Numerical investigation of discriminated forward scattering: optimizing imaging optics for dense sprays

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Abstract

This work presents results from a numerical model for scattered light imaging systems applied to representative spray configurations. A number of particle size distributions are simulated using two different optical arrangements which discriminate imaging light using a combination of time-gating, polarization, and spatial filtering. Results from the simulations show the advantages of each imaging instrument and highlight the importance of understanding the spatial and temporal distortion imparted to the source light, which has the potential to significantly change the nature of the collected light signal. The results presented in this work show marked differences in performance for the chosen optical arrangements, depending on the physical parameters of the spray under investigation.

Introduction

Optical diagnostics are important tools for understanding atomizing sprays, where the analysis of sensitive flow fields is often not possible using intrusive measurement methods. Increasingly, there is a need for measurements in adverse environments, e.g. in the near nozzle region of fuel injection sprays, where interference from light scattering presents significant challenges to conventional optical methods.

When light transits a highly scattering medium, most of the photons which make up that light participate in multiple scattering interactions. Each of these interactions has the potential to change the properties of the transiting photon in a manner which disturbs the fidelity of its optical information. Experimental work in turbid media has shown that transillumination images can be significantly improved by limiting light collection to a subset of photons which are minimally distorted by scattering. The literature includes numerous demonstrations of image contrast improvement by means of discriminating a small portion of the total transmitted intensity from the bulk of the light collected in a forward-scatter geometry, most often realized by time-gating or spatially limiting the detected light.

Until recently, the complex nature of the detected signal has limited analysis of the effects of this filtering process to qualitative comparisons of image results. The advent of a validated numerical model for scattered light imaging systems provides a tool for detailed quantitative analysis of scattering, light collection, and the information obtained by an imaging instrument. The model simulates the relevant parameters of both the optics and the turbid measurement volume which constitute the imaging system by leveraging a Monte Carlo solution for light propagation in a random distribution of scatterers coupled directly to a ray-tracing implementation which tracks light information through the optical components to the detection plane. This enables analysis and optimization of the imaging system, and a direct means of calculating and understanding the image contrast enhancement produced by the instrument. This work presents an application of the validated model where representative spray configurations with different particle sizes are examined using two different optical arrangements. Results from the simulations highlight the importance of understanding the spatial and temporal distortion imparted to the source light, which has the potential to significantly change the nature of the collected light signal.

Simulation details

For each simulation the scattering volume is represented by a random distribution of droplets with a modified Rosin-Rammler distribution of particle sizes. The mean particle size and number density of the scatterers are varied to represent individual sprays with a range of mean drop sizes and optical depths issuing into ambient atmospheric conditions. Source light in the simulation originates as a short (100 fs) well-collimated laser pulse incident on the spray and collected in a forward-scatter geometry by the imaging optics. A nominal wavelength of 800 nm is assumed for the source, and the effects of absorption are assumed to be negligible. The spray structure or fluid dynamic features to be imaged by the optical system are represented in the simulations by a resolution test chart,

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which modulates the source light transmitted by the system with spatial information. This allows the effectiveness of the system for viewing specific spray features in the plane of interest to be quantified by the fringe visibility, or contrast, given by:

$$\text{Contrast} = \frac{I_{max} - I_{min}}{I_{max} + I_{min}} \tag{1}$$

where Imax is the maximum and Imin is the minimum intensity of the transmitted bar chart test pattern. Simulations for two optical arrangements are examined in this work. Both imaging systems eliminate a sizeable portion of the forward-scattered source light by time-gating and spatially filtering the collected signal. Each system includes an optical Kerr-effect (OKE) time-gate implemented using crossed Glan-polarizers which bracket a Kerr cell, consisting of a cuvette filled with liquid carbon-disulfide. Light which crosses the Kerr cell is subjected to a time-dependent birefringence which rotates its polarization, allowing transmission of the optical signal through the second polarizer during the a short (2 ps) time window. The first optical arrangement is shown in Fig. 1(a). This system is termed a "source projection" scheme, in reference to the action of the first lens, which is placed one focal distance from the plane of interest within the spray. This placement determines the efficiency of the light collection from the object plane. This results in a spatial filtering effect in which the collection of uncollimated light which has scattered prior to crossing the object plane is reduced, while the collection of well-collimated light remains unaffected. The source projection arrangement increases the amount of collimated light collected by the first lens from the object plane, which has the potential to increase image contrast when significant amounts of collimated light are present in the transmitted signal.

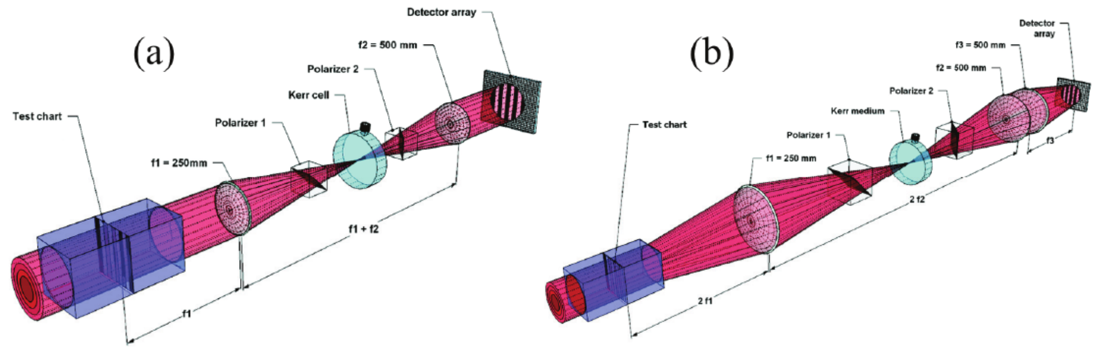

Figure 1. Simulated optical systems: (a) "source projection" light collection optics; first lens placed at 1 f, shadow image projected to detector. (b) "source imaging" light collection optics; first lens placed at 2 f, object plane spatial intensity imaged to detector at unit magnification.

The second optical arrangement is shown in Fig. 1(b). This system is termed a "source imaging" scheme, due to the arrangement of the collection optics which correspond to the conditions for imaging the object plane to the detection plane with unit magnification. Here, the first lens is positioned two focal distances from the object plane within the spray. This collection scheme reduces the amount of light contributed by each point in the object plane, since the irradiance filling the aperture of the lens decreases according to the inverse square of the distance from the object. However, this arrangement forms a spatial intensity at the detector which exhibits a conjugate optical relationship to the object plane, preserving a higher frequency spatial information, which can contribute to increased image contrast.

Results and Discussion

By applying the validated model for scattered light imaging systems to a specific scattering medium, the advantages presented by different arrangements of imaging optics can be quantitatively evaluated. This work presents simulation results for two time-gated imaging systems with fundamentally different light collection schemes. Results presented in this work show marked differences in performance for the chosen optical arrangements, depending on the physical parameters of the spray under investigation. Results from the simulation highlight the importance of understanding the spatial and temporal distortion imparted to the source light, which has significant effect on the nature of the collected light signal, which in turn determines which optical arrangement can be most effective for imaging in the spray.