Quantitative three-dimensional imaging using computed tomography and structured illumination

E. Kristensson*, E. Berrocal, and M. Aldén
Division of Combustion Physics, Lund University, Sweden

Abstract

An imaging technique capable of measuring the extinction coefficient in three dimensions is presented and demonstrated on two different atomizing spray systems with promising results. The approach is able to suppress unwanted effects due to both multiple scattering and light extinction, which, for spray imaging, seriously hampers the performance of conventional imaging techniques. The main concept consists in illuminating the sample of interest with a light source that is spatially modulated and to measure the transmission in two dimensions at several viewing angles. This, in turn, allows the local extinction coefficient to be calculated in three dimensions by means of standard computed tomography algorithms, in this case filtered-back projection. These algorithms are based on the Beer-Lambert law and it is therefore essential to detect only the unperturbed (ballistic) light. All extraneous light must be suppressed, hence the use of structured illumination. To improve the filtering capabilities even further, a novel "crossed" structured illumination approach is tested and implemented. With this approach the sample is illuminated with a light source that is spatially modulated both in the vertical and horizontal direction. In the paper, the accuracy and limitation of this new method is first evaluated by probing several homogeneous milk solutions at various levels of turbidity, where the opacity is altered through dilution. The presented approach shows good agreement with theory up to an estimated optical depth of ∼5, whereas conventional transmission imaging shows discrepancies already at $OD > 1$. Interestingly, this value represents the limit of the single scattering regime ($OD < 1$). In the single scattering regime, most of the existing laser-based diagnostics are unaffected by errors introduced by multiple light scattering. The results presented in this paper demonstrate the potential of exceeding this limit for transmission imaging by the implementation of structured illumination. To test the method two different optically dense aerated spray systems are probed; one transient GDI nozzle injected with iso-octane and one quasi-steady state multi-hole nozzle injected with water. In order to temporally freeze the transient GDI spray pulsed lasers (Nd:YAG) are implemented. The resulting 3D renditions show almost no sign of image artefacts that may occur due to errors in the reconstruction process or if the number of viewing angles are too few. In addition, any skewness in the spatial distribution of the droplets, ordinarily caused by extinction, is avoided with the presented method. The performance of the filtered-back projection algorithm is evaluated by comparing the experimentally measured optical depth with the opacity calculated from the reconstructed 3D result. Due to the limited dynamic range of the camera (14-bit), the technique is limited to regions within the sprays where the optical depth is reduced below ∼6. However, the method is compatible with other filtering approaches, such as temporal-, spatial- and polarization filtering (as is utilized for Ballistic imaging), which potentially could increase the range of applicability even further. Perhaps one of the main benefits with the presented approach concerns its relatively low experimental cost, the technique can for instance be used to study non-reacting, optically dense sprays running in steady-state operation using a simple cw laser combined with an inexpensive non-gated camera.

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*Corresponding author: elias.kristensson@forbrf.lth.se