scattering is also extracted and shown in (d) and (h). Image I_1 of the modulated laser sheet crossing Spray1 is shown for T = 2 mm in (i) and T = 1 mm in (j). Finally, the intensity profiles along the horizontal axis, at 3 mm below the spray orifice, are plotted in (k) and (l).

Two peaks of light intensity can be observed in the profiles given in (k) and (l). The first maximum originates from the light scattered when entering the hollow-cone spray, while the second one arise from the light scattered in the opposite side of the spray. The intensity reduction between the first and the second peak is due to laser extinction and is apparent in each profile. In the middle of the spray, no droplets were introduced in order to create the inner conical structure. However, in the conventional images, a large number of photons falsely appear as though originating from this region as a result of multiple scattering. This intensity equals 30% in Spray 1 and 35% in Spray 2 respectively, at 3 mm from nozzle tip. In the SLIPI images, this unwanted light is strongly suppressed, revealing the true spray structure within the central region. It is also observed from (k) and (l) that the SLIPI intensity profiles tend to be closer to the single scattering signal when reducing the spatial period of the incident modulation. Note that, as the detected amount of singly scattered photons remains constant in all images, the ratio single/multiple scattering increases while reducing the period of the incident modulation. It is calculated for Spray 2 (l), that an unwanted light contribution of 71% and 91% of the total light intensity is suppressed with T = 2 mm and T = 1 mm, respectively. When reducing the period from 2 to 1 mm, the gradients of the modulation becomes sharper and the variations of its amplitude are more visible. This feature improves the SLIPI operation, which extracts the amplitude of the modulation on a pixel-to-pixel basis. Nevertheless, decreasing the period will eventually degrade the SLIPI image, as the finite resolution of the detection system begin to limit proper imaging of the modulation. Furthermore, as the contribution of multiple scattering is strongly position dependant, a finer vertical displacement of the lines between each pair-wise image is desired. This partly explains the filtering improvement observed at T = 1 mm. These results suggest that the technique could be optimized by increasing the number of images. To verify such a hypothesis and to estimate the limit the filtering process, MC simulation will be further performed.

Conclusion

By means of a Monte Carlo model in association with a ray-tracing approach, we have numerically tested the capability of SLIPI for the suppression of multiple scattering in laser sheet images of dense fuel sprays. It is calculated that up to 91% of the unwanted light intensity could be removed, providing images containing a high level of single scattering intensity. It is also observed that the capability of the technique increases when employing a modulated laser sheet of smaller spatial period. The use of such simulations is required to further understand the specific effects of both the modulation frequency and the illumination displacement in the framework of the SLIPI process. These preliminary results confirm the possibility of SLIPI in extracting a signal close to the "pure" single scattering signal, even when probing a fuel spray of only 0.17% transmission through the dense region. Such an achievement is making SLIPI a promising and affordable imaging technique for the future study of Diesel and gas-turbine sprays.

Acknowledgements

Support for this work was provided by CECOST through Swedish Statens Energimyndigheten (grant no. 20437-1), and the Swedish Vetenskapsrådet (grant no. 621-2004-5504). The authors also acknowledge the Swedish Foundation for Strategic Research (contract A3 05:183).

References

1. R. J. Adrian, *Exp. Fluids* 39:159-69 (2005)
2. H.-G. Maas, A. Grün and D. Papantoniou, *Exp. Fluids.* 15:133-146 (1993)
3. L. A. Melton, J. F. Verdieck, *Proc. of the 20th International Symposium on Combustion*, 1283-1290 (1984)
4. J. Pastor, J. Lopez, J. Enrique and J. Benajes, *Opt. Express*, 10:309-323, (2002)
5. A. Serpenguzel, S. Kucuksenel, and R. Chang, *Opt. Express* 10:1118-1132 (2002)
6. R. Domann, and Y. Hardalupas, 20:209-218 (2003)
7. D. Talley, J. Verdieck, S. Lee, V. McDonnell, and G. Samuelsen, paper AIAA-96-0469 (1996)
8. R. Abu-Gharbieh, J. Persson, M. Forsth, A. Rosen, A. Karlstrom, T. Gustavsson, *Appl. Opt.* 39:1260-1267 (2000)
9. V. Sick and B. Stojkovic, *Appl. Opt.* 40:2435-2442 (2001)
10. E. Berrocal, I. Meglinski, and M. Jermy, *Opt. Express*, 13:9181-9195 (2005)
11. D.Stepowski, O.Werquin, C.Roze, T.Girasole, *13th Int. Symp. on Applications of Laser Techniques to Fluid Mechanics*, paper 1061, Lisbon (2006)
12. E. Kristensson, E. Berrocal, M. Richter, S.-G. Pettersson, and M. Aldén, *Opt. Lett.* 33:2752-2754 (2008)
13. E. Berrocal, E. Kristensson, M. Richter, M. Linne, and M. Aldén, *Opt. Express* 16:17870-17881 (2008)
14. E. Berrocal, D. Sedarsky, M. Paciaroni, I. Meglinski, and M. Linne, *Opt. Express* 15:10649-10665 (2007)
15. Wang, L. Jacques S.L. and Zheng L., 47:131-146 (1995)
16. H. van de Hulst, *Light scattering by small particles*, Dover, N.Y., (1981)