Recent Developments in Experimental Methods for Quantification of High-speed, Aerodynamically Driven Liquid Breakup

D.R. Guildenbecher
Sandia National Laboratories
Albuquerque, NM 87185 USA

Abstract
The breakup of liquids due to aerodynamic forces has been experimentally investigated for many decades. Despite the large body of work, few investigations have quantified secondary droplet sizes and velocities, especially near the site of breakup. This is mostly due to experimental challenges and the limited temporal resolution of historical diagnostics. This work summarizes our recent efforts to develop and apply new diagnostics for these challenging multiphase flows. We begin by reviewing previous work including our own using traditional imaging and phase Doppler anemometry of the breakup of liquid drops in a cross-flow. Next, we discuss the development and application of digital in-line holography (DIH) for these flows. This method provides 3D realization of secondary droplet positions and sizes in a large measurement volume. Finally, we discuss new work extending the DIH diagnostic to kHz repetition rates. This method has been applied to study the fragmentation of a 1 mm liquid column in cross flows of atmospheric air up to ~70 m/s. Measured quantities include secondary droplet 3D positions, in-plane morphologies, and three-component velocities all at 100 kHz. The data from these new diagnostics will be useful for development and validation of atomization models.
**Introduction**

The transformation of a bulk liquid into a disperse spray has been widely studied with hundreds if not thousands of scientific publications spanning at least the last century. To simplify investigation, the process is often divided into a number of sub-processes as illustrated in Figure 1. Each of these sub-processes has itself been widely investigated and a number of diagnostic tools have been developed to address their unique challenges. Despite this body of work, a complete understanding and predictive modeling of these complex, multiphase processes remains elusive.

This work presents a review, from the perspective of the author’s own efforts, of the diagnostic tools which have been developed for multiphase flows of this nature. Particular emphasis is placed on diagnostics of aerodynamic breakup of liquid drops, sometimes referred to a secondary breakup. Figure 2 shows example experimental images of the process [1]. Here an initially spherical drop of diameter \( d_0 \) falls into an air steam which flows from left to right across the field of view. Aerodynamic forces cause the drop to deform and eventually fragment into many secondary droplets. For liquids of low viscosity, such as those studied here, this process is typical characterized by the non-dimensional Weber number, \( We = \rho d_0 v_0^2 / \sigma \), where \( \rho \) is the gas-phase density, \( v_0 \) is the relative gas velocity, and \( \sigma \) is the interfacial surface tension. As illustrated in Figure 2 various breakup morphologies are typically observed as \( We \) increases.

Aerodynamic breakup of this nature has itself been widely studied as summarized in a number of recent review articles [2-5]. However, relatively few experimental investigations of the secondary droplet sizes, velocities, and spatial distribution have been performed. This is likely due to the experimental challenges presented by this flow. In particular, as shown in Figure 2, the process is highly transient, results in a wide range of secondary droplet sizes including highly non-spherical structures, and disperses drops over a relatively large volume. As is discussed later in this work, these issues present extreme challenges for many of the common, commercially available spray diagnostics. Consequently, continued diagnostic development is needed to better resolve this flow.

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**Figure 1.** Stages of a canonical spray process

<table>
<thead>
<tr>
<th>Start</th>
<th>Initiation</th>
<th>Deformation</th>
<th>Fragmentation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vibrational (no breakup) (( We \leq 9 ))</td>
<td></td>
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<tr>
<td>Bag (( 9 &lt; We &lt; 15 ))</td>
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<tr>
<td>Multimode (( 15 \leq We \leq 31 ))</td>
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<tr>
<td>Sheet-thinning (( We \geq 31 ))</td>
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**Figure 2.** Shadowgraphs of ethanol drops undergoing aerodynamic fragmentation. Time increases from left to right, disruptive forces increase from top to bottom. Images are from Guildenbecher and Sojka [1].
This work begins with a brief review of widely available diagnostics for these environments including laser diffraction methods, phase Doppler anemometry, and imaging. Some of the advantages and challenges of each technique are highlighted. The second half of the discussion considers the author’s more recent work on digital in-line holography (DIH). This method is shown to have its own distinct advantages and challenges. Finally, the work concludes with an outlook on future diagnostic development.

While the work presented here emphasis investigation of aerodynamic breakup, many of the diagnostics tools discussed are applicable to several of the other spray processes shown in Figure 1. For example, the primary breakup of the liquid and potentially the target interaction regions also produce disperse non-spherical droplets whose size and velocity must be quantified. Many of the lessons discussed here can be applied to those regions as well.

Finally, before proceeding, it is emphasized that this work focuses heavily on the author’s own experiences. This paper is by no means a complete review of all diagnostics. Even those methods, which are discussed, are generally only considered with respect to the author’s own work. For additional details and more in-depth reviews the reader is referred to the large body of literature, e.g. [6-9].

Common Diagnostic Methods
The literature contains many diagnostics for measurement of drop properties. In some early work, wax and other liquids were sprayed and subsequently cooled to effectively freeze drops mid-flight. This allowed droplets to be collected and analyzed under a microscope. However, these techniques are rather obtrusive and can generally only be applied to specialized liquids such as wax or metals which tend to freeze at or near room temperature. Rather, the vast majority of diagnostics attempt to quantify drop properties in-flight using non-obtrusive methods. Most of these utilize optical principles. With the invention of the laser and photodetectors in the second half of the twentieth century, a wide range of methods have been proposed which take advantage of the unique directionality and coherence of lasers to probe drop properties. Here we review a few of the most popular and commercially available techniques currently in use.

Laser Diffraction (LD)
When collimated and coherent light propagates over a particle, the wavelike properties of light result in a diffraction pattern with a spatial intensity distribution that is a function of the particle size. In a laser diffraction (LD) instrument, a collimated laser beam is propagated through a polydisperse particle field. The diffraction patterns from each particle are summed together using a Fourier lens and the resulting spatial intensity pattern is recorded on a specially designed logarithmic detector. Under the assumption that the particles are spherical, a theoretical model can be constructed which describes the spatial intensity pattern as a function of the particle size distribution (p.s.d.). To find the p.s.d., inversion techniques are used to fit the measured intensity pattern to this model using an assumed functional form of the p.s.d. (e.g. log-normal, gamma, etc.)

A number of LD instruments are commercially available. In practice they consist of a transmitter (laser) and receiver, often mounted together on a common rail. To use the instrument, a spray is positioned between the transmitter and receiver such that the laser beam propagates through the spray field. The instrument provides a measure of the line-of-sight averaged p.s.d.

LD instruments have a number of advantages. They are relatively robust, easy to use, and can have a fast sampling rate (up to kHz). However, they do not provide detailed spatial information. In addition, they provide no measure of velocity and may be subject to size-velocity biases. Furthermore, because data fitting routines rely on spherical models, LD instruments may provide inaccurate results for non-spherical drops. As shown in Figure 2, some highly non-spherical structures are present during the course of drop breakup. Due to these drawbacks, it appears that LD instruments are ill-suited to this problem, and the author has never attempted such a measurement. Nevertheless, it is important to note that LD instruments have found extensive use in industrial process monitoring and for scientific applications where a line-of-sight mean size distribution is acceptable and particle sphericity is well-understood (e.g. aerosol characterization, micro-particle studies, etc.).

Phase Doppler Anemometry (PDA)
For more detailed investigation of secondary drop properties, it is desirable to have simultaneous size and velocity measurements at a point. This can be achieved with Phase Doppler Anemometry (PDA). PDA was introduced as an extension of Laser Doppler Velocimetry (LDV). In LDV, two coherent laser beams are made to cross at a point. The intersection of the laser beams defines the measurement volume which can often be a few hundred microns in dimension. Coherent interference of the two beams results in alternating light and dark fringes, with spatial frequency that can be calculated from the beam crossing angle and laser properties. When a particle travels through these fringes, light is scattered and collected by a receiver. By measuring the temporal frequency of the scattered light, the velocity of individual particles can be measured. In PDA, two separate receivers are utilized with a known angle between them. Assuming spherical particles, the temporal
phase difference between the light scattered into the two receivers can be related through geometric optics to the particle diameter. Therefore, a PDA instrument uses two or more receivers to measure the diameter and velocity of individual particles as they pass through the measurement volume.

Various PDA instruments are commercially available. In practice, they often consist of multiple lasers crossed in orthogonal planes which enable simultaneous measurement of two or even three components of velocity. In addition, it is common to have two or more receiver pairs with different collection angles. This increases the particle size dynamic range and provides some ability to reject non-spherical particles. Commercial PDA processors consist of fast analog and digital signal processing which allows for measurement of individual particle sizes and velocities at kHz rates.

Some of the author’s first attempts to quantify the secondary droplets in Figure 2 were performed with a PDA instrument [10]. Because PDA measures individual drops at a point, it was necessary to repeat the flow many thousands of times in order sufficiently quantify the statistics of the secondary drops. This was achieved by injecting a continuous stream of initial drops into an air jet using the configuration show in Figure 3. (Note, much of the measurements discussed throughout the remainder of this work were acquired with this facility [10-14]. Consequently, it is possible to provide quantitative comparison between many of the diagnostics. Furthermore, taken together these measurements result in a well-defined flow for model development and validation.)

Because PDA is limited to the measurement of spherical droplets, it was decided to place the PDA measurement volume at a far downstream position \((x = 150 \text{ mm}, \ y = -17 \text{ mm}, \ z = 0 \text{ mm})\), with the coordinate system shown in Figure 3) where the initial drop had completely fragmented and all secondary droplets appeared spherical in images of the flow. After running the facility for a lengthy time, over 11000 drops were measured with the PDA, resulting in the size distribution shown by the red dotted line in Figure 4 [10].

These results demonstrate that PDA can be used to quantify this flow. However, there are a number of limitations. Most importantly, as already mentioned PDA is only capable of measuring spherical droplets and is therefore ill-suited to measurements near the site of breakup where many of the drops are non-spherical. In addition, because PDA is a point measurement technique, significant experimental repetition would be needed to quantify ensemble spatial or temporal statistics or to quantify other flow conditions. We attempted such measurements at various times but with limited success due to the extremely long experimental durations required. Consequently, we have found that PDA is a good technique for comparison and validation of other diagnostics (as discussed in later sections). However, it is ill-suited as the main diagnostic for this flow.

Image Analysis

Finally, many labs have access to photography equipment, including high-speed cameras, capable of acquiring images of the flow similar to those in Figure 2. With appropriately defined image processing routines, it is possible detect continuous regions and quantify their in-plane sizes and velocities. Again, a number of commercial software packages are available to perform these tasks.

In Flock et al. [11] and Kulkarni et al. [12] we used image analysis to quantify the initial trajectory and deformation of the drops shown in Figure 2. These data provide detailed initial and boundary conditions useful for modeling. However, due to the limitations caused by the depth of focus we chose not to try to quantify the secondary droplet properties using these methods. As seen in Figure 2 many of the secondary drops are out of focus and quantification of the size distribution from these images would be susceptible to this bias.

Nevertheless, with increased magnification and careful selection of the depth of field, it might be possible to quantify secondary droplets from images of the flow. However, in light of our recent developments in digital holography, discussed in the remainder of this work, we believe that such measurements are no longer necessary.

**Figure 3.** Continuous air-jet facility for investigation of aerodynamic breakup of liquid drops. Image from Flock et al. [11].

**Figure 4.** Size distribution measured by PDA and DIH [10].
Holography

Background

Holography is an optical technique which allows for three-dimensional imaging of a scene. The technique was first proposed by Gabor [15] in 1948 before the invention of the laser. With development of the laser, holography became a topic of intense research.

In laser holography, a coherent laser beam is made to propagate through or reflect off an object. This results in a change in the phase and amplitude of the light. To capture this, a second reference beam is made to interfere with the scattered object beam forming interference fringes of light and dark intensity. Traditionally, these interference fringes were recorded on a photographic plate. After wet chemical processing to fix the image, the hologram would again be exposed to the reference wave. Diffraction caused by interaction of the reference wave with the hologram would result in the formation of a conjugate object wave. Finally, this would form a three-dimensional (3D) image of the object at the original location(s).

Holography has been used for a number of applications, including extensive use for investigation of particles. Faeth and co-workers [16-20] were perhaps the first to use holography to investigate aerodynamic breakup of liquids as discussed here. In those works, an off-axis holography configuration was used to record a hologram on a photographic plate. Holograms were reconstructed on a viewing screen and, in what must have been a time consuming process, individual drops were manually measured at their in focus location.

Digital in-line holography (DIH)

Digital holography refers to the use of digital sensors (CCD or CMOS) to record the hologram and numerical processing to perform the refocusing steps [21]. By eliminating wet chemical processing and optical reconstruction, the experimental process is greatly simplified. In addition, cameras (double exposure or video) can be used to achieve temporal resolution of the scene. Because of these advantages, digital holography has revolutionized measurements for a wide range of applications, including extensive use for particles [22].

Compared to traditional photographic plates, digital sensors have significantly less spatial resolution. As a consequence, the high spatial frequency fringes created by an off-axis reference wave are not easily resolved. This necessitates the use of an in-line configuration as shown in Figure 5. Here is it assumed that the particle field under investigation is sufficiently dilute such that a significant amount of the original collimated beam propagates to the sensor undisturbed, forming the reference wave. A vast majority of the investigations of particles and spray fields use this Digital in-line holography (DIH) configuration.

Figure 5. Basic configuration for digital in-line holography (DIH) of a particle field.

The author’s first application of DIH for investigation of aerodynamic breakup is detailed in Gao et al. [10]. There, an experimental arrangement very similar to Figure 5 was used to record breakup at a condition comparable to the second row in Figure 2 (sometimes referred to as bag-type breakup). An example hologram is shown in Figure 6(a) along with a zoomed-in region in Figure 6(b). The diffraction patterns from the individual secondary droplets are easily observed along with a large diffraction pattern from the intact ring.

These images are numerically refocused by solving the diffraction integral equation given by

$$E(x, y; z) = \left[ I_0(x, y) E^*(x, y) \right] \otimes g(x, y; z), \quad (1)$$

where $E(x, y; z)$ is the reconstructed complex amplitude at optical depth, $z$; $I_0(x, y)$ is the recorded hologram; $x$ and $y$ are the spatial coordinates in the hologram plane (see Figure 5 for coordinate system); $E^*(x, y)$ is the conjugate reference wave (assumed constant for a plane wave); $\otimes$ is the convolution operation; and $g(x, y; z)$ is the diffraction kernel [21, 22]. Equation (1) is numerically evaluated to find $E(x, y; z)$ at any $z$, and the
The reconstructed light field is visualized using its amplitude \( A = |E| \). For example, Figure 6(c) and (d) show example amplitude images when the hologram is numerically refocused to the \( z \)-positions shown.

The optical arrangement and numerical refocusing shown in Figure 5 and Figure 6, respectively, are relatively straightforward. On the other hand, the definition and validation of processing algorithms to automatically extract the 3D positions and in-plane sizes of particles in these images requires significant research and development. Our own efforts along the lines have focused on methods which are computationally efficient and minimize the need for user-tunable parameters [23-26]. Validation has been performed using a number of known particle fields [23-26] and canonical flows [27].

With any processing method, the major challenge to overcome is the depth-focus-problem discussed in [22]. Due to the limited angular aperture from which particles are reconstructed, the out-of-focus, \( z \)-position has significantly higher uncertainty compared to the in-plane (\( x \)-\( y \)) positions. Validation of our own methods indicates that measured particle \( z \)-positions are accurate to within about one particle diameter. The literature contains a number of other particle localization methods. In [24] we attempted to compare the accuracy of some of these methods. There it was shown that depth accuracy is indeed a function of the chosen algorithm. Still, most methods are accurate to about 1-2 particle diameters. It is not yet clear which, if any, method will prove the most accurate and universally accepted, and it is likely that development of particle localization methods will remain an active area of research for some time to come.

Figure 7 shows the measured 3D particle positions and sizes measured from the hologram shown in Figure 6(a) [10]. In this case, two holograms of the flow were recorded with short inter-frame time (62 \( \mu \)s), and three-component (3C) particle velocities were determined by matching measured positions between the two reconstructed particle fields. In [10] the accuracy of the measurements were validated by comparing the total volume of measured secondary drops, including the volume of the ring shown in Figure 7, with the initial volume of the spherical drop. Agreement of those values with 2.2% indicates a high degree of accuracy. Furthermore, a magnified DIH configuration was used to record 18 holograms of the secondary drops produced from breakup of the bag. The blue line in Figure 4 shows the measured probability density function. Good agreement with the PDA measurement in red again confirms the accuracy of the results. Further details on these results are available in Gao et al. [10].

A number of advantages of DIH are apparent: (1) Due to the large effective measurement volume, DIH is able to quantify hundreds of drops from a single experimental realization. Consequently, compared to alternative methods such as PDA, DIH enables quantification of drop statistics with limited experimental repetition. (2) Unlike LD and PDA methods, DIH is able to accurately quantify highly non-spherical structures. As a result, DIH measurements can be performed very near the site of breakup. This can be a major advantage for development and validation of breakup models because uncertainty introduced by transport processes between the site of breakup and the measurement location are eliminated. (3) Finally, DIH provides detailed 3D spatial resolution, which is impossible to obtain on a single-shot basis for LD or PDA techniques.

**Stereo DIH**

Despite the clear advantage of DIH for this application, some challenges exist. As already mentioned, one of the most important challenges is the depth-of-focus problem. For velocity measurements, this results in significantly higher uncertainty in the out-of-plane, \( z \)-direction compared to the in-plane (\( x \)-\( y \)) directions. For example in Gao et al. [10] higher scatter in the measured \( z \)-velocities was observed compared to the \( y \)-velocities. Process symmetry dictates that these two quantities should be similar and the differences are likely due to the depth of focus effects. Without additional corrections, this effect significantly limits the usefulness of the out-of-plane velocity component measured with DIH.

To address this Gao et al. [13, 14] proposed the stereo DIH configuration shown in Figure 8 with example results shown in Figure 9. By adding a second field
of view it is possible to use the stereo relation to create an alternative measure of the $z$-velocity as detailed in [13]. The effectiveness of this method is illustrated in Figure 9. The left images show the measured in-plane (top) and out-of-plane (bottom) particle positions and velocities using the classical single-view DIH configuration (equivalent to Figure 5). Here, the main air-flow direction is along the $x$-direction, and the highest velocity magnitudes are expected along this direction. The results from the single view configuration (left) clearly display many erroneous velocity vectors in the $z$-direction. On the other hand, with the stereo configuration and appropriate inter-view matching, the results shown on the right hand side of Figure 9 appear to be much more accurate.

**Figure 8.** Experimental configuration for cross-beam, two-view DIH of aerodynamic fragmentation [13, 14].

**Figure 9.** (Top) Size and $x$-$y$ velocities measured in the hologram plane and (bottom) $x$-$z$ velocities measured in the out-of-plane direction from (a) single DIH and (b) the crossed-beam two-view DIH configuration [14].
In addition to improving the accuracy of the measured out-of-plane, z-velocities we also find that stereo matching effectively eliminates erroneously detected regions. For example, see the large regions circled in red in the lower left corner of Figure 9(a). Due to their close proximity, multiple drops have been incorrectly detected as one large drop in the single-view DIH. These types of errors can significantly affect the measured mean diameters, particularly the volume weighted mean which weights individual particles by the cube of their diameter. In contrast in Figure 9(b) almost all of the falsely detected regions are eliminated. This is a consequence of the stereo matching which is also used to eliminate regions which have significantly different measured diameters in the two views.

Combined these advantages make the stereo-DIH configuration particularly useful for this application. In addition, the entire experimental configuration was constructed using the a double-pulsed Nd:YAG laser and interline transfer cameras which many laboratories already have for stereo particle image velocimetry (PIV). Consequently, this particular configuration is one that may prove very useful to others.

Figure 10 shows select results obtained with this configuration. These show the mean measured diameters recorded at two different We and multiple delay times (time between triggering of the photodiode shown in Figure 3 and recording of the DIH images). Each data point is constructed from 44 realizations of the flow with the uncertainty bars showing the standard deviation of the mean from each realization. These results illustrate how stereo-DIH can be applied to obtain detailed measurements of the flow with a high degree of accuracy. Further results, including velocity measurements are given in [14].

All of the DIH results discussed thus far have been obtained using the same experimental configuration (Figure 3). Throughout these works, we have attempted to investigate a common set of materials and operating conditions. (Although some experiments were performed years apart and some variations in conditions is inevitable). Combined, we believe these results present a uniquely detailed dataset for model derivation and validation. To summarize, Flock et al. [11] presents detailed quantification of initial drop trajectories and deformation; Kulkarni et al. [12] present further analysis of the deformation rates and times; Gao et al. [10] present 3D DIH and PDA measurements of bag breakup conditions; and Gao et al. [13, 14] present detailed temporal statistics of secondary droplet sizes and velocities for both the bag and sheet-thinning morphologies.

Figure 10. Evolution of the characteristic mean drop sizes quantified with the crossed-beam two-view DIH configuration: (a) number mean diameter and (b) mass median diameter (MMD). Uncertainty bars show the standard deviation measured from 44 realizations of the flow [14].

High-speed DIH

The DIH results presented thus far were obtained with low speed lasers and cameras (max 10 Hz repetition rate typical). With this it was only possible to obtain a single image (or two in double-exposure mode) per breakup event. Extension of the methods to kHz recording rates would enable detailed temporal quantification of breakup from single experimental realizations. Toward this end, Guildenbecher et al. [28] present new data processing methods for multi-frame tracking of particles from high-speed DIH recordings.

In additional work, Guildenbecher et al. [29] applied these methods to investigate the breakup of column of liquid water in a shock tube. Figure 11 shows example results. The top row shows sample DIH images from a recording at 100 kHz. In these experiments, an initially 1 mm diameter column of deionized water has been subjected to a step change in convective flow velocity of approximately 45 m/s. Images are shown at a slightly downstream location where the jet has begun to deform and fragment into secondary droplets. The middle row in Figure 11 shows the individual droplet trajectories which have been automatically tracked using the methods discussed in [28].
Figure 11. 100 kHz DIH recording of the breakup of a water jet in a shock tube. (top row) Example experimental holograms for $We = 33$, (middle row) the corresponding amplitude images which have been numerically refocused to $z = 80$ mm, and (bottom row) the measured particle sizes (circles) and in-plane velocities (arrows). The center of the field of view is 12 mm downstream of the initial jet centerline [29].

The results in Figure 11 demonstrate that camera technology and processing methods have matured to the point where detailed, 3D and temporal resolution of single breakup events is now possible. Additional results are presented in [29] where it is shown that these methods can be used to derived detailed statistics of secondary drop sizes, velocities, production rates, and mass flow rates. We are unaware of any other measurement technique that can achieve these results without significant experimental repetition. With further development and validation of processing methods and wide spread availability of high-speed cameras, we believe this technology may become a vital new tool for diagnostics of multiphase flows.

Finally, the discussion has demonstrated the many advantages of DIH for measurement of aerodynamic breakup. There are, of course, challenges as well. Perhaps most significant are the limitations on particle number density. As is clearly observed in Figure 11 (and to some extent in Figure 9) in regions of high particle number density, processing algorithms are challenged to separate and extract individual particles. In [26] we presented some potential methods to address these issues, although it is clear that much more algorithm development is needed to robustly separate individual particles in regions of high number density. Furthermore, at some point the number density may become so high that neighboring diffraction patterns strongly interfere with one another causing smearing and loss of information in the refocused images. (Some such effects may be occurring at locations near the intact water column in Figure 11.) To some extent it might be possible to improve these results using lasers with optimized (short) coherence lengths and/or non-linear optical methods. Regardless, DIH will always be challenged in regions of high number density.

Due to the many factors affecting the measurement, it is difficult to exactly quantify the particle density where DIH is no longer viable. However, from the author’s own experience, it seems that traditional LD and PDA are often capable of quantifying droplets in regions of high number density where DIH would likely fail. For this reason LD and PDA measurements will likely remain vital for industrial and applied sprays, while DIH and related methods may prove vital for improved quantification of detailed spray phenomena, such as the aerodynamic breakup of isolated drops studied here.

Conclusions

This work reviews various methods for quantification of drop statistics from the breakup of a liquid in an aerodynamic flow. Commercially available techniques, including laser diffraction and phase Doppler anemometry, are discussed but shown to be challenged by the transient nature of the flow and the presence of highly non-spherical structures. As an alternative, digital in-line holography (DIH) is presented. Specific advantages of DIH include the ability to quantify all particles in a large measurement volume on a single-shot basis, accurate measurement of non-spherical particles, and temporal resolution using double exposure or high-speed cameras. DIH results are presented which we believe are the most highly resolved measurements of aerody-
namic breakup available in the literature. These data should be critical for development and validation of new models.

Although the work presented here represents significant progress in the diagnostics of multiphase flows, much more work remains to be done. Development of DIH specifically requires further work to improve the accuracy and efficiency of particle localization algorithms. This is particularly true for high-speed DIH which is at its infancy.

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