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Abstract
We describe further development of ballistic imaging adapted for the liquid core of an atomizing spray. To fully understand spray breakup dynamics, one must measure the velocity and acceleration vectors that describe the forces active in primary breakup. This information is inaccessible to most optical diagnostics, as the signal is occluded by strong scattering in the medium. Ballistic imaging mitigates this scattering noise, resolving clean shadowgram-type images of structures within the dense spray region. We demonstrate that velocity data can be extracted from ballistic images of a spray relevant to fuel-injection applications, by implementing a simple, targeted correlation method for determining velocity from pairs of spray images. This work presents the first ballistic images of a liquid-fuel injector for scramjet combustion, and the first velocity information from ballistic images relevant to breakup in the near-field of a spray.

Keywords
acceleration vectors, ballistic imaging, breakup dynamics, dense sprays, fuel injectors, liquid cores, optical diagnostics, scattering noise, scramjet combustion, shadowgram

Disciplines
Applied Mechanics | Mechanical Engineering | Physics

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Fast-framing ballistic imaging of velocity in an aerated spray

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We describe further development of ballistic imaging adapted for the liquid core of an atomizing spray. To fully understand spray breakup dynamics, one must measure the velocity and acceleration vectors that describe the forces active in primary breakup. This information is inaccessible to most optical diagnostics, as the signal is occluded by strong scattering in the medium. Ballistic imaging mitigates this scattering noise, resolving clean shadowgram-type images of structures within the dense spray region. We demonstrate that velocity data can be extracted from ballistic images of a spray relevant to fuel-injection applications, by implementing a simple, targeted correlation method for determining velocity from pairs of spray images. This work presents the first ballistic images of a liquid-fuel injector for scramjet combustion, and the first velocity information from ballistic images relevant to breakup in the near-field of a spray. © 2009 Optical Society of America

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The supersonic combustion ramjet (scramjet) is an important example of an application where the advantages of liquid fuels are extremely beneficial and precise control of the combustion conditions is essential for safe operation. Scramjet engines are designed to provide low weight, high thrust, and performance that far exceeds the capabilities of turbine engines. They contain no moving parts and operate by stabilizing a supersonic reacting flow within a carefully designed combustor using the dynamics of the flow itself.

The high-energy density of liquid fuels make them a natural choice for aeronautics, where ambient air can be utilized as an oxidizer. The principal difficulty in utilizing a liquid fuel lies in controlling the fuel/air mixture fraction in a reacting flow. To maximize combustion efficiency, it is necessary to rapidly disperse the fuel into the airstream using a spray. As a consequence, the fluid dynamics of liquid breakup are directly coupled to mixture preparation, such that a detailed understanding of spray fluid dynamics is essential for the design of efficient combustion. One of the chief difficulties in scramjet operation is maintaining stable delivery of well-mixed reactants to the supersonic combustion reaction. It is desirable to construct the combustor such that the reaction is controlled by the rate of mixing, rather than the kinetic rates of reaction in the flow [1]. This motivates the search for additional means of controlling the liquid breakup and hence mixing rates in a supersonic reacting flow.

One approach to this problem is to supplement the fuel with a gas-phase component prior to injection. This enhances spray atomization in a manner analogous to cavitation [2,3], accelerating breakup and improving fuel delivery without substantially altering the flow within the combustor. For this approach to be effective, the spray design and run conditions must be selected to deliver appropriate liquid breakup. With ballistic imaging, it is possible to acquire breakup information from dense regions of the spray that are inaccessible to conventional imaging techniques, thereby enabling effective injector design and intelligent selection of run conditions.

Images for this study were generated by a time-gated ballistic imaging system specifically designed for transient fuel sprays, applied to an aerated liquid jet issuing into ambient air. This spray was generated by the Barbotage Injection Rig installed at Wright-Patterson AFB. The system is supplied by a nitrogen-pressurized water reservoir and bottled nitrogen. The separate liquid and gas flows are controlled by a set of choke valves and continuously measured by a set of turbine mass flowmeters and sonic nozzles, respectively. The separate flows are directed to a nozzle that mixes these streams at a perpendicular flowpoint. This arrangement rapidly merges the liquid and gas flows at elevated pressures (~ 1.14 MPa). After mixing, the amalgamated flow continues through a convergent connecting volume to a straight nozzle with a large length-to-diameter ratio (~ 10).

The laser source used in this measurement was an ultrafast system capable of generating two 100 fs laser pulses with a user-selected time separation. The source consists of a single mode-locked Ti:sapphire oscillator that seeds two regenerative amplifiers, each pumped by an independent Q-switched Nd:YLF laser. The output of both regenerative amplifiers is combined in a single beam, with adjustable inter-pulse spacing controlled by the pump laser timing. Dual pulses with 1 mJ of energy, a pulse width of

100 fs, and a time separation of 10 μs were used to obtain time-resolved image pairs of the aerated spray.

A detailed description of the ballistic imaging instrument applied here can be found elsewhere [4]. In brief, when light passes through a highly turbid medium, the photons that make up that light experience varying numbers of scattering events. These scattering interactions change the properties of the transmitted light, resulting in gradual depolarization, loss of coherence, and changes in propagation direction. Ballistic imaging preferentially selects photons that are minimally affected by these changes induced by the scattering process. Light scattered from the measurement volume is collected to form a line-of-sight shadow image, excluding photons that contribute to image noise and retaining the light that most accurately represents the internal structure of the region of interest.

In the current work, we direct forward-scattered light from the spray through an optical Kerr-effect shutter composed of crossed polarizers and a carbon disulfide (CS_2) Kerr medium (see Fig. 1). The shutter is activated by an ultrafast laser pulse, resulting in a gate time of ~2 ps. This arrangement limits detection to the first photons arriving at the detector (within the gate time) that possess vertical linear polarization. As a result, only photons that are minimally depolarized and redirected by scattering are collected to form an image. By employing a fast-framing complementary metal oxide semiconductor camera and the ultrafast laser source described above, consecutive ballistic images with a temporal separation of 10 μs were acquired. This fast detection scheme allows the determination of velocity information from pairs of ballistic images, based on the apparent motion, or "optical flow," of the spatial intensity between corresponding images [5]. Note that the nature of the signal field limits velocity estimation to the components that lie within the image plane, and significant systematic errors due to out-of-plane motion are mitigated by the finite depth of focus of the image collection optics. A variety of methods have been developed to calculate the motion of the spatial intensity in successive images [6,7]. The results presented here are based on region matching, using normalized cross-correlation of subregions from corresponding image pairs.

Prior to analysis, the images are divided by an adjusted image background. The adjusted background is formed by a morphological opening followed by a Gaussian smoothing of the measured background. This adjustment eliminates small scale structures caused by laser speckle in the measured background.

Velocities are determined from a set of square image regions that are selected from the t_1 image and cross correlated with a set of square regions from the t_2 image. Peaks in the cross correlations indicate displacements for the selected regions, yielding x and y velocity components.

The spray images analyzed in this work are challenging in the sense that they present large variations in structure throughout the field of view (FOV). Small droplets appear on the spray periphery, while the interior of the spray includes large liquid structures and voids with varying amounts of contrast (see Fig. 2). To acquire velocity information throughout the spray, three approaches were applied to select the image regions used to calculate velocity: particle-tracking correlation analysis was applied to obtain velocity for small droplets resolved in the images, conventional grid correlation analysis was applied across the entire FOV, and image segmentation with subsequent grid correlation analysis was applied over the fluid features larger than the small droplet-size threshold. Velocities resulting from each of these targeting approaches are shown in Fig. 3; here the vector lengths indicate the displacement from the t_1 image (shown in Fig. 2) to the t_2 image. The velocity indicated by the measured mass flow at the nozzle exit is 35 m/s, which compares reasonably well with the mean (20 m/s) and range (0–60 m/s) of the calculated velocities. The mixed nature of the velocity vectors reflects the turbulence of the flow and the fact that this is a line-of-sight technique, not a planar technique. Vectors are validated by an autocorrelation check and by correlation strength. Tests of the three approaches using a known velocity field indicate errors on the order of 1% (particle tracking, PT), 5% (grid), and 3% (hybrid).

For the PT approach, a threshold is applied to the background-corrected t_1 image. Connectivity-based image segmentation [8] is then applied to automatically identify liquid spray structures. Distinct regions smaller than a stable droplet-size threshold [9] are identified as individual droplets. A correlation

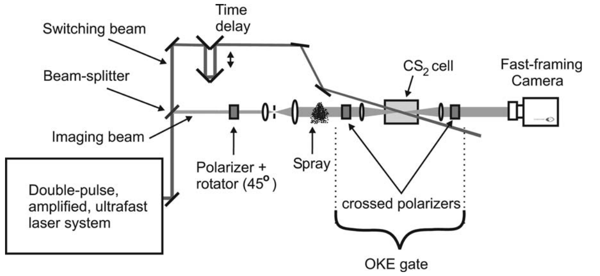

Fig. 1. Schematic of the ballistic imaging instrument.

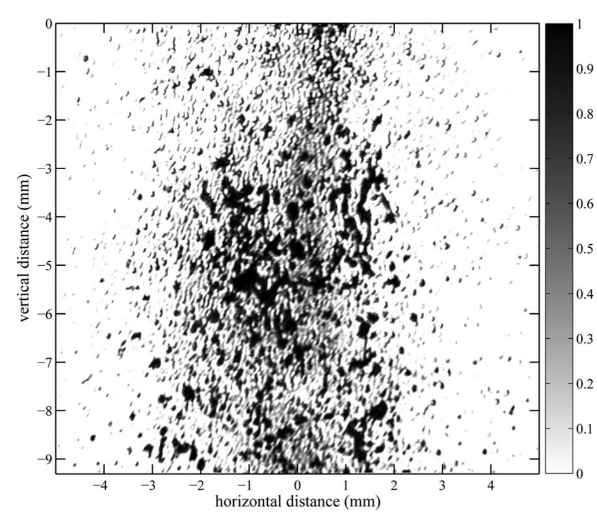

Fig. 2. Barbotage spray with 10% aeration.

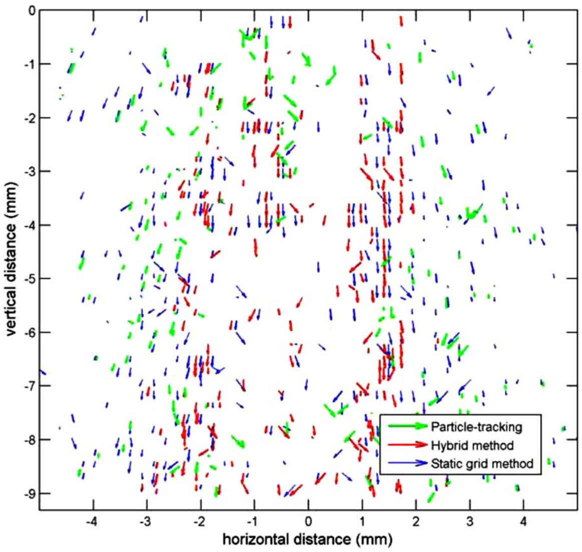

Fig. 3. (Color online) Velocity vectors for spray with 10% aeration. The t_1 image used in this analysis is shown in Fig. 2.

window from the t_1 image is defined to encompass each droplet and is correlated with a search field formed from the t_2 image. For the grid approach, the entire t_1 image is segmented by a regular grid such that each grid element defines a correlation window. Each of these windows is correlated with a search field formed from a t_2 image subregion centered at the same location. The third approach targets large liquid-spray structures and essentially combines the PT and grid approaches. Here, large distinct regions are identified by connectivity, analogous to the PT approach, and a preliminary window is formed for each large region identified in the t_1 image. This preliminary window is then divided by a regular grid such that each grid element represents a correlation window, and these regions are correlated with subregions from the t_2 image centered at the same location.

Each of the targeting methods discussed here employs the same algorithm to determine velocities after image regions are selected. The characteristic difference that defines each approach is the focused selection of the image features useful for correlating various regions in the spray. The PT approach selects and matches entire connected regions, yielding more accurate vectors on the spray periphery. The grid approach presents an unguided selection of features but covers the entire FOV. The third (hybrid) approach selects features within larger connected regions, facilitating more accurate correlation of interior spray structure.

Related methods for velocity analysis are routinely applied for gas-phase flows. These techniques include Mie scattering from seeded particles for particle-image velocimetry (PIV), and Rayleigh or laser-induced fluorescence of gas-phase species. The errors associated with nonseeded image flow analysis are explored in the literature [10,11]. Significant errors are reported for slowly varying spatial intensity fields that lack distinct features to facilitate well-defined cross-correlation peaks. The seeded methods of PIV are well characterized and rely on sharp images of single particles that produce distinct cross-correlation peaks. The sharpness of the peaks results in very accurate velocities but also require that the signal is easily differentiated from background noise. For this reason, PIV is generally not applicable in turbid media, where signal contribution from multiply scattered source light is significant, although in some cases PIV techniques have been extended to dilute two-phase flows using fluorescent tracers or other methods that aid in differentiating the signal from background light [12,13].

This Letter reports velocities obtained within a fuel-injection spray, a turbid two-phase environment. This is made possible by the noise reduction of the ballistic imaging measurement that generates a signal field with strong contrast between liquid and gas-phase regions. Support for this research was provided by the U.S. Air Force Research Laboratory under contract FA8650-04-M-2442 (Barry Kiel, Technical Monitor) and the Air Force Office of Scientific Research (USAFOSE) (Anne Matsuura, Program Manager). D. Sedarsky is supported by the Swedish Vetenskapsrdet.

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