Near Field Fluid Structure Analysis for Jets in Crossflow with Ballistic Imaging

D. Sedarsky*
Department of Physics, Lund University, Lund, 22362 Sweden
M. Paciaroni
Innovative Scientific Solutions, Inc., Dayton, Ohio, 45440 USA
J. Zelina
Propulsion Directorate, Air Force Research Laboratory, Dayton, Ohio 45433 USA
M. Linne
Sandia National Laboratories, Livermore, California 94551 USA

Abstract
In this work we present ballistic images of a liquid jet produced by a plain-orifice atomizer ejecting into a crossflow of air. This arrangement is relevant to fuel injection within a lean, premixed, prevaporized (LPP) gas turbine duct 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 Figure 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 (termed “column breakup”), and subsequent fragmentation. In contrast, deformation increases the frontal cross-section of the jet column increasing drag interaction along the liquid-gas shear layer. This leads to a stripping of smaller ligaments and fragments directly from the column surface (termed “surface stripping”).

While the onset of jet-column breakup is well characterized, the time required to complete the process is more difficult to measure with conventional imaging techniques due to the high optical density in this region. Even the most advanced models do not account for other important structural features, such as wake effects, this results in an under prediction 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 the breakup process remain because experimental observations of primary breakup are complicated by dense spray effects such as multiple scattering and low signal levels. When properly applied, ballistic imaging can mitigate these difficulties, providing high resolution, single-shot images of the liquid core in a dense spray.

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 application of the diagnostic technique to a jet in crossflow (JICF) and present new data including statistics for relevant spray features (e.g. mean droplet size, and number density) for various experimental conditions (e.g. different Weber numbers). Series of these images reveal a near-nozzle flow field undergoing breakup; under some conditions, periodic features are evident on the windward edge of the JICF, facilitating investigation of the gas-liquid shear layer instabilities and their frequency components.

* david.sedarsky@forbrf.lth.se
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. A large number of performance considerations for these combustion systems (e.g., NOx and soot production, hydrocarbon and CO emissions) are 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 Figure 1. The balance of aerodynamic drag, liquid inertia, surface tension, and viscous forces induces both deflection and deformation of the jet column. The pressure difference between the upstream and wake regions, as well as momentum transfer from the crossflow lead to a curved liquid-jet profile. Under some conditions, these interactions augment instabilities along the jet boundary, eventually breaking the liquid column into large segments near the point of curvature. This process and subsequent fragmentation is termed “column breakup.”

In contrast, deformation increases the frontal cross-section of the jet column, increasing aerodynamic drag interaction between the jet and the crossflow. This leads to stripping of smaller ligaments and fragments directly from the column surface. This process is termed “surface stripping.” 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 ($\sigma_l$):

$$\text{We}_g = \frac{\rho_g u_g^2 d}{\sigma_l}$$  \hspace{1cm} (1)

Gas-turbine-based jets in crossflow typically operate in the range of $100 < \text{We}_g < 2000$, 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. The dominant force is determined by the liquid/air momentum flux ratio. Furthermore, liquid viscosity acts in opposition to inertial forces and can affect jet penetration heights and jet stability.

Recently developed models for liquid jets in crossflow by Madabhushi [1] and Zuo et al.[2] both use a modified version of the wave breakup approach of Reitz [3] (termed the “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 [4] showed that the jet evolution is significantly influenced by the onset of a shear breakup mechanism rather than a wave breakup approach. The main feature of column breakup 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 at 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 [5].

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 due to the optical density in this region [6]. Even the most advanced models still do not account for important structural features, such as wake effects, and this results in an under prediction 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 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 of primary breakup in this dense spray region has been demonstrated recently by Linne et al. [7]. Ballistic imaging can meet this need providing high resolution, single-shot images of the liquid core in a dense spray.

![Figure 1. Ballistic, snake, and diffuse photons.](image-url)
Specific Objectives

The purpose of the work we present here is to demonstrate the utility of ballistic imaging for resolving structure within liquid jets in crossflow; thus allowing visualization and image analysis under conditions where effective measurements with conventional techniques are not possible. In this work, we applied ballistic imaging to a liquid jet in a crossflow of air. This paper will briefly describe the jet and experimental arrangement, present a selection of the data, and discuss the results. We further demonstrate the utility of ballistic imaging by applying image analysis to reveal the structure of the water jet, periodic disturbances along the upstream jet profile, and statistics for drop number density and size. This analysis is briefly outlined, and some relevant results are shown.

Experimental Arrangement

A full description of the development and evaluation of the ballistic imaging instrument referenced in this paper can be found in an earlier paper by Paciaroni and Linne [6]. In general, ballistic imaging is an extension of shadowgraphy designed to mitigate distortion caused by multiply scattered light in the measurement volume. When light passes through a highly turbid medium, some photons pass straight through without scattering (see Fig. 2a). These few photons are termed “ballistic.” Because they travel the shortest path, they exit first (see Fig. 2b). A larger group of photons are scattered only once or twice; termed “snake” photons, they exit the medium traveling in the same direction as the input light but with a somewhat larger solid angle. Photons exiting the medium that have encountered multiple scattering events, “diffuse photons” are the most numerous in materials with a high extinction coefficient. However, these photons are scattered into a very large solid angle and exit last.

![Figure 2. Ballistic, snake, and diffuse photons.](image)

The undisturbed path of ballistic photons allow the retention of intact image information of structures that may be embedded within the turbid medium. The ballistic photons can provide a diffraction-limited shadowgram image of these structures.

The problem of obtaining a high-resolution image through highly scattering materials is thus a matter of eliminating the diffuse light from the ballistic and snake light. This can be done using discrimination methods that make use of the properties of the transmitted light. For example, propagation direction, exit time, polarization, and coherence properties can all be used for segregation.

The ballistic imaging system was optimized to provide high resolution, single-shot images of the liquid core in very dense atomizing sprays using time gating [6]. In time gating, a very fast shutter consisting of an optical Kerr effect (OKE) gate [8] capable of as short as 2-ps gating times is used to select just the leading edge of the transmitted light pulse and reject the later, multiply scattered photons. Additionally, the geometry of the OKE gate employed here creates a spatial and polarization gating effects. These effects are detailed in [9]. The complete system used for this work is shown in Figure 3.

![Figure 3. The ballistic imaging system.](image)

A jet-in-crossflow test apparatus was developed to demonstrate the diagnostic in a relevant flowfield. The crossflow is generated by a 4.1 hp centrifugal fan which supplies air to a straight test channel, 3.1m in length, with internal dimensions of 86 x 86 mm. The liquid jet is generated by means of a pressurized accumulator which supplies a non-turbulent flow of water to a plain-orifice atomizer nozzle. This delivery system supplies a steady, non-turbulent flow to the nozzle, and was built to match a system designed by the University of California Irvine Combustion Laboratory [10].

Various rates were chosen to provide Weber numbers relevant to the model presented by Madabhushi et al.[1] The specific properties of each flow studied are detailed in Table 1, where the Reynolds number (Re) of the liquid is given by:

$$\text{Re}_l \equiv \frac{u_d d}{\nu}$$  

(2)
Jet in Crossflow Image Analysis

The study of a dynamic, turbulent, unsteady system, such as a jet in crossflow, often requires a great number of instantaneous (single-shot) measurements to fully describe the range and modes of operation for the system. By acquiring a large data set, a statistically significant number of measurements can be examined to show average parameter values and system behavior. This approach, while effective, can result in difficult or untenable data analysis burdens. For the case of spray imaging in general, and ballistic imaging specifically, this situation necessitates the use of automated image analysis software tools.

Image analysis for the work presented here was carried out using Xflow, a free software package utilizing the MatLab image processing routines, and developed specifically for ballistic images of jets in crossflow. This MatLab code is licensed under the lesser GNU public license and can be freely distributed and edited to deal specifically with any type of spray image. The analysis for jet-in-crossflow images relies on threshold and connectivity segmentation of image regions and focuses on five interrelated image features: the main jet, resolved drops, resolved voids, the periodic structure on the upstream jet profile, and a droplet distribution determined by fitting measurement data.

The main jet is defined as the largest connected object in the image, as such this feature encompasses the jet and any attached ligaments. The direction of jet propagation is from the top of the image down, and the direction of the crossflow is from left to right.

Drops are defined as liquid regions appearing in the image distinct from the main jet. Drop areas are assumed to be spherical cross-sections for determination of drop diameters, and drop-like features with diameters smaller than the resolution limit of the imaging optics are excluded from this feature set.

voids are low-signal regions appearing within the main jet or within large drops. Void areas are also assumed to be spherical cross-sections for determining void diameters, and void-like features below the resolution limit are likewise excluded from the analysis.

Periodic structure is defined as variation from an exponential-fit baseline, calculated from the windward jet profile. The peaks of this “variation curve” indicate gas-liquid shear layer disturbances on the windward face of the jet. This potentially allows frequency analysis of the variation curve to be related to models and theoretical predictions for gas-liquid shear layer instabilities.

Further characterization of the spray breakup conditions and drop sizes is accomplished by fitting the available drop size information from many images to a modified Rosin-Rammler distribution. Care should be taken to ensure the images for this analysis are of high quality, adequately represent the spray under observation, and are generated under the same run conditions to ensure an accurate determination of the representative drop distribution.

Threshold and connectivity segmentation is an appropriate choice for separating structures in ballistic images, due to the nature of the jet-in-crossflow spatial features. However, the choice of threshold level can be a point of concern. High quality images with good signal-to-noise levels are, to some degree, insensitive to changes in detection threshold. In contrast, images with significant noise levels can be sensitive to small changes in threshold, leading to large uncertainties in the segmentation results. To address this concern, the threshold level used in this work is a dynamic parameter calculated individually for each image, using a method suggested by Otsu [11]. Here, the choice of threshold level is based on an algorithm that minimizes the intraclass variance of the light and dark pixels.

### Table 1. Jet run conditions.

<table>
<thead>
<tr>
<th>Case no.</th>
<th>Nozzle (mm)</th>
<th>(u_g) (m/s)</th>
<th>(u_l) (m/s)</th>
<th>(We_g)</th>
<th>(Re_l)</th>
<th>Mom. flux ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.5</td>
<td>72</td>
<td>21</td>
<td>130</td>
<td>10k</td>
<td>68</td>
</tr>
<tr>
<td>2</td>
<td>0.5</td>
<td>48</td>
<td>21</td>
<td>58</td>
<td>10k</td>
<td>153</td>
</tr>
<tr>
<td>3</td>
<td>0.7</td>
<td>72</td>
<td>21</td>
<td>181</td>
<td>15k</td>
<td>68</td>
</tr>
<tr>
<td>4</td>
<td>0.7</td>
<td>48</td>
<td>21</td>
<td>81</td>
<td>15k</td>
<td>153</td>
</tr>
<tr>
<td>5</td>
<td>1.0</td>
<td>72</td>
<td>21</td>
<td>259</td>
<td>21k</td>
<td>68</td>
</tr>
<tr>
<td>6</td>
<td>1.0</td>
<td>48</td>
<td>21</td>
<td>115</td>
<td>21k</td>
<td>153</td>
</tr>
<tr>
<td>7</td>
<td>0.5</td>
<td>67</td>
<td>15</td>
<td>112</td>
<td>7k</td>
<td>40</td>
</tr>
<tr>
<td>8</td>
<td>0.5</td>
<td>62</td>
<td>13.5</td>
<td>96</td>
<td>7k</td>
<td>38</td>
</tr>
<tr>
<td>9</td>
<td>0.5</td>
<td>48</td>
<td>10.4</td>
<td>58</td>
<td>5k</td>
<td>37</td>
</tr>
<tr>
<td>10</td>
<td>1.25</td>
<td>72</td>
<td>21</td>
<td>324</td>
<td>26k</td>
<td>68</td>
</tr>
</tbody>
</table>

Results and Discussion

An example image for Case no. 5 is shown in Figure 4. The field of view is approximately 6 mm. In the image, one can see dark areas representing a continuous fluid phase and light areas representing the gas phase. The plain-orifice inlet nozzle is located at the top of the image in Figure 4. The jet issued from the top, and one can see some of the liquid being stripped away from the main jet as it flows downward. A small amount of laser speckle that is smaller than the resolution limit of the system can be seen in the gas-phase portion of the image (see notation in Figure 4). These should not be in-
interpreted as small droplets. It is important to note that this spray was quite dense to normal imaging techniques. Interesting features in Figure 5 include the appearance of periodic structures along the jet column, evidence of aerodynamic stripping of the jet, and the formation of ligaments, and non-spherical primary droplets. Selected statistics from the images collected are presented in Table 2. Composite images, showing the entire spatial extent of the measurements for each run condition, are shown below. Figure 7 shows composite images for cases 1 through 5, and Figure 8 shows cases 6 through 9.

It is apparent on examining the composite images, that different breakup mechanisms are more active in some cases than in others. Cases 3 and 4 (see Figure 7), for example, exhibit little or no periodic structure on the entire length of their upstream jet profiles, indicating that a surface breakup mechanism may be dominant under these run conditions.

Drop size analysis for optically dense spray regions is possible with ballistic imaging under some conditions. However, this analysis is not straightforward for non-symmetric sprays, or sprays that are poorly described by simple drop distribution functions. Selected analysis results for cases 1 through 5 are shown in Table 2. The Sauter mean diameters shown here are derived by fitting drop size information to a modified Rosin-Rammler distribution. It is important to consider the field of view encompassed by the data set in both the drop size calculation and when comparing results across data sets.

Figure 5 shows periodic structure taken from upstream jet profile in the example image shown in Figure 4. The curve values are determined first by fitting an exponential baseline to the boundary pixels which form the upstream profile of the jet. The boundary pixels are then ordered, by tracing the upstream profile of the jet downward from the inlet, forming a profile curve referenced to the edge of the image. This profile is differenced with the calculated baseline to form a level curve with peaks representing the structure of the upstream jet profile.

The important frequency components of this profile curve can be examined directly by taking the discrete Fourier transform. The Fourier transform of the profile curve from Figure 5 is shown below in Figure 6. The length of one pixel in the source image for Figures 4, 5, and 6 is approximately 9 µm.

Table 2. Results extracted from the images.

<table>
<thead>
<tr>
<th>Case no.</th>
<th>Ave. no. Drops</th>
<th>SMD (µm)</th>
<th>We₉</th>
<th>Distance from inlet (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>128</td>
<td>72</td>
<td>130</td>
<td>4.5</td>
</tr>
<tr>
<td>2</td>
<td>155</td>
<td>100</td>
<td>58</td>
<td>4.5</td>
</tr>
<tr>
<td>3</td>
<td>175</td>
<td>95</td>
<td>181</td>
<td>9</td>
</tr>
<tr>
<td>4</td>
<td>90</td>
<td>64</td>
<td>81</td>
<td>9</td>
</tr>
<tr>
<td>5</td>
<td>80</td>
<td>101</td>
<td>259</td>
<td>6</td>
</tr>
</tbody>
</table>

Figure 5. Upstream jet profile for the “periodic structure” region shown in Figure 4.
Figure 4. Fourier transform results for the “variation curve” shown in Figure 4.

Conclusions

Ballistic imaging is well suited for imaging in turbid media where traditional imaging techniques are ineffective. This work shows that single-shot ballistic imaging can provide insight into primary breakup phenomena for dense sprays. Using this technique, it is possible to obtain high resolution images in dense spray regions revealing important fluid structures and interactions that are not visible with conventional techniques. With properly applied image analysis, it is also possible to estimate parameters such as drop size and frequency information present in some atomization regimes.

Acknowledgements

Support for the experimental work described above was provided by a grant from the US Air Force Research Lab under contract number FA8650-04-M-2442. Some of the equipment used was provided by Army Research Office via ARO Project Number DAAD19-02-1-0221. Mr. Sedarsky is supported by the Swedish Vetenskapsrådet (621-2004-5504) and Dr. Paciaroni was supported by the Swedish Statens Energimyndigheten (CECOST Fellowship).

Nomenclature

\( \rho_g \) gas density \( [kg/m^3] \)
\( u_g \) gas velocity \( [m/s] \)
\( u_l \) gas velocity \( [m/s] \)
\( d \) jet orifice diameter \( [m] \)
\( \sigma_l \) surface tension \( [N/m] \)
\( \nu \) kinematic viscosity \( [m^2/s] \)
\( We_g \) Weber number
\( Re_l \) Reynolds number
\( J \) Momentum flux ratio

References

Figure 5. Composite images for run conditions 1 through 5.
Figure 6. Composite images for run conditions 6 through 9.