MEASURING DROPLET SIZE OF AGRICULTURAL SPRAY NOZZLES—MEASUREMENT DISTANCE AND AIRSPEED EFFECTS

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With a number of new spray testing laboratories going into operation and each gearing up to measure spray atomization from agricultural spray nozzles using laser diffraction, establishing and following a set of scientific standard procedures is crucial to long-term data generation and standardization across the industry. It has long been recognized that while offering ease of use as compared to other methods, laser diffraction measurements do not account for measurement bias effects due to differential velocities between differing sized spray droplets, and in many cases significantly overestimate the fine droplet portion of the spray. Droplet sizes and velocities were measured for three agricultural flat fan nozzles (8002, 8008, and 6510) each at three spray pressures (138, 276, and 414 kPa) at four downstream distances (15.2, 30.5, 45.7, and 76.2 cm) across a range of concurrent air velocities (0.7–80.5 m/s). At air velocities below 6.7 m/s, large gradients in droplet velocities resulted in overestimation of both the 10% volume diameter ($D_{v0.1}$) by more than 10% and the percent volume of the spray less than 100 μm ($V_{<100}$) was overestimated two- to three-fold. The optimal measurement distance to reduce droplet measurement bias to less than 5% was found to be 30.5 cm with a concurrent air velocity of 6.7 m/s for measuring droplet size from ground nozzles. For aerial spray nozzles, the optimal distance was 45.7 cm. Use of these methods provides for more accurate droplet size data for use in efficacy testing and drift assessments, and significantly increases inter-lab reproducibility.

KEY WORDS: *spray atomization, laser diffraction, droplet size, agricultural sprays, application technology*

1. INTRODUCTION

Measurement of spray droplet size is a critical part of evaluating the performance of spray technologies. The resulting droplet size spectrum from any technology, or combination of technologies, drives both on-target deposition (Fritz et al., 2007; Himel, 1969; Salyani et al., 1988; Smith et al., 2000), as well as off-target movement and drift (Bouse, 1994; Hewitt, 2000; Hewitt et al., 2002). While there are a number of systems and methods available that are being used to measure agricultural spray droplet sizes, the type of measurement system (Dodge, 1987), test methods applied during the measurement process (Tishkoff, 1984) and differences in sampling areas from the different instruments (Hammond, 1981) can greatly influenc the fina results. Droplet sizing methods typically fall into two major classes—spatially and temporally derived data—which differ depending on differences in droplet size specifi velocities within a given spray (Lefebvre, 1989). Spatial sampling measurements result from observing a single volume over a short enough time span that the number and volume of spray droplets within the volume do not change (Lefebvre, 1989). In contrast, temporal samples observe individual droplets moving through a fi ed area within a fi ed time span, effectively accounting for the differing velocities of different-sized droplets (Lefebvre, 1989). While these two sampling methods can produce the same results if all droplets within a sampled spray are moving at the same velocity, typically smaller droplets (assuming an air stream velocity less than the droplet exit velocity) will decelerate more quickly than the larger droplets. This will result in a larger concentration of smaller droplets downstream of the nozzle and therefore spatially derived droplet size data tend to yield smaller mean diameters than temporally derived, which Frost and Lake (1981) called erroneous data.

This difference has been documented for agricultural sprays by a number of researchers, including Young and Bachalo (1988), Arnold (1990), Chapple et al. (1995), and Doble et al. (1985). Overall, Chapple et al. (1995) conclude that spatial sampling methods overestimate the small diameter fraction of the spray as compared to temporal sampling methods, which are not appropriate when collecting data for labeling, formula registration, and, most importantly, estimating or modeling potential drift.

The Spray Drift Task Force (SDTF) compared three nozzles at two liquid pressures, across airspeeds ranging from 0 to 54 m/s (SDTF, 1997), and found large spatial biases at airspeeds below 3 m/s and similar droplet sizes measured at 8 and 36 m/s (SDTF, 1997). These spatial biases were minimal at air stream velocities from 13 to 27 m/s as a result of the air stream velocity being close to the nozzle exit velocities. The fina conclusion of that work was that air stream velocities below 8–11 m/s should not be used with spatial sampling methods as a result of the large bias in over sampling the smallest droplet diameter portion of the spray (SDTF, 1997). Teske et al. (2002) noted that for atomization studies conducted with nozzles in air streams with velocities associated with aerial application conditions; this spatial bias error is only 2–5 percent.

While ideally, based on previous research,temporal sampling methods such as a PDPA would be used,the need for multiple, chordal traverses with these types of systems, versus a complete transect across the plume, make laser diffraction devices the more common choice. To address this issue of spatial versus temporal sampling with laser diffraction, and determine a set of standard methods and practices to be used for measuring agricultural sprays, a number of standards and methods have been proposed. The British Crop Production Council (BCPC) (Dobleet al., 1985), the American Society of Agricultural and Biological Engineers (ANSI/ASAE, 2009), and the American Society for Testing and Materials (ASTM, 2009) noted that there were differences between methods, which should be documented, or proposed relative classificatio schemes that classifie an unknown nozzle against a set of curves developed from established reference nozzles. The objective of these standards was to provide a method by which nozzles could be evaluated by multiple laboratories but retain similar relative classifica tions. However, these classificatio schemes and classes are now being ignored by many labs and nozzle producers, in favor of numerical size data, or are used as indicators of potential drift and for comparison of potential drift reduction from new technologies.

The issue of spatial sampling and the inherent bias with laser diffraction systems is well researched and documented with a number of groups proposing solutions to address these concerns. This work explored the degree of spatial bias on droplet size using the authors' present laboratory setup under a variety of measurement scenarios. The data collected provide a basis for establishing standard measurement methods for the specifie measurement facilities that, to what degree possible, alleviate the spatial sampling bias, for the majority of spray technologies tested. The objective was to determine the effects of airspeed and measurement distance on measured droplet velocities and on spatial and temporal droplet size and laser diffraction droplet size data. The results will help determine the most appropriate measurement protocols to minimize droplet sizing errors.

2. METHODS

This study examined three fla fan nozzles selected to cover a broad spectrum of droplet size ranges. Each nozzle was evaluated for droplet velocity at the nozzle and four downstream distances for three operating pressures. An imaging system was used to measure these velocities along with droplet size data. Using the measured droplet size and velocity data, both spatial and temporal distributions were determined and compared. Additionally, droplet size distributions were measured for each nozzle, pressure, and downstream distance using a laser diffraction instrument. The results are presented and discussed and a fina standard measurement protocol is presented. The specifi methods and procedures are discussed in the following sections.

2.1 Operational Setup – Nozzles and Wind Tunnels

All testing were conducted in the United States Department of Agriculture, Agricultural Research Service (USDA-ARS), Aerial Application Technology (AAT) group's low- and high-speed wind tunnels. The low-speed wind tunnel (1.2 m × 1.2 m × 12.2 m) has an operational capacity of 0–8 m/s, with airfl w generated from a 1 m diameter axial fl w fan. A set of corrugated fl w straighteners are positioned approximately 1.2 m downstream of the fan to insure minimum turbulence in the air stream. The tunnel is built in 2.4 m sections that can be disassembled and rearranged as needed. For this study, a 20 cm gap was created between the fina two sections (9.8 m downstream of the fan) to allow insertion of the measurement systems. A series of linear traverses were secured within the tunnel at 9.8 m from the fan. One traverse allowed for positioning a second vertical traverse with respect to distance from the plane of measurement. The nozzle body was positioned on the vertical traverse but offset 15 cm to prevent interference with airfl w. Sprayed material was carried through the last 2.4 m section of tunnel and exited the hanger that housed the tunnel (water-only spray solution). The high-speed wind tunnel has an operational range of 27–98 m/s through a 0.3 m × 0.3 m outlet. Airfl w is provided by a 1.3 m centrifugal fan powered by a 149 kW diesel engine. Air is directed through a 0.3 m × 0.3 m × 1.5 m tunnel section to an outlet. A fl w straightener consisting of 2.5 cm × 46 cm stacked tubes is positioned 1 m upstream of the outlet. A section of airfoil boom is mounted directly at the tunnel outlet on a vertical traverse to allow for positioning of the nozzle. A nozzle body and nozzle are affi ed on the center of the boom, which is then positioned such that the nozzle outlet is centered horizontally and vertically on the tunnel outlet.

Nozzles for both wind tunnels were fed from 19 L stainless steel pressure tanks that were pressurized using an air compressor. All plumbing and tubing from the tank to the nozzle were 6.4 mm or greater internal diameter to prevent fl w restrictions. Pressure was controlled via a pressure regulator and measured using an electronic pressure gauge (PX409-100GUSB, Omega Engineering, Stamford CT) that was positioned within 20 cm of the nozzle outlet. Three standard fla fan nozzles (8002, 8008, and 6510) were selected to provide a range of droplet sizes. Each nozzle was tested at three pressures [138, 276, and 414 kPa (20, 40, and 60 psi)]. Droplet size and velocities were measured at 15.2, 45.7, and 76.2 cm (6, 18, and 30 in) distance between the nozzle outlet and measurement plane. An additional measurement distance of 30.5 cm (12 inches) was conducted for the 0.67, 3.1, and 6.7 m/s airspeeds, which reflect a minimum distance between the nozzle and measurement plane for which large angle fla fan nozzles can practically be measured. Measurements were made at airspeeds of 0.67, 3.1, 6.7, 35.8, 53.6, 62.6, 71.5, and 80.5 m/s (1.5, 7, 15, 80, 120, 140, 160, and 180 mph).

2.2 Imaging System—LaVision

A LaVision Spray Master (LaVision Inc., Ypsilanti, MI) was used to measure both droplet size and velocity. Initially the system was setup in Particle Image Velocimetry (PIV) (LaVision, 2007a) mode to measure the flui exit velocity at the nozzle for each operating pressure. In this mode, the laser (532 nm Nd:YAG double pulsed) was operated as a light sheet with pulses 8 ns apart and a double-framed image taken in sync with the laser pulses. The supplied software processed the collected images and returnedan averaged vector fiel showing mean droplet magnitude and direction over an area approximately 80 mm × 65 mm. These data were also available as a text fil from which an overall mean velocity for each nozzle at each operational pressure was determined.

The next step was to configur the LaVision system in Shadowgraphy mode (LaVision, 2007b), which takes a series of paired images that are separated by microseconds (10 μs for low speed and 7 μs for high speed). Images are backlit using pulsed laser flashes The camera was focused on a 19 × 19 mm (0.75 × 0.75 in) area centered on the fla fan spray plane with a depth of fiel of approximately 3 mm and a minimum resolution of approximately 60 μm. Three measurement replications were made with each replication consisting of a minimum of 150 paired images being collected. The objective was to collect a minimum of 10,000 spray droplets, prior to post processing. For the low-speedtests, the nozzle was traversed and for the high-speed tests, the camera and laser were traversed. The DaVis Software (Version 7.2, LaVision Inc., Ypsilanti, MI) returned both raw data file with listing of each droplet detected and measured as well as a statistical summary reporting the 10, 50, and 90 percent volume diameters ($D_{v0.1}$, $D_{v0.5}$, and $D_{v0.9}$, respectively), which are the droplet diameters such that 10, 50, or 90 percent of the spray volume is contained in droplets of equal or lesser diameter. These droplet mean diameters are not velocity weighted and represent a spatial sample.

To develop the temporal distributions, the raw size and velocity data were post-processed using custom FORTRAN coding (Microsoft Developer Studio, Fortran Power Station 4.0, Microsoft Corporation). The raw data contained droplet size and velocity data for both images in each pair. In most cases, there were droplets in one image that were not contained in the other due to movement out of frame. As the droplet velocity is calculated based on the change in droplet position between the paired frames and the time difference between frames, if the paired droplet is not detected in both frames it is assigned a velocity of zero. To resolve this, only droplets detected in the firs frame with non-zero velocity were used to calculate to post-processed spatial and temporal distribution. For this work, a velocity-weighted distribution was determined. Similar to a volume weight distribution, a velocity-weighted distribution also includes the average velocity for each size bin. The volume fraction of each size bin, VF_i, can then be determine using the average bin velocity, Vel_i, and the total volume of each bin, Vol_i. VF_i for each bin i was calculated using Eq. 1.

$$VF_i = \frac{\mathrm{Vel}_i \times \mathrm{Vol}_i}{\sum(\mathrm{Vel}_i \times \mathrm{Vol}_i)} \tag{1}$$

From this volume-weighted, or temporal, distribution, the $D_{v0.1}$, $D_{v0.5}$, and $D_{v0.9}$ were determined following the method presented by Dodge et al. (1987). The spatially derived $D_{v0.1}$, $D_{v0.5}$, and $D_{v0.9}$ were determined using standard methods (Hinds, 1982). The percent difference between the spatial and temporal data was determined and reported.

2.3 Laser Diffraction System—Sympatec HELOS

A Sympatec HELOS laser diffraction system (Sympatec Inc., Clausthal, Germany) was also used to measure droplet sizes for all nozzles, pressures, airspeeds, and measurement distances. The Helos system utilizes a 623 nm He:Ne laser and was fitte with a lens (denoted by manufacturer as R7) with a dynamic size range of 0.5–3,500 μm, divided across 32 sizing bins. The laser system has two components, the emitter and the receiver, which were positioned across from each other and outside of the wind tunnel. Due to vibration effects from both wind tunnels and the traverse system used with the high-speed tunnel, a force stability of three (damps the top three sizing bins) was used. Throughout the testing, it was ensured that no droplets were detected in bins within three channels of the firs damped channel. A minimum of three measurement replications were made with each replication consisting of a single traverse of either the nozzle or laser such that the whole spray plume was sampled. During the low-speed [<6.7 m/s (15 mph)] testing, the laser was positioned horizontally and centered across the tunnel outlet downwind of the spray nozzle with the spray nozzle being traversed during each measurement. The high-speed tunnel testing required the spray nozzle to remain stationary to insure that the spray remained within the tunnel outlet air stream. The laser system was traversed using a forklift fitte with a mount. To prevent vibration effect from fouling the measurements the laser had to be elevated such that the laser was above the spray prior to measurement. The forklift was then shut off. The laser was then traverseddownward by slowly releasing the vertical lift hydraulics, which resulted in a measurement time of approximately 12–15 s. Laser diffraction measurements were not made at six inches for all airspeeds as well as twelve inches for airspeeds greater than 6.7 m/s due to presence of ligaments in the spray, as observed during the shadowgraphy process. In addition to the $D_{v0.1}$, $D_{v0.5}$, and $D_{v0.9}$, the percent spray volume less than 100 μm ($V_{<100}$) was also reported from the laser diffraction results. Only data for the laser diffraction droplet sizing results for the three nozzles operating at the 276 kPa spray pressure arereported. Complete data sets, including difference between spatial and temporal data for all nozzles/pressures/airspeeds/distances as well as more detailed droplet velocity data, are available from the authors upon request.

3. RESULTS

Average droplet velocities out of the nozzle, as measured using the LaVision PIV method, showed velocities ranging from 12.7 to 25.2 m/s for pressures ranging from 138 to 414 kPa. The smallest orific nozzle (8002) had the lowest overall average exit velocities (12.7, 18.4, and 22.8 m/s at pressures of 138, 276, and 414 kPa, respectively). The two larger nozzles (8008 and 6510) had very similar velocities (14.4, 20.5, and 25.4 m/s for the 8008 and 14.8, 20.2, and 25.2 m/s for the 6510) at pressures of 138, 276, and 414 kPa, respectively. As spray droplets are ejected into the measurement environment, they immediately began to either accelerate or decelerate to match the surrounding air stream's velocity. As discussed previously, smaller droplets will come to air stream velocity much quicker than the larger droplets. However, as the average exit velocities show, there is typically a large difference in droplet and air stream velocities. This work looks atair stream velocities from 0.7–6.7 m/s to simulate ground application conditions and 35.8–80.5 m/s to replicate aerial application conditions. As later results will illustrate, the closer the nozzle's exit velocity and the tunnel's air stream velocity are, the more closely the spatially and temporally derived size data will match.

3.1 8002 Flat Fan Nozzle

Temporal and Spatial Data Across All Distances: For the 8002 nozzle operated at a pressure 138 kPa (20 psi), the spatially derived $D_{v0.1}$ values were 10–20% less than the temporal data with a concurrent airfl w 0.7 m/s and 3–5% less at 6.7 m/s across all the distances tested. Similarly, $D_{v0.5}$ spatial values were 4–20% and 1.5–4% less than temporal at 0.7 and 6.7 m/s, respectively; and $D_{v0.9}$ spatial values were 4–15% and 1–4% less than temporal at 0.7 and 6.7 m/s, respectively. At air velocities of 35.8 and 80.5 m/s, respectively, spatially derived $D_{v0.1}$ values were 4–8% and 1.5–2.5% greater than temporal. $D_{v0.5}$ spatial values were 3.5% and 1–2% greater than temporal while $D_{v0.9}$ spatial values were 2–4% and 1–2% greater than temporal, for the same airspeed ranges. The differences were smallest for the closest measurement distances for all cases.

At 414 kPa (60 psi), these trends continue but the differences between the spatial and temporal data increase 5–10% at air speeds of 6.7 m/s and less and 1–2% at air speeds greater than 35.8 m/s. At 276 kPa (40 psi) the trends are the same as well with the differences falling between the 138 and 414 kPa results. At all pressures and distances and for air speeds 0.7–6.7 m/s, the average droplet velocity, across all diameters, was greater than the concurrent air velocity, with the smallest droplets in the spray having a lower average velocity than the mean and the largest droplet having greater average velocity than the mean. Droplet velocities were less at further measurement distance in all cases. At airspeeds of 35.8 m/s and greater, these trends reverse with average droplet velocities being less than the surrounding air velocity. Additionally, the smaller diameter droplet velocities were greater than the mean while the larger droplet velocities are less. At these higher airspeeds, average droplet velocities were lower at closer distance and increased with measurement distance.

Laser Diffraction Droplet Size Measurements: Droplet size data for the 8002 nozzle at 276 kPa measured using laser diffraction at each measurement distance and air speed are shown in Table 1. Droplet size data arenot reported for air speeds of 35.8 m/s and

TABLE 1: Droplet median diameters measured using Sympatec laser diffraction system for an 8002 fla fan nozzles operating at 276 kPa (40 psi). No data arepresented at the 15.2 and 30.5 cm distance for airspeeds greater than 6.7 m/s due to ligaments present in the spray cloud

Airspeed (m/s)	**15.2 cm (6 in)**				**30.5 cm (12 in)**			
	$D_{v0.1}$ (μm)	$D_{v0.5}$ (μm)	$D_{v0.9}$ (μm)	$V_{<100}$ (%vol)	$D_{v0.1}$ (μm)	$D_{v0.5}$ (μm)	$D_{v0.9}$ (μm)	$V_{<100}$ (%vol)
0.7	75.6	182.3	336.6	19.08	74.2	160.0	296.7	20.22
3.1	83.3	196.8	345.0	14.78	84.4	185.8	326.4	15.19
6.7	93.0	207.9	356.3	11.77	92.8	203.0	343.0	11.87
Airspeed (m/s)	**45.7 cm (18 in)**				**76.2 cm (30 in)**			
	$D_{v0.1}$ (μm)	$D_{v0.5}$ (μm)	$D_{v0.9}$ (μm)	$V_{<100}$ (%vol)	$D_{v0.1}$ (μm)	$D_{v0.5}$ (μm)	$D_{v0.9}$ (μm)	$V_{<100}$ (%vol)
0.7	86.8	170.8	298.8	14.47	96.5	194.9	307.3	10.74
3.1	89.5	186.3	330.6	13.27	94.1	193.3	331.0	11.62
6.7	92.7	199.2	348.4	12.05	96.2	201.6	347.4	10.97
35.8	106.4	219.5	370.5	8.61	106.1	216.9	369.8	8.72
53.6	98.5	209.8	348.1	10.34	94.8	209.0	361.0	11.27
62.6	92.0	199.2	335.3	12.09	89.6	199.2	340.9	12.76
71.5	87.3	188.9	327.2	13.48	83.7	185.0	305.0	14.58
80.5	76.4	166.5	276.4	17.74	75.1	167.2	278.8	18.06

greater for the 15.2 and 30.5 cm measurement distances due to the presence of ligaments in the spray cloud, as confirme by the LaVision imagery data collected. At 15.2 and 30.5 cm inthe 6.7 m/s airstream, measured $D_{v0.1}$ values were larger than those from the 0.7 and 3.1 m/s air velocities, while the $V_{<100}$ values were lower (Table 1). These results were expected and were a result of the spatial bias, as discussed previously. Similar trends to a lesser degree were also seen with the $D_{v0.5}$ and $D_{v0.9}$ values. At the greater measurement distances (45.7 and 76.2 cm) these differences were much less as all of the spray droplets had time to accelerate/decelerate closer to air stream velocities.

At air speeds from 35.8 to 80.5 m/s, $D_{v0.1}$, $D_{v0.5}$, and $D_{v0.9}$ values decreased with increasing airspeed as a result of secondary breakup up due to air shear. At these airspeeds, $D_{v0.1}$, $D_{v0.5}$, and $D_{v0.9}$ and $V_{<100}$ values were very similar at both the 45.7 and 76.2 cm measurement distances. These trends hold for this nozzle at the other two operating pressures, but with greater drop let velocities as a result of the greater exit velocities of the nozzles. Another trend seen was larger $D_{v0.1}$, $D_{v0.5}$, and $D_{v0.9}$ values at all airspeed and distance combinations with higher pressures. This was due to higher the higher exit velocities, which in turn resulted in lower differential velocities between the airstream and the spray, decreasing secondary breakup. With the higher pressures, $V_{<100}$

for higher airspeeds (35.8–71.5 m/s) tended to be less than, or equal to, those seen at the lower airspeeds (0.7–6.7 m/s) as a result of both the increased spray exit velocity reducing air shear effects at higher velocities and the overestimate of fine from spatial bias at lower velocities. As an extreme example of this: at 276 kPa spray pressure, the $V_{<100}$ value measured in 0.7 m/s at 30.5 cm is 20%, which was greater than that measured at 45.7 cm at an air velocity of 80.5 m/s (17.7%) (Table 1). This is a good illustration of the potential impact of the spatial bias.

3.2 8008 Flat Fan Nozzle

While the results remain similar for the 8008 nozzle across all liquid pressures, as compared to the 8002 nozzle, the distance effect at the lower air velocities (0.7–6.7 m/s) was greater. Differences between spatial and temporal data ranged from 1–5%, at 15.2 cm distance for air velocities 6.7 m/s or less and all pressures, to over 20% at 76.2 cm distance. This was a result of the spray being composed of larger droplets with fewer fine such that over sampling the fine that were present had a greater impact on the differences between spatial and temporal data. Droplet velocity trends at airspeeds 0.7–6.7 m/s were similar to the 8002 nozzle for both large and small droplet diameters, but with few smaller droplets and a greater number of larger droplets, which tended to maintain their momentum.As a result, the average velocities tended to be 3–5 m/s faster at the lower air velocities. However, at the higher airspeeds ($\leq$35.8 m/s) the greater number of smaller droplets with the 8002 tended to accelerate quicker the larger droplets, resulting in overall average droplet velocities with the 8008 that were 1–2 m/s slower. While the $V_{<100}$ was less than for the 8008 nozzle (Table 2) than the 8002 nozzle, the spatial bias effect at the lowest airspeed (0.7 m/s) still resulted in twofold or greater overestimates of the fin portion of the spray. At higher air velocities ($\geq$35.8 m/s), the difference between spatial and temporal data was 5% or less for all pressures and both distances. At these higher airspeeds, even though droplet velocities never reached homogeneity, they were sufficientl close that the results from laser diffraction were nearly identical, with a few small differences, between the 45.7 and 76.2 cm distances. The laser diffraction results also indicated that the air shear effect on droplet formation was minimal until air velocities exceed 35.8 m/s.

3.3 6510 Flat Fan Nozzle

The trends seen with the 8008 nozzle were also seen with the 6510, with measurement distance having a greater impact on the difference between the spatial and temporal data than air velocity. Again, differences range from 1–5% at 15.2 cm for air velocities 6.7 m/s or less and all liquid pressures to over 20% at 76.2 cm. The same reasoning discussed for the differences with the 8008 nozzle holds here. Droplet velocities for large and small diameters and overall averages were similar to the 8008 nozzle. While

TABLE 2: Droplet median diameters measured using Sympatec laser diffraction system for an 8008 fla fan nozzles operating at 276 kPa (40) psi. No data are presented at the 15.2 and 30.5 cm distance for airspeeds greater than 6.7 m/s due to ligaments present in the spray cloud

Airspeed (m/s)	**15.2 cm (6 in)**				**30.5 cm (12 in)**			
	$D_{v0.1}$ (μm)	$D_{v0.5}$ (μm)	$D_{v0.9}$ (μm)	$V_{<100}$ ($\%_{vol}$)	$D_{v0.1}$ (μm)	$D_{v0.5}$ (μm)	$D_{v0.9}$ (μm)	$V_{<100}$ ($\%_{vol}$)
0.7	147.9	360.9	663.8	4.64	130.8	352.0	668.9	5.40
3.1	162.6	370.8	666.7	3.49	155.6	376.7	690.1	3.63
6.7	178.0	386.1	696.1	2.59	179.3	398.2	710.4	2.51
Airspeed (m/s)	**45.7 cm (18 in)**				**76.2 cm (30 in)**			
	$D_{v0.1}$ (μm)	$D_{v0.5}$ (μm)	$D_{v0.9}$ (μm)	$V_{<100}$ ($\%_{vol}$)	$D_{v0.1}$ (μm)	$D_{v0.5}$ (μm)	$D_{v0.9}$ (μm)	$V_{<100}$ ($\%_{vol}$)
0.7	127.6	310.4	588.9	5.15	138.4	297.6	591.5	4.60
3.1	144.7	342.2	615.3	3.82	143.4	333.1	626.1	3.93
6.7	164.2	366.5	642.8	2.77	153.2	359.1	656.0	3.36
35.8	231.3	454.4	769.5	0.77	228.7	457.5	760.6	0.90
53.6	185.1	374.4	620.3	2.09	182.3	368.6	591.9	2.27
62.6	152.1	310.0	491.4	3.79	150.1	313.6	509.6	4.04
71.5	125.3	264.0	430.3	6.19	121.2	262.2	419.3	6.71
80.5	101.8	224.1	380.4	9.65	102.0	229.1	384.5	9.63

droplets were larger and spatial bias was less, laser diffraction measurements of $V_{<100}$ were overestimated 2–3 times at the lowest (0.7 m/s) air velocity versus the 6.7 m/s air velocity (Tables 3). Like the 8008 nozzle, the 6510 nozzle laser diffraction results showed the effects of air shear at air velocities greater than 35.8 m/s (Table 3).

4. CONCLUSION AND DISCUSSION

The results seen with this work support and agree with those observed by past researchers, as discussed previously. It is also apparent that the spatial bias is much greater for fine sprays and the estimates of the fine portion of a spray ($D_{v0.1}$ and percent volume less than 100 μm diameter), which is typically the most critical measure of concern with respect to mitigating spray drift. The spatial bias error can be significantl reduced by using a measurement distance in combination with an air stream of sufficien velocity to accelerate/decelerate droplets to create a more uniform velocity field While this method does not completely remove the spatial bias, it can, if applied correctly, reduce this error to no more than 2–3 percent, which is within the variance of normal spray measurements. When testing agricultural ground sprayer nozzles, the authors have selected a

TABLE 3: Droplet median diameters measured using Sympatec laser diffraction system for a 6510 fla fan nozzles operating at 276 kPa (40 psi). No data are presented at the 15.2 and 30.5 cm distance for airspeeds greater than 6.7 m/s due to ligaments present in the spray cloud

Airspeed (m/s)	15.2 cm (6 in)				30.5 cm (12 in)			
	$D_{v0.1}$ (μm)	$D_{v0.5}$ (μm)	$D_{v0.9}$ (μm)	$V_{<100}$ ($\%_{vol}$)	$D_{v0.1}$ (μm)	$D_{v0.5}$ (μm)	$D_{v0.9}$ (μm)	$V_{<100}$ ($\%_{vol}$)
0.7	180.7	455.9	884.4	3.38	154.4	439.0	828.8	3.61
3.1	196.1	468.2	918.2	2.50	182.7	461.5	856.5	2.79
6.7	211.8	483.7	956.0	1.86	211.8	486.8	894.6	1.87
Airspeed (m/s)	**45.7 cm (18 in)**				**76.2 cm (30 in)**			
	$D_{v0.1}$ (μm)	$D_{v0.5}$ (μm)	$D_{v0.9}$ (μm)	$V_{<100}$ ($\%_{vol}$)	$D_{v0.1}$ (μm)	$D_{v0.5}$ (μm)	$D_{v0.9}$ (μm)	$V_{<100}$ ($\%_{vol}$)
0.7	146.3	396.5	780.7	3.70	152.9	370.0	776.0	3.68
3.1	168.8	431.6	808.4	2.82	164.0	410.1	803.0	2.66
6.7	192.3	456.5	827.7	2.03	183.7	444.7	834.8	2.03
35.8	274.1	538.8	860.5	0.52	277.0	549.2	882.9	0.53
53.6	218.7	452.5	772.6	1.41	220.3	448.7	734.9	1.40
62.6	163.6	340.6	551.3	3.29	163.4	342.0	537.3	3.40
71.5	134.2	291.2	494.6	5.37	134.7	292.4	481.6	5.41
80.5	107.5	242.0	423.7	8.66	103.6	236.9	402.1	9.37

measurement distance of 30.5 cm and an air stream velocity of 6.7 m/s. While the spatial bias is typically less across all tested nozzles and liquid pressures, measured at 45.7 cm, practical considerations of nozzle plume geometry and wind tunnel widthare important. A typical fla fan ground nozzle has a spray angle from 80 to 110 degrees. At a distance of 45.7 cm from the nozzle exit, the width of the plume is 0.77 to 1.31 m, respectively for the 80 and 100 degree fla fans. This does not allow for a full traverse of the plume in a 1.22 m tall tunnel (as is the case with the authors' wind tunnel). At a distance of 30.5 cm these widths are reduced to 0.51–0.87 m, respectively for the 80 and 100 degree fla fans. There is still some spray impingement on the ceiling and floo of the tunnel, but the 6.7 m/s air velocity prevents any of the affected spray from passing through the line of measurement. While some of the published references discussed measurement distances of 15 cm or less, the authors observed ligaments, or un-atomized conglomerates of spray liquid, from all nozzles tested with this study at the 15.2 cm location. With the high air speed testing, only measurement distance was an issue, as spatial biases were less than several percent for all combinations tested. Again as a result of observed ligaments at the 15.2 and 30.5 cm distances, the authors recommend a measurement distance of 45.7 cm.

While the 76.2 cm distance would also serve, it would also allow for significan spread of the spray plume, which will typically foul the laser instrument sensors.

The laser diffraction droplet sizing method offers a quick and easy method for testing and comparing spray from agricultural spray technologies. However, like any measurement or sampling technique, laser diffraction can potentially bias the absolute droplet size results measured from a given system. Methods such as reference nozzles and curvesare a useful tool for comparison of inter-laboratory results. Accurate, absolute droplet size data are critical to providing an understanding of product effica y, as well as for use in assessing spray technologies and methods for potential levels of drift and off-target damage. Selection of appropriate concurrent airfl w and measurement distances can be used to minimize biases typically seen with spatial measurement methods. Using the methods recommended, the authors' conducted a round-robin testing of ground and aerial spray nozzles at three laboratories with significan agreement in droplet size parameters across a variety of nozzles types, pressures, and simulated airspeeds (aerial nozzles only) (Fritz et al., InPrint).

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REFERENCES

ANSI/ASAE S572.1, Spray Nozzle Classificatio by Droplet Spectra, American Society of Agricultural Engineers, St. Joseph, MI. 4, pp. 1–3, 2009.

Arnold, A. C., A Comparative study of droplet sizing equipment for agricultural fan-spray atomizers, *Aerosol Sci. Tech.*, vol. **12**, no. 2, pp. 431–445, 1990.

ASTM E1260, Standard Test Method for Determining Liquid Droplet Size Characteristics in a Spray Using Optical Nonimaging Light Scattering Instruments, Annual Book of Standards, 14.02, ASTM International, West Conshonhocken, PA., pp. 1–4, 2009.

Bouse, L. F., Effect of nozzle type and operation on spray droplet size, *Trans. ASABE*, vol. **37**, no. 5, pp. 1389–1400, 1994.

Chapple, A. C., Taylor, R. A. J., and Hall, F. R., The transformation of spatially determined droplet sizes to their temporal equivalent for agricultural sprays, *J. Agric. Engng. Res.*, vol. **60**, no. 1, pp. 49–56, 1995.

Doble, S. J, Matthews, G. A., Rutherford, I., and Southcombe, E. S. E., A system for classifying hydraulic nozzles and other atomizers into categories of spray quality, *Proc. Brighton Crop Prot. Conf. - Weeds*, pp. 1125–1133, 1985.

Dodge, L. G., Comparison of performance of droplet-sizing instruments, *Appl. Optics*, vol. **26**, no. 7, pp. 1328–1341, 1987.

Dodge, L. E., Rhodes, D. J., and Reitz, R. D., Droplet-size measurement techniques for sprays: Comparison of malvern and laser-diffraction and aerometrics phase/doppler, *Appl. Optics*, vol. **26**, no. 11, pp. 2144–2154, 1987.

Fritz, B. K., Hoffmann, W. C., Kruger, G. R., Henry, R. S., Hewitt, A., and Czaczyk, Z., Comparison of drop size data from ground and aerial application nozzles at three testing laboratories, *Atomization Sprays*, vol. **24**, no. 2, pp. 181–192, 2014.

Fritz, B. K., Hoffmann, W. C., Martin, D. E., and Thomson, S. J., Aerial application methods for increasing spray deposits on wheat heads, *Appl. Engr. Agric.*, vol. **23**, no. 6, pp. 709–715, 2007.

Frost, A. R. and Lake, J. R., The significanc of droplet velocity to the determination of droplet size distributions of agricultural sprays, *J. Agric. Engng. Res.*, vol. **26**, no. 4, pp. 367–370, 1981.

Hammond, Jr., D. C., Deconvolution technique for line-of-sight optical scattering measurements in axisymmetric sprays, *Appl. Optics*, vol. **20**, no. 3, pp. 493–499, 1981.

Hewitt, A. J., Spray drift: Impact of requirements to protect the environment, *Crop. Prot.*, vol. **19**, no. 1, pp. 623–627, 2000.

Hewitt, A. J., Johnson, D. R., Fish, J. D., Hermansky, C. G., and Valcore, D. L., Development of the spray drift task force database for aerial applications, *Environ. Tox. Chem.*, vol. **21**, no. 3, pp. 648–658, 2002.

Himel, C. M., The optimum size for insecticide spray droplets, *J. Econ. Entom.*, vol. **62**, no. 4, pp. 919–925(7), 1969.

Hinds, W. C., *Aerosol Technology: Properties, Behavior, and Measurement of Airborne Particles*, John Wiley, New York, p. 432, 1982.

LaVision, *Flow Master: Product Manual for DaVis 7.2*, LaVision GmbH, Göttingen, Germany, 2007a.

LaVision, *Sizing Master Shadow: Product Manual for DaVis 7.2*, LaVision GmbH, Göttingen, Germany, 2007b.

Lefebvre, A. H., *Atomization and Sprays*, Norman Chigier, Ed., New York: Hemisphere Publishing, 1989.

Salyani, M., Droplet size effect on spray deposition efficien y of citrus leaves, *Trans. ASABE*, vol. **31**, no. 6, pp. 1680–1684, 1988.

Smith, D. B., Askew, S. D., Morris, W. H., Shaw, D. R., and Boyette, M., Droplet size and leaf morphology effect on pesticide spray deposition, *Trans. ASABE*, vol. **43**, no. 2, pp. 255–259, 2000.

Spray Drift Task Force (SDTF), *Study No. A95-010, Miscellaneous Nozzle Study*, EPA MRID No. 44310401, pp. 1–15, 1997.

Teske, M. E., Thistle, H. W., Hewitt, A. J., and Kirk, I. W., Conversion of Droplet size distributions from pms optical array probe to malvern laser diffraction, *Atomization Sprays*, vol. **12**, no. 1-3, pp. 267–281, 2002.

Tishkoff, J. M., Spray characterization: practices and requirements, *Opt. Eng.*, vol. **23**, no. 5, pp. 557–560, 1984.

Young, B. W. and Bachalo, W. D., The Direct Comparison of Three "In-Flight" Droplet Sizing Techniques for Pesticide Spray Research, InGovesbet, G. and Grehan, G., Eds, *Optical Particle Sizing: Theory and Practice*, New York: Plenum Press, pp. 483–497, 1988.