Ballistic imaging of the liquid core for a steady jet in crossflow

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A time-gated ballistic imaging instrument is used to obtain high-spatial-resolution, single-shot images of the liquid core in a water spray issuing into a gaseous crossflow. We describe further development of the diagnostic technique to improve spatial resolution and present images and statistics for various jets under crossflow experimental conditions (different Weber numbers). Series of these images reveal a near-nozzle flow field undergoing breakup and subsequent droplet formation by stripping. One can also detect signatures of spatially periodic behavior in the liquid core and formation of small voids during breakup. © 2005 Optical Society of America

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1. Introduction

The process of fuel–air mixture preparation is key to flame stabilization and fuel-conversion efficiency in a wide variety of air- and ground-based power-generation systems. For example, flames in modern gas turbines that are fed by lean premixed prevaporized (LPP) fuel ducts are stabilized in recirculation zones that can shift with changes in load. Flow-field strain rates within the recirculation zones that exceed the extinction strain rate for the local fuel–air mixture can lead to reduced combustion efficiency and reduced static and dynamic stability. Moreover, localized heat release originating from nonuniform fuel-droplet distributions can potentially drive thermoacoustic instabilities, increasing heat transfer to the combustor wall and introducing the potential for significant damage. Mixture preparation has a controlling effect on emissions as well. Overly fuel rich mixing zones can produce large amounts of soot; mixing zones that fall outside the flammability limits are quenched and produce hydrocarbon and CO emissions, and mixing zones near the stoichiometric fuel–air ratio produce high NOX emissions associated with high temperatures. These performance considerations are all controlled by mixture preparation, a process that is not fully understood.

The work reported here focuses on steady, liquid sprays in crossflow that are relevant to gas-turbine LPP combustors, as one example. The characteristic geometry for an LPP duct incorporates the injection of liquid fuel into a high-temperature and -pressure air stream as depicted schematically in Fig. 1. The balance of aerodynamic drag, liquid inertia, surface tension, and viscous forces induces both deflection and deformation of the jet column. Deflection leads to a curved liquid-jet profile, breaking the liquid column into large segments near the point of curvature (called “column breakup”), and subsequent fragmentation. In contrast, deformation increases the frontal cross section of the jet column and increases the drag, which leads to stripping of smaller ligaments and fragments directly from the column surface (called “surface stripping”). The same forces cause secondary breakup of ligaments and fragments into droplets, which may break down even further before being evaporated. Small droplets are also entrained in the near-wall region owing to the wake flow that develops behind the liquid column.

The relevant global parameter used to capture this balance of forces is the jet Weber number based on the gas density ($\rho_g$), gas velocity ($u_g$), jet-orifice diameter ($d$), and liquid surface tension ($\sigma_l$):

$$\text{We}_g = \frac{\rho_g u_g^2 d}{\sigma_l}$$  

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Gas-turbine-based jets in crossflow typically operate in the range of $100 < We_{a} < 2000$, which is a range dominated by shear breakup driven by aerodynamic drag. Both column breakup and surface stripping are included within the shear breakup mechanism. Which of the two dominates is determined by the liquid/air momentum flux ratio. Furthermore, liquid viscosity acts in opposition to inertial forces, and it can affect jet penetration heights and jet stability.

Models for liquid jets in crossflow recently developed by Madabhushi and Zuo et al. both utilized a modified version of the wave breakup approach of Reitz (the so-called blob model). A number of experimental results have shown, however, that the mechanism of liquid jet in crossflow atomization is quite different from the standard wave breakup approach. Cavaliere and co-workers showed that the jet evolution is significantly influenced by the onset of a shear breakup mechanism rather than a wave breakup approach. Column breakup's main feature is the appearance of waves on the windward surface of the liquid column, which are then amplified by aerodynamic forces leading to fracture of the column in a wave trough. The onset of observable wave growth usually coincides with an alignment, or at least partial alignment, of the jet with the direction of the airflow. As noted earlier, surface breakup is characterized by stripping of liquid from the surface of the jet. Examination of the breakup process suggests that both the column and surface breakup mechanisms are usually active, but one is dominant, depending on the flow conditions.

While the onset of jet-column breakup is well characterized, the time required to complete the process is more difficult to measure with conventional techniques because of the optical density in this region. Even the most advanced models still do not account for other important structural features, such as wake effects, and this results in an underprediction of the volume flux in the near-wall region. Dense spray effects on breakup and atomization are also typically ignored, leading to uncertainties in the near field. Errors in the near field can be important when fuel injection is closely coupled to an anchored flame. These problems in understanding remain because there have been no experimental observations of the primary breakup of the liquid core in the dense spray region, because such a core is obscured by a dense fog of droplets. Ballistic imaging can meet this need, providing high-resolution, single-shot images of the liquid core in a dense spray.

2. Singe-Shot, Time-Gated, Two-Band Ballistic Imaging

The initial development and evaluation of the basic ballistic imaging instrument used here is described in detail by Paciaroni and Linne. In this companion paper, we describe further development of the technique and demonstrate its application to a spray.

Ballistic imaging is a form of shadowgraphy that generates images by using light with specific signatures, and there are many ways to do this. 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 Fig. 2a). These relatively few photons are termed “ballistic.” Because they travel the shortest path, they also exit first (see Fig. 2b). 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 these photons are also scattered into a very large solid angle and they exit last. As a result of their undisturbed path, ballistic photons retain an undistorted image of structures that may be embedded within the turbid medium. If used in a shadowgram arrangement, the ballistic photons can provide diffraction-limited imaging of these structures. Unfortunately, in most highly scattering or absorbing environments, the number of transmitted ballistic photons is often insufficient to provide the necessary signal-to-noise ratio to form an image in a single-shot format. In such a case, the snake photons 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 turbid 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 by discrimination methods that make use of the properties that identify the ballistic and snake light. As already suggested, the direction taken by transmitted light, together with exit time, can be used to segregate diffuse photons from the imaging photons. In addition, polarization and coherence are both preserved by the ballistic photons, and they can also be used for segregation. Coherence is not used here because snake photons are not well preserved by such techniques, and their contribution is necessary to form a single-shot image.

The system used here was optimized to provide high-resolution, single-shot images of the liquid core in very dense atomizing sprays\(^7\) by using weak spatial filtering (to select the light exiting at narrow scattering angles) together with time gating. The original design used a spatial filter in front of the camera to reject switching light that was forward scattered. Here we have eliminated that filter, but it is important to point out that any properly designed imaging optical train acts as a weak spatial filter in the sense that it has a defined system aperture and acceptance angle. In time gating, a very fast shutter consisting of an optical Kerr effect (OKE) gate\(^8\) capable of gating times as short as 2 ps is used to select just the leading edge containing ballistic and snake photons.

The complete system used for this work is shown in Fig. 3. A 1 kHz repetition rate Coherent Legend Ti:sapphire regenerative amplifier, seeded with a Spectra-Physics Tsunami Ti:sapphire mode-locked laser, generates 40 fs, 2.5 mJ pulses centered in wavelength at about 800 nm. The linearly polarized beam is split into OKE gating and imaging beams. In previous work standard dielectric beam splitters were used, but they were replaced by bandpass filters in this work (for reasons discussed just below). The polarization state of the imaging beam is first linearized, and then the polarization is rotated 45° because the OKE gate relies upon polarization switching. The imaging beam is time delayed by using an adjustable length delay arm, allowing one to control the delay between the arrival of the switching and imaging pulses at the OKE gate, for optimum time gating. The imaging beam then passes through an optics train consisting of a telescope that controls the imaging beam size at the object, a system to relay the beam through the OKE switch, a telescope for imaging onto a display screen, and a second bandpass filter to reject scattered switching light. This optical system was designed and optimized using OSLO, a commercial ray-trace code. By careful choice of available optics, we have ensured that the optical train itself is diffraction limited; there are no spurious aberrations or distortions introduced by the imaging optics themselves.

The OKE gate works in the following manner. When there is no switching pulse present, no image is transferred to the display screen. This is 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 OKE polarizer, the imaging beam is focused into the Kerr active liquid (CS\(_2\)) in this case) with an \(F/\#5\) achromat, and then upcollimated 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 by either the duration of the laser pulse or the molecular response time of the Kerr medium, whichever is longer. In our case, the incident laser pulse is much shorter in duration than the molecular relaxation time of 2 ps for CS\(_2\); a gate time of 2 ps has been confirmed by direct measurement. Past the OKE gate, the image was relayed to a display screen and the image was captured by a Roper Scientific PI-Max camera.

The system described by Paciaroni and Linne\(^7\) included a spatial filter at the location of the short-pass filter in Fig. 3. The spatial filter was used because the same wavelength of light was used for switching and imaging, and some switching light was scattered forward into the imaging system. The spatial filter removed most of that interference. A compromise was involved in the choice of aperture for the spatial filter, however, because the aperture must be located at the focal point. That point identifies the Fourier plane,
where the high-spatial-frequency components of the image reside off axis. These high-frequency components are therefore lost if they are blocked by the aperture, and this degrades spatial resolution. Paciaroni and Linne chose an aperture that preserved the high-frequency components, but this allowed some switching light to enter the imaging system. This produced a small but noticeable degradation in contrast, leading to degradation in spatial resolution. It is possible to reject much of this forward scatter by using alternative trapping techniques, but the alignment process must be repeated everytime anything in the imaging system is changed.

Others have used the second harmonic of the laser to switch the OKE gate while imaging with the first harmonic (usually with Nd:YAG at 532 nm and 1.064 μm). This two-wavelength technique allows one to reject scattered switching light with a low-pass optical filter. It was not possible to use that approach here, however, because CS₂ absorbs light at the second harmonic of Ti:sapphire. The amplifier used in the work described here emits over twice the pulse energy and increasing the switching beam diameter. Next, crossed polarizers can also remove high-spatial-frequency components. We do not see their contribution at this point, but they could become the next limitation if the spatial filtering effects were removed.

It is worth mentioning that the camera itself does not limit spatial resolution. More common planar imaging systems use a camera that acquires a predefined, diffuse image from within a flowfield located some distance away, and it relies heavily upon the camera lens, image intensifier if one is used, and the architecture of the imaging chip. In contrast, a ballistic image is relayed within a laser beam from the sample volume to a screen. One can use diffraction-limited relay optics to create an image of virtually any size at the screen. The camera can then be adjusted to select a portion of a magnified image. Diffraction then controls spatial resolution for features originating at the sample, not the camera. The camera does impose a limit on spatial dynamic range, however, set by the pixel dimension relative to the overall size of the imaging chip.

3. Spray Experiments

A quasi-steady water jet experiment was developed to demonstrate the diagnostic in a relevant flowfield. It used an accumulator to provide pressurized water
(up to 550 kPa) to a nozzle for about 15 min of steady spray time (see Fig. 5). A second nitrogen bottle was used to supply a controllable crossflow of gas at atmospheric pressure. Two simple water nozzles were built to emulate the cases studied by Madabhushi et al. The data presented here cannot be compared in an easy way with their predictions, as the ballistic images were acquired just 3–4 mm from the jet exit, but they can be used to augment future model development work. The nozzles used here employed simple constant area passages with diameters of 0.789 and 1.722 mm. The nitrogen jet was 4.37 mm diameter in both cases, and it was centered on the water jet before each experiment commenced. The nitrogen flow pattern was not characterized.

The nitrogen and water flow rates were metered simply by providing a constant pressure drop across the orifice that formed either jet. The nitrogen flows were determined by using a calibrated rotameter (calibrated by a mass flow meter), while the water flow rate was measured volumetrically. The various rates were chosen to provide Weber numbers relevant to the model presented by Madabhushi et al. The specific properties of each flow studied are detailed in Table 1, where the Reynolds number of the liquid is given by \( Re_l = \frac{u_l d}{v} \) (where \( v \) is the kinematic viscosity), and the momentum flux ratio is given by \( \frac{\rho_l u_l^2}{\rho_g u_g^2} \). Sets of 40 images were acquired for each case. The case with maximum gas velocity, for the jet diameter \( d = 7.89 \times 10^{-4} \text{ m} \), was not included because there was a question about drift in the nitrogen mass flow rate for that case.

### Table 1. Jet Run Conditions

<table>
<thead>
<tr>
<th>Case</th>
<th>Jet Diameter ( d ) (m)</th>
<th>Gas Velocity ( u_g ) (m/s)</th>
<th>Liquid Velocity ( u_l ) (m/s)</th>
<th>( We_l )</th>
<th>( Re_l )</th>
<th>Momentum Flux Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>( 7.89 \times 10^{-4} )</td>
<td>66.7</td>
<td>29.0</td>
<td>56</td>
<td>22,800</td>
<td>161</td>
</tr>
<tr>
<td>2</td>
<td>( 7.89 \times 10^{-4} )</td>
<td>100</td>
<td>29.0</td>
<td>126</td>
<td>22,800</td>
<td>72</td>
</tr>
<tr>
<td>3</td>
<td>( 1.73 \times 10^{-3} )</td>
<td>70.7</td>
<td>17.4</td>
<td>138</td>
<td>30,100</td>
<td>52</td>
</tr>
<tr>
<td>4</td>
<td>( 1.73 \times 10^{-3} )</td>
<td>88.7</td>
<td>17.4</td>
<td>218</td>
<td>30,100</td>
<td>33</td>
</tr>
<tr>
<td>5</td>
<td>( 1.73 \times 10^{-3} )</td>
<td>106.7</td>
<td>17.4</td>
<td>316</td>
<td>30,100</td>
<td>23</td>
</tr>
</tbody>
</table>

4. Results

An example image from case 2 is shown in Fig. 6. The field of view is approximately 3.5 mm. In the image, one can see dark areas representing a continuous fluid phase and light areas representing the gas phase. After background subtraction, each raw image was normalized by an image of the beam with no liquid flow. This removed the laser speckle patterns that were repeatable and flattened the Gaussian profile of the imaging beam. This normalization procedure improved the overall signal-to-noise ratio from 4:1 to 20:1, it provided better visual access to the dark regions of the imaging beam, and it improved droplet detection. A small amount of beam jitter caused a loss of spatial resolution of the order of one micrometer, but this was considered a good compromise given the improvement in overall image quality.

The top of the image in Fig. 6 is the location of the nozzle. The jet issued from the top, and one can see the liquid column breaking up as the liquid flows downward. The gas flow is from right to left in the images. A small amount of laser speckle that is smaller than the resolution limit of the system remains within the gas-phase portion of the image after background subtraction and normalization (see the note in Fig. 6). These should not be interpreted as small droplets. It is also necessary to point out that this spray, while not as dense as an atomizing diesel
fuel spray for example, was quite dense to passive imaging techniques.

The interesting fluid features in Fig. 6 include expansion of the liquid core cross section as it moves downstream, deflection, and perhaps deformation of the jet, appearance of periodic structures along the jet column, evidence for aerodynamic stripping of the jet, and the formation of ligaments, nonspherical primary droplets, and voids. There was some unsteadiness in the spray, as evidenced by the variation from shot to shot in Fig. 7. Variability is diminished in the slower flow case (case 1), and so we speculate that it may be caused by some inherent instability of the nitrogen flow.

The effect of Weber number can be observed in Fig. 8a (case 1) to 8f (case 5). The difference between cases 1 and 2 (Figs. 8a and 8b) differ only in gas velocity. The higher $W_e$ case (Fig. 8b) experiences greater atomization, deflection by the gas, and potentially greater deformation as well. Periodic structures are observed in both cases, but ligaments are larger and more frequent in the higher $W_e$ case. These observations are borne out by statistics taken from the entire collection of images, as presented in Table 2 below.

A larger jet diameter is used to increase the value of $W_e$ for cases 3, 4, and 5. Case 2 (the smaller $d$ case, Fig. 8b) looks quite different from case 3 (the larger $d$ case, Fig. 8c), even though their respective Weber numbers are not very different. This is because the liquid–gas momentum flux ratio changes significantly with the larger jet diameter. Note that case 3 had some very infrequent evidence of bag breakup, as shown in Fig. 8d. Voids are not common in cases 3, 4, and 5, but otherwise they show a progression of features with $W_e$ similar to cases 1 and 2.

The image files were scanned manually for statistics on ligament size and number, droplet size and number, void size and number, and the spatial frequencies of clearly identifiable periodic structures. When the two-dimensional image of a primary droplet was elliptical or oblong, the short dimension was taken.

Figures 9 and 10 contain drop size distributions for the five cases described in Table 1. These data represent averages over all of the images in each case group, presented for a limited number of size classes because the data were extracted manually. It is important to point out that droplets smaller than 20 μm can not be detected by this imaging technique; so the measured distributions necessarily cut off at that point. As shown in the figures, however, most of the distributions fall well above this small cutoff value, except for case 5. The other plots have the approximate shape of a lognormal distribution with approximately the same average size.
Table 2. Results Extracted from Images

<table>
<thead>
<tr>
<th>Case</th>
<th>Ave. No. Drops</th>
<th>SMD&lt;sup&gt;a&lt;/sup&gt; (µm)</th>
<th>Total No. Voids Obs.</th>
<th>Total No. Ligaments</th>
<th>Periodic Wavelengths&lt;sup&gt;b&lt;/sup&gt; (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>71</td>
<td>46.7</td>
<td>19</td>
<td>54</td>
<td>us: 150,175,200,250,275,300,350</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>ds: 175,225,300</td>
</tr>
<tr>
<td>2</td>
<td>96</td>
<td>46.7</td>
<td>39</td>
<td>92</td>
<td>us: 225,300,325</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>ds: 175,250,300,500</td>
</tr>
<tr>
<td>3</td>
<td>29</td>
<td>53.5</td>
<td>14</td>
<td>46</td>
<td>us: 150,225,250,275,300,350,400</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>ds: 150</td>
</tr>
<tr>
<td>4</td>
<td>54</td>
<td>45.6</td>
<td>24</td>
<td>81</td>
<td>us: 150,200,250,300,350,400</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>ds: 175,250,300,325,375,400</td>
</tr>
<tr>
<td>5</td>
<td>108</td>
<td>—</td>
<td>13</td>
<td>78</td>
<td>us: 150,200,250,300,475,600</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>ds: 225,250,300,325,350,400,750</td>
</tr>
</tbody>
</table>

<sup>a</sup>SMD, Sauter mean diameter.

<sup>b</sup>us, upstream side; ds, downstream side.

Table 2 contains a summary of the data extracted from these images. The Sauter mean diameters in the table were inferred by fitting a lognormal distribution to each curve in Figs. 9 and 10 (except for case 5, where there were insufficient data to describe the distribution). Instead of presenting averages for voids and ligaments, the total number observed out of 14 images is presented because there were some images containing neither. The data in the column labeled “Periodic Wavelengths” represent all of the wavelengths for what appeared to be periodic structures in the jets.

Clearly, there are some judgements involved in the manual process of data extraction from these images. Future work will utilize image processing to automate this function, but it is possible to introduce significant errors unless great care is applied to implementation issues such as edge detection. For the time being, therefore, human judgement has been used.

Despite variation in the data, one can extract some preliminary observations. Not surprisingly, the number of droplets and ligaments produced increases with $We$, while the low $We$ and $Re$ cases produce more voids. The Sauter mean diameter of the primary droplets does not vary significantly for cases 1–4. Case 5 has evolved into a somewhat different regime. It has the largest $We$ and $Re$, together with the smallest momentum ratio. The droplet size distribution for this case has moved down into a notably smaller size range. Finally, there seems to be an increase in the wavelength of periodic structures with $We$, but it is not a pronounced trend.

5. Conclusion

Ballistic imaging is a fairly new diagnostic tool for the near field of an atomizing spray. Our latest implementation provides single-shot images with very good spatial resolution, sufficient to extract new information about a highly relevant spray. This initial work reveals a near-nozzle flow field undergoing breakup via stripping. One can also detect signatures of spatially periodic behavior and a few voids. These results will contribute to the development of a physical model that can be included in subroutines of
computational fluid dynamics codes that describe spray breakup.

Future work will focus upon an experiment with upstream gas flow that is more uniform across the jet, and it will be better characterized. More image sequences will be acquired at more locations along the liquid core, and automatic image analysis software will be used to extract higher quality statistics.

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