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BALLISTIC IMAGING OF THE NEAR FIELD FOR JETS IN GASEOUS CROSSFLOW

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ABSTRACT This paper focuses upon steady, liquid sprays in crossflow, relevant to fuel injection within a lean, premixed, prevaporized (LPP) gas turbine duct for 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 (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").

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. Even the most advanced models still do not account for other 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 can meet this need, providing high resolution, single-shot images of the liquid core in a dense spray.

A time-gated ballistic imaging instrument is used here 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 and present images and statistics for various jet in crossflow experimental conditions (e.g. different Weber numbers). Series of these images reveal a near-nozzle flow field undergoing breakup and subsequent droplet formation via stripping. Signal from droplets smaller than the resolution limit of the imaging system is visible in the areas between resolved droplets. This unresolved signal is essentially a measure of local extinction in the image. It is important to note that apparent features inside the jet and droplets cannot be interpreted as extinction features or refraction features as normally seen in shadowgraphy. Apparent features in the jet and droplets are due to noise sources such as edge diffraction. An extension of ballistic imaging to detect the velocity of the liquid gas interface of a droplet is also demonstrated. In addition, we describe a simple extension that will provide images of the force vectors that act to break apart intact liquid features in sprays.

Keywords: Ballistic Imaging, Primary Breakup, Dense Sprays, Laser Diagnostics, Imaging

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. 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. 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 ("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 ("surface stripping"). The relevant global parameter used to capture this balance of forces is the jet Weber number based on the gas density (ρ_g), gas velocity (u_g), jet-orifice diameter (d), and liquid surface tension (σ_l):

$$We_g = \frac{\rho_g u_g^2 d}{\sigma_l}$$

Gas-turbine-based jets in crossflow typically operate in the range of $100 < We_g < 2000$, 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 [9]. 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.

2. SPECIFIC OBJECTIVES

The purpose of the work we present here is to demonstrate the utility of ballistic imaging to obtain high resolution images of the core of a dense spray; a task which is not possible using conventional imaging techniques. In this work we applied ballistic imaging to a water 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 velocity and local extinction information present in the ballistic image data. This analysis is briefly outlined, and the resulting velocity and extinction data are shown.

3. 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 to shadowgraphy. When light passes through a highly turbid medium, some photons can 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 also scattered into a very large solid angle and exit last. 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 image of these structures.

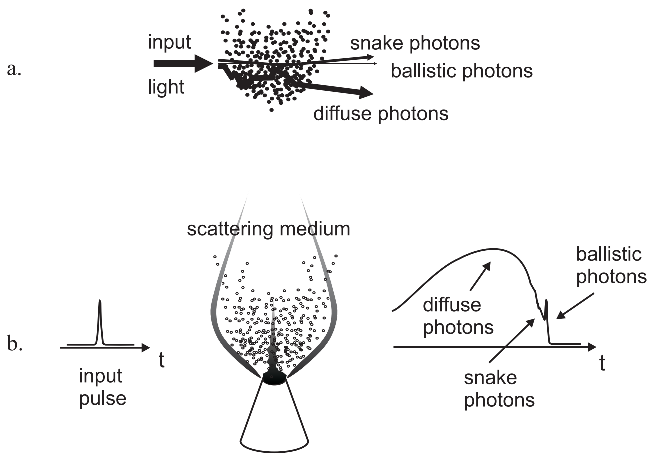

Fig. 2. Ballistic, snake, and diffuse photons.

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 [6] using spatial filtering (to select the light exiting at narrow scattering angles) together with time gating. In time gating, a very fast shutter consisting of an optical Kerr effect (OKE) gate [11] 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. The complete system used for this work is shown in Fig. 3.

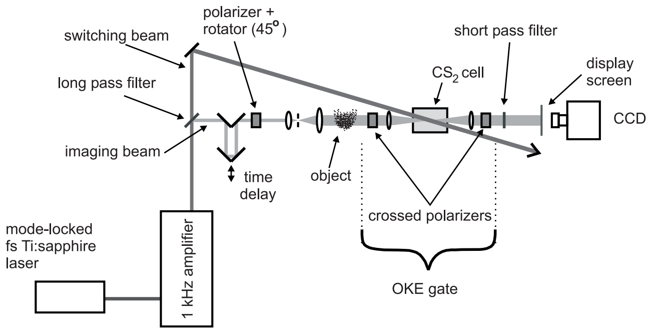

Fig. 3. The ballistic imaging system.

A 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 15 minutes of steady spray time (see Fig. 4). A second nitrogen bottle was used to supply a controlled crossflow. Two simple water nozzles were built to emulate the cases studied by Madabhushi *et al.*[1]. A more extensive description of the jet and crossflow construction and calibration is detailed in an earlier paper [7].

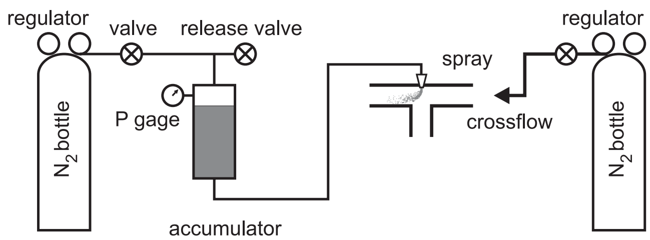

Fig. 4. Jet-in-crossflow apparatus.

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 of the liquid is given by $\mathrm{Re}_l \equiv (u_l d / \nu)$ (where ν is the kinematic viscosity), and the momentum flux ratio is given by $(\rho_l u_l)^2 / (\rho_g u_g)^2$.

4. RESULTS AND DISCUSSION

An example image for Case no. 2 is shown in Fig. 5. The field of view is ~6 mm. In the image, one can see dark areas representing a continuous fluid phase and light areas representing the gas phase. The top of the image in Fig. 5 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. 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 Fig. 5). These should not be interpreted as small droplets. It is important to note that this spray was quite dense to normal imaging techniques. Interesting features in Fig. 5 include expansion of the liquid core cross-section as it moves downstream, deflection and deformation of the jet, appearance of periodic structures along the jet column, evidence of aerodynamic stripping of the jet, and the formation of ligaments, non-spherical primary droplets, and voids. Statistics taken from the entire collection of images are presented in Table 2.

Table 1. Jet run conditions.

Case no.	Jet dia. (mm)	Gas Velocity (m/s)	Liquid Velocity (m/s)	We_g	Re_l	Mom. flux ratio
1	1.27	50.8	67.0	58	89k	1344
2	1.27	74.3	99.4	124	133k	1383
3	1.27	73.4	96.0	121	128k	1322
4	1.27	93.0	123.3	194	164k	1360
5	1.27	102.5	136.9	236	183k	1378

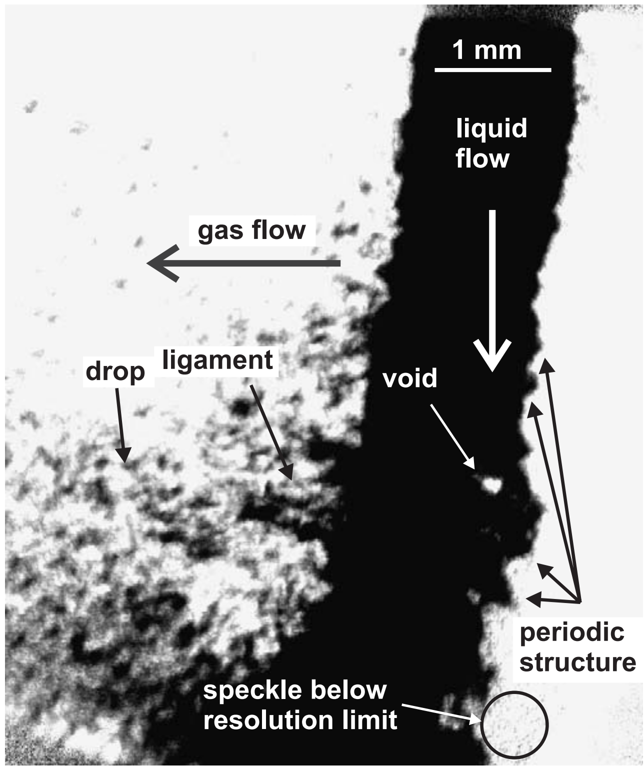

Fig. 5. Example image for case no. 2.

Table 2. Results extracted from the images.

Case no.	Ave. no. Drops	SMD (μm)	Run no.*
1	20	91	9
2	56	48	4
3	66	141	20
4	20	220	12
5	39	224	6

* specific 50 image data set analyzed for each case

A local extinction image for Case no. 2 is shown in Fig. 6. Analysis of a ballistic image in this fashion was first proposed by Terry Parker [8] in 2005. This image is obtained by normalizing the intensity data of a ballistic image to the background intensity detected in an upstream region containing no liquid-phase particles. The natural logarithm of this normalized intensity is taken, yielding an intensity signal that is proportional to extinction. This demonstrates that one can extract the droplet volume fraction for the unresolved droplets simultaneously with the resolved features in the ballistic images. The black line in the figure is included to mark the division between the resolved liquid features and the areas which contain no resolved droplets. Apparent features inside the black division are due to noise sources. These sources include edge diffraction from the jet and surrounding visible droplets and stray refracted or scattered light from elsewhere in imaged region. These false features appear even in solid objects imaged with the ballistic imaging system, such as the nozzle of the spray apparatus. Using the same cross-flow and ballistic imaging arrangement, we shut off the gas flow and slowed the liquid to a steady drip in order to acquire images for velocity analysis. This was required because the laser system emitted pulses at 1 kHz, and normal fluid flows are much faster than that. Steady drips, however, can be acquired with 1 ms time separation. The application of this technique to faster fluid structures simply requires a faster, commercially available laser system.

For the analysis we acquire a pairs of ballistic images with a known time separation. Applying image analysis algorithms, we extract large features from image 1, and correlate them with features extracted from image 2. This allows us to calculate the bulk motion of the large features. With this information we can correctly place correlation windows to calculate the small-scale motion of the drop/jet edges. This method is discussed in greater detail in a paper by Sedarsky, *et al.*[10] Results of this analysis are shown in Fig. 6. This method is effective in determining velocity information from pairs of ballistic images, provided the image time separation is small enough to allow for good feature correlation. If one could obtain three images taken at sufficiently short intervals, it would be possible to apply a similar method to obtain acceleration vectors. From acceleration data, given some knowledge about the composition of the liquid and gas under observation, one can determine forces acting on the features tracked by this method.

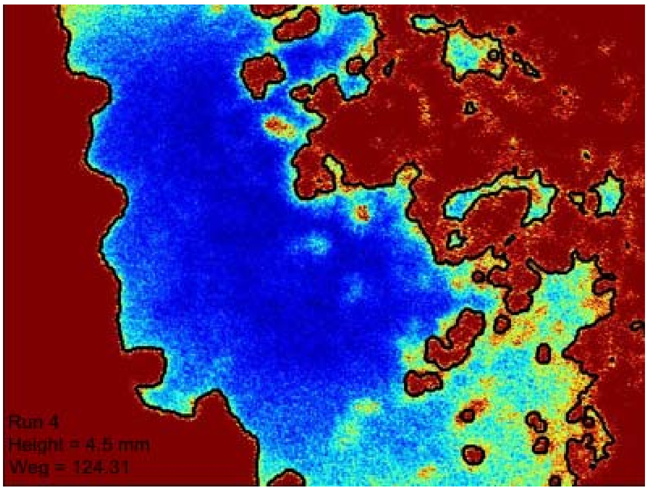

Fig. 6. Extinction image of water-jet in crossflow.

5. CONCLUSIONS

Ballistic imaging has tremendous potential 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. With this technique it is now possible to obtain high resolution images of the core of a dense spray, and using image analysis techniques, it is possible to extract velocity and acceleration information which reveal the forces driving primary breakup. In addition, ballistic images can provide insight into breakup and spray structure between resolved liquid-phase features by extracting droplet volume fraction in these regions.

6. ACKNOWLEDGEMENTS

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7. NOMENCLATURE

ρ_g	gas density	[kg/m^3]
u_g	gas velocity	[m/s]
d	jet orifice diameter	[m]
σ_l	surface tension	[N/m]
We_g	Weber number	[kg/m^3]
Re_l	Reynolds number	[kg/m^3]
ν	kinematic viscosity	[m^2/s]

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