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Ballistic Imaging for the Liquid Core of an Atomizing Spray

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ABSTRACT

We have developed a technique to image the near-field liquid core within an atomizing spray. To obtain high fidelity images of the liquid core in such a spray has been very challenging up to this point. In this paper, we describe the successful use of a time-gated ballistic imaging instrument to obtain high spatial resolution, single-shot images of the liquid core in a transient, atomizing Diesel fuel spray issuing into air at one bar. Sequential time series of these images reveal a developing flow field undergoing primary breakup. One can detect signatures of harmonic behavior, shear induced structures and the development of voids. We present images at various times after start of injection and at various positions at a fixed time after injection.

I. INTRODUCTION

Diesel engines offer significantly higher thermal efficiency than do spark-ignited engines, owing to their higher compression ratios. Unfortunately, pollutant emissions from Diesels are difficult to control because fuel-air mixture formation is a transient, two-phase fluid mechanical event, with the added complication of a variable ignition delay (which depends upon environment, fuel properties and fuel/air mixing). Moreover, emission from a Diesel engine is characterized by a tradeoff between soot and NOx formation [1]; engine or combustion modifications that decrease one of these will often increase the other. As described by Flynn *et al.* [2]; NO is formed at the hot, nonpremixed flame front and in the high temperature combustion products, while soot is formed in the fuel-rich core of the spray. Fuel/air mixture preparation using a spray is thus a controlling factor for Diesel engine performance and emissions.

Spray behavior is controlled by a large number of processes [3-5]. Internal flow effects in the nozzle prior to exit, including turbulence and cavitation, are important. Initial breakup of the liquid core is thought to be driven by the growth of harmonic disturbances, originating most likely in these internal flows. Aerodynamic drag forces (especially at high gas densities) are thought to amplify these harmonic disturbances until they overcome surface tension and shed mass in the form of primary droplets. There is in fact a controversy regarding the existence of liquid core, and if there is one, what its length might be, and this uncertainty is especially pronounced in transient Diesel fuel sprays. Smallwood and Gülder [6], in fact, have postulated that there actually is no liquid core in the spray; they speculate that cavitation within the jet itself destroys the core very near the jet exit. In contrast, de Villers *et al.* [7] predict an intact core that sheds mass primarily via turbulence. They assume no cavitation, but their results appear surprisingly similar to our water jet images [8]. These differences occur because each injector has different internal geometry, orifice size, fuel delivery rate, and so on. Each of these phenomena can thus have varying importance, depending upon the specific injector. The physical and thermodynamic states of the liquid (e.g. density, viscosity and surface tension) and the gas are also critical.

Modern engine design techniques rely quite heavily upon computational fluid dynamics (CFD). At present, however, one weak link in the CFD process is the description of liquid fuel spray breakup, and this is unfortunate, given the importance of mixture preparation. To describe primary breakup in engine codes, Yi and Reitz [9] use a simplified model describing the sudden appearance of very large "blobs" with specific momentum and turbulence intensity that then break up into finer droplets and vaporize. Such a model relies upon experimental observations from existing injectors to set adjustable constants; the fundamental underlying physics of spray breakup is thus not fully captured. While discussing this point, Yi and Reitz recently observed that, "The primary breakup process is very important in sprays because it initiates the atomization and provides initial conditions for the following breakup…A complete and correct understanding of the primary break up is critical for the study of spray atomization. However, since primary breakup usually occurs in the dense spray region, where observing the detailed structure is still a challenge, understanding of primary breakup is not yet completely established."

Large Eddy Simulation (LES) has also been used to describe to Diesel sprays (e.g. de Villers *et al.* [7]). Such an approach to the subject of spray breakup uses the full capacity of modern computers, rendering it impossible to include engine in-cylinder mixing and reaction together with the spray breakup routine. All the same, LES can reveal processes, and the insights provided can thus be used to refine the more simplified models used in engine codes. In their paper describing LES of Diesel sprays, de Villers *et al.* state, "The mechanisms by which high speed jets disintegrate have been under investigation for nearly 200 years. It is thus surprising at first sight to note that very little is in fact known about this process in the case of Diesel injectors at high injection velocities. This deficiency can be blamed mostly on

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the small length and time scales and high liquid fractions in the atomization zone, making detailed measurements very difficult, especially in the jet interior." Across the computational spectrum, theorists have clearly stated a need for more detailed observation of primary breakup of the liquid core in the near field (within 10 nozzle diameters from the exit) of an atomizing spray. The objectives of the work presented here are to provide exactly this kind of information using a new laser diagnostic technique.

A research group at Argonne National Laboratory [10-16] has successfully used X-ray absorption techniques to provide two-dimensional images of high-pressure fuel spray structure. The fuel spray is illuminated with an x-ray beam generated by a monochromatic synchrotron, in a line-of-sight configuration. Fuel mass locations are determined by the level of x-ray beam extinction, which is detected by a fast-framing two-dimensional x-ray pixel array detector (PAD). This group has combined the x-ray measurements with tomography algorithms to create three-dimensional images and motion pictures of gasoline direct injection hollow cone sprays. Insufficient x-ray absorption of fuel, however, requires the use of additives, while low signal-to-noise (SNR) levels require averaging over several injection cycles. Furthermore, the PAD detector is sensitive and easily damaged by the high-energy source.

In contrast, ballistic imaging (the technique applied here) is a form of shadowgraphy that can acquire images through turbid materials that are opaque to traditional imaging techniques. A single ballistic image of the very near field of a spray (a water jet in a LOX injector) was provided by the ballistic imaging group at CUNY (Galland, *et al.* [17]). The spatial resolution of their image was approximately 1 mm. This same group used image-processing techniques to slightly improve their spatial resolution [18].

II. TIME-GATED BALLISTIC IMAGING

The ballistic imaging instrument used in this work (described in detail by Paciaroni and Linne [19]) adapts the time-gated geometry originally developed for medical imaging by the group ay CUNY, but it provides significantly better spatial resolution (40 - 50 µm) while maintaining high temporal resolution (one laser pulse, no averaging is required). Because this is an optical technique, the instrument does not require a synchrotron. It thus provides high fidelity images in a geometry that can be used by spray researchers in their own laboratories. In this section we describe the instrument, and in the following sections we describe the application of the instrument to a transient Diesel fuel spray.

When light passes through a highly turbid medium, some of the photons actually pass straight through without scattering, exiting the medium within roughly the same solid angle that they entered (see Figure 1a). These relatively few photons are termed "ballistic". Because they travel the shortest path, they also exit first (see Figure 1b). A somewhat larger group of photons is called the "snake" photon group, because they are scattered just once or twice. They exit the medium in the same direction as the input light but with a somewhat larger solid angle than the ballistic photons. Because they travel a bit further, they exit just after the ballistic photons. Light exiting the medium that has scattered multiply ("diffuse photons") has a larger photon number density, but it also is scattered into a very large solid angle and it exits last.

Owing to their undisturbed path, ballistic photons retain an undistorted image of structures that are embedded within the turbid material (the liquid core of an atomizing spray in this case). If used in a shadowgram arrangement, the ballistic photons can provide diffraction-limited imaging of these structures. Unfortunately, in most highly scattering and/or absorbing environments, the number of transmitted ballistic photons is often insufficient to provide the necessary SNR to form a single-frame image. In such a case, the snake photons retain slightly distorted information and can be used in imaging, together with the ballistic photons, with little degradation of resolution. In contrast, diffuse photons retain no memory of the structure within the material. If allowed to participate in the formation of an image, the various paths these multiply scattered photons take through the material will cause each image point they form to appear as if it came from an entirely different part of the object, and this will seriously degrade resolution. Unfortunately, diffuse photons are the most numerous when light is transmitted through highly scattering media. The problem of obtaining a high-resolution image through highly scattering materials is thus a matter of separating and eliminating the diffuse light from the ballistic and snake light. This can be done using discrimination methods that make use of the properties that are retained by the ballistic and snake light, but are lost in multiple scattering events. As already alluded, the direction taken by transmitted light, together with exit time, can help to segregate diffuse photons from the imaging photons. This is done here via

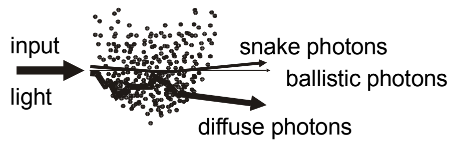


Figure 1a. Geometric schematic of ballistic imaging.

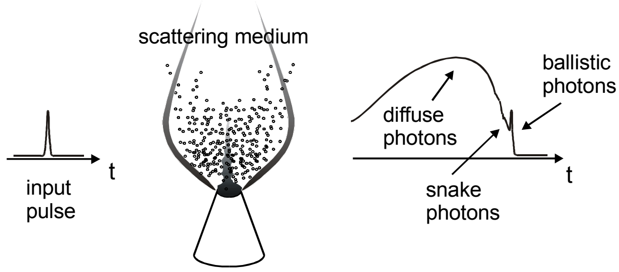


Figure 1b. Time-domain schematic of ballistic imaging with a short pulse.

spatial filtering (to select the light exiting at narrow scattering angles), together with time gating. In time gating, a very fast shutter {an optical Kerr effect (OKE) gate [20]} is used to select just the leading edge containing ballistic and snake photons.

The time-gated ballistic imaging instrument used here is shown in Figure 2. A 1-kHz repetition rate Spectra-Physics Spitfire Ti:Sapphire regenerative amplifier, seeded with a Spectra-Physics Tsunami Ti:Sapphire mode-locked laser, generates 80 fs, 1mJ pulses centered in wavelength at ~ 800 nm. The linearly polarized beam is split into OKE gating and imaging beams; 30% of the optical power is used as the imaging beam while the remaining power is used to create the OKE time gate.

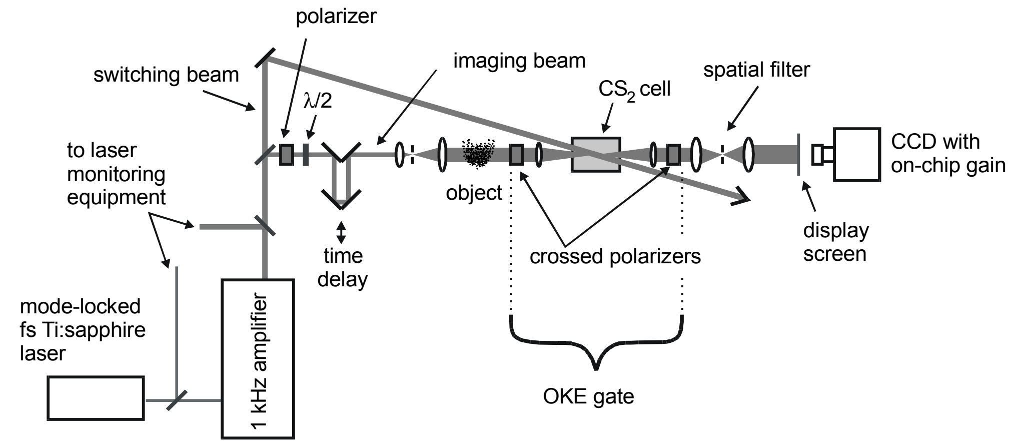


Figure 2. Layout of OKE-switched ballistic imaging instrument.

The polarization state of the imaging beam is first cleaned up with a polarizer, because the OKE gate relies upon polarization switching, and then the polarization is rotated 45º. The imaging beam is then time delayed, to control the timing of the switching and imaging pulses, using an adjustable length delay arm. The imaging beam then passes through an optics train consisting of a telescope (with spatial filter) that controls the imaging beam size at the object, a system to relay the bean through the OKE switch, and a combined spatial filter/telescope for imaging onto a display screen.

The OKE gate works in the following manner. When there is no switching pulse present, no image is transferred to the display screen because the OKE gate uses crossed calcite polarizers. The first polarizer in the OKE gate (second polarizer used in the imaging beam) is oriented to pass the polarization orientation of the imaging beam. The second OKE polarizer is oriented normal to the first, blocking an unperturbed imaging beam. The measured extinction ratio of the polarizers is $>10^5$; without a switching pulse present there is $<10^{-5}$ transmission of the imaging beam through the second polarizer. Following the first polarizer, the imaging beam is focused into the Kerr active liquid (CS_2 in this case) with an F/#5 achromat, and then up-collimated with an F/#10 achromat. At the arrival of a switching pulse, the intense electric field of the pulse causes the CS_2 dipoles to align along the polarization vector of the switching beam, creating temporary birefringence in the liquid. This birefringence rotates the polarization of the imaging beam, allowing most of it (~ 70% - 75%) to pass through the second polarizer. This OKE induced birefringence is limited in time to ~ 2 ps for CS_2, forming a very fast shutter. Past the OKE gate, the image is relayed to a display screen and the image is captured by a Roper Scientific Cascade 650 CCD camera equipped with on-chip multiplication gain. Detailed system development work [19] has demonstrated that we can routinely achieve a spatial resolution around 40-50 μm (depending upon the level of extinction imposed by the droplet mist) in a single frame.

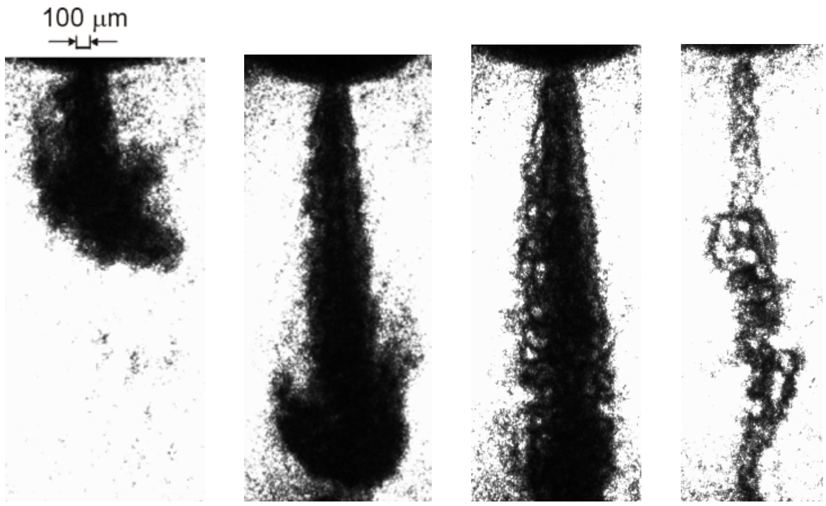
III. DIESEL SPRAY FACILITY

The ballistic imaging system just described has been applied to a transient spray generated by a Sturman® Diesel fuel injector. The Sturman injector is capable of providing programmed injection events, such as two injections of controllable duration and spacing, within a total spray time between 3 and 8 ms. The injector uses a hydraulic system to drive the injector needle, and that is controlled by a solenoid valve via a proprietary control box interfaced to a PC. The images presented here were all acquired within just one injection event of about 3.8 ms duration. Two nozzles were studied. One had a single hole in the injector tip (155 $\pm$ 1 μm) and the other used a more commercial set of six holes (110 $\pm$ 2 μm each) arrayed evenly around the nozzle. The exact dimensions of the nozzle were undetermined at the time of this writing, but the length to diameter ratio of both nozzles appears to be in excess of 5. Most of our data were acquired with the single-hole unit because ballistic imaging is a line-of-sight technique. In the 6-hole configuration, the overlap of 3 sprays is observed. During early times, however, just one spray can be discriminated and so we confine our measurements to early times in that unit. Diesel fuel was used and the peak fuel pressure inside the nozzle tip was about 950 bar. The jet issued into still air at 1 bar.

IV. EXPERIMENTAL RESULTS

A series of imaging experiments were conducted in order to characterize primary breakup of the near field, for the single-hole injector just discussed. First, images were acquired at the nozzle exit for a sequence of time delays after start of injection, and then images were acquired at various distances past the injector at two time delays (~ 100 µs and ~ 2 ms). Here we present just a few representative images. More detail will be included in a forthcoming journal article.

Figure 3 contains ballistic images of the single-hole spray at the nozzle, covering various times after the beginning of the injection event. All of the images in Figure 3 include the edge if the injector tip at the top of the image. The time delays used are shown in the figure. Readers must be cautioned that the system cannot resolve features smaller than 40 – 50 µm in size. Because a laser beam carries the image, diffraction spots are an inevitable background problem in these raw images. They should not be interpreted as edge features or small droplets.



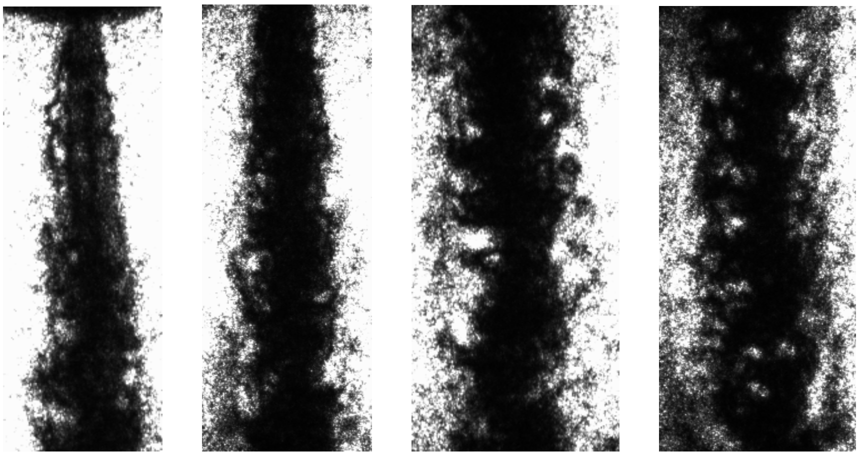
a. 3 µs a/s b. 11 µs a/s c. 1950 µs a/s d. 20 µs b/e

Figure 3. Ballistic images of the liquid core in a transient diesel spray; a/s = time after start of injection, b/e = time before the end of injection.

At early times, the spray develops a classic mushroom shape caused by vortex roll-up at the spray tip. Additional images (not shown here) indicate a very early and weaker vortex, and the developing momentum of the spray then punches through it. This behavior is captured in Figure 3a where a second vortex is developing in the jet that has already passed through the first. A fully developed vortex is shown at the tip of the spray as it penetrates the air in Figure 3b. Note the appearance of harmonic signatures along the body of the liquid core at this point in time. Following this initial jet development, the spray exhibits an almost steady structure throughout a large portion of the event (generally between 500 µs and 3 ms). Figure 3c is typical of this developed spray. Again, one can detect harmonic behavior, and voids begin to appear at the jet periphery. It is not clear that they originate from the flow inside the injector, however, as they seem to appear and develop further downstream in the jet (see e.g. Fig. 4). The image hints at formation via entrainment. Similar behavior appears in our steady, turbulent water jet images [8] and to a lesser extent in the LES results presented by de Villers *et al.* [7]. Figure 3d shows the final portion of the spray, in which a very weak stream of fluid is emitted from the nozzle just prior to final closing. This regime is certainly of interest for the formation of unburned hydrocarbons. Perhaps the most interesting outcome is that we cannot conclusively detect shedding of primary droplets in these images, as we did in our turbulent water jet [8]. This does not mean they are not present; visual observation confirms the formation of a thick fog of droplets. It simply indicates that the primary droplets must be smaller than our current detection limit of 40 – 50 µm.

Next, the development of the spray as a function of the position past the nozzle was investigated. Figure 4 contains images of the spray during the time when the spray had become fully developed (~ 2 ms after start of injection). The nozzle was moved 2 mm between each frame, so there is some overlap between each image (each image is roughly 4 mm in extent). As before, one can see the growth of the liquid core, including what appear to be harmonic structures and small shear-induced structures. Voids persist and seem to grow slightly with distance. Past the point shown in Figure 4d, the spray has grown to the point where it is difficult to identify boundaries between the liquid core and the air. This is probably caused by the growth of the core beyond the dimensions of the image beam.

Finally, Figure 5 shows one image taken from the six-hole injector at a fairly early time. The injector was mounted so that one of the jets would be normal to the imaging beam. Because the holes are arrayed at 60º increments, however, three jets are imaged simultaneously in this configuration. Each spray points downwards, however, and the jets to the side of the central jet are foreshortened. One can thus detect the ends of the side sprays in the image. The central spray



a. at nozzle b. 2 mm below a. c. 2 mm below b. d. 2 mm below c.

Figure 4. Ballistic images of the liquid core in a transient diesel spray as a function of position at ~ 2 ms after start of injection.

is labeled. It is not possible to image just one jet with the nozzle mounted this way at longer times. For the jets that can be imaged, however, there seems to be little difference between the jet produced by a multi-hole injector and a single hole injector. This suggestion bears further investigation.

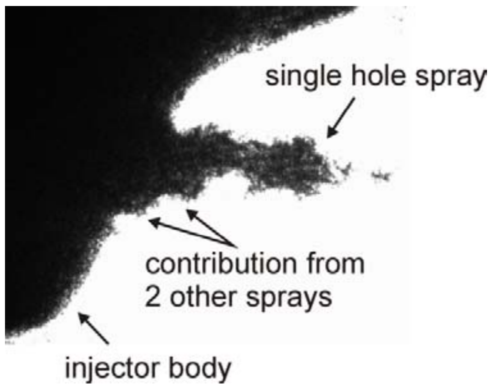


Figure 5. Ballistic image of the liquid core in a transient diesel spray, 6-hole injector.

While these images are new and certainly instructive, work remains to be done in the development of the diagnostic technique. The images contain background structures caused by diffraction. This is to be expected when a laser beam is used for imaging. Background structures smaller than our resolution limit can be removed by appropriate use of image processing algorithms. Moreover, while the spatial resolution of our system is superior to other single-frame systems described in the literature, it would be improved if we could achieve 10 μm spatial resolution. It might then be possible ti image primary droplets in such a spray. Work on this is ongoing. Finally, we face a dynamic range problem caused by the serious loss of light within the spray. Whenever we attempt to image interior structures, the light at the sides of the core saturates the detector. We are exploring various solutions to this problem as well.

V. CONCLUSIONS

We have proven the ability of OKE-gated ballistic imaging to acquire high-resolution, two-dimensional, single-shot images of the liquid core of an atomizing, transient Diesel spray issuing into ambient air. The liquid core shows strong evidence for the development of harmonic structures, shear induced structures at the edge of the core, and development of voids. The evolution of the liquid core is characterized by the growth of these structures with downstream position. We detect no primary droplets, indicating that they are probably smaller than 40 – 50 μm.

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