AIRSPEED AND ORIFICE SIZE AFFECT SPRAY DROPLET SPECTRUM FROM AN AERIAL ELECTROSTATIC NOZZLE FOR FIXED-WING APPLICATIONS

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ABSTRACT. *The aerial electrostatic spraying system patented by the USDA-ARS is a unique aerial application system which inductively charges spray particles for the purpose of increasing deposition and efficacy. While this system has many potential benefits, very little is known about how changes in airspeed or nozzle orifice size affect the spray droplet spectrum of charged spray. This study quantified these effects in a controlled high-speed wind tunnel at fixed-wing airspeeds (177-306 km/h). These tests were conducted at the USDA-ARS Aerial Application Technology research facilities in College Station, Texas. Laser diffraction data showed that increases in airspeed produced smaller spray droplets for all nozzle orifices tested, as quantified by standard spray droplet parameters. Generally, an increase in nozzle orifice size increased the coarseness of the spray droplet spectra at all airspeeds. The results from this study will help aerial applicators better understand how changes in airspeed and nozzle orifice size affect droplet size from an aerial electrostatic nozzle.*

Keywords. *Electrostatic charging, Aerial application, Aerial spraying, Agricultural aviation, Spray droplet spectrum, Laser diffraction.*

Recent increases in fuel prices have forced aerial applicators to consider alternative spray technologies that may be able to provide the needed deposition and efficacy at lower application rates. Aerial electrostatic spraying systems, including the system patented by the United States Department of Agriculture-Agricultural Research Service (USDA-ARS), described by Carlton (1999), and currently marketed by Spectrum Electrostatic Sprayers, Inc. (Dobbins, 2000; Houston, Tex.) may provide such a benefit. Many aerial applicators around the world currently use this system, but very few data exist which describe its spray quality at various fixed-wing airspeeds and nozzle orifice sizes. Aerial applicators need operational spray parameter knowledge to help them decide which combination of spray parameter selections will increase spray deposition and reduce off-target drift. Over the past 50 years, much foundational work has been conducted to better understand electrical atomization and electrostatic charging of spray particles (Carlton and Isler, 1966; Threadgill, 1973; Carlton, 1975; Carlton and Bouse, 1977, 1978, 1980; Inculet and Fischer, 1989). Practical applications based on this improved understanding led to field studies using electrostatically charged sprays for both ground application (Herzog et al., 1983; Giles and Law, 1990; Giles and Blewett, 1991; Cooper et al., 1992; Giles et al., 1992; Cooper et al., 1998; Maski and Durairaj, 2010) and aerial application (Cooper et al., 1992; Kihm et al., 1992; Carlton et al., 1995; Kirk et al., 2001; Fritz et al., 2007; Martin et al., 2007). In 2002, an initial field evaluation and uncharged droplet spectrum analysis of the original Spectrum aerial electrostatic system was conducted (Gordon et al., 2002) and only limited, field-collected droplet spectra data for this system with water sensitive papers has been reported (Fritz et al., 2007; Martin et al., 2007; Latheef et al., 2008). These four previous aerial studies used the same charging system with similar atomization characteristics. Recently, the original Spectrum aerial electrostatic nozzle was slightly redesigned and is now manufactured in Brazil.

OBJECTIVES

A performance evaluation of this redesigned Spectrum aerial electrostatic nozzle was the focus of this study and will be hereto referred to as the Brazilian aerial electrostatic nozzle. The objectives of the study were as follows:

- To quantify the effects of typical fixed-wing airspeeds and nozzle orifice sizes on the atomization of charged spray from the Brazilian aerial electrostatic nozzle in a controlled wind tunnel.
- To quantify the electrostatic performance characteristics (Q/M, charge to mass ratio) of the nozzle for each of the test orifices and at each test airspeed.

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Materials and Methods

Electrostatic Nozzle Setup

All spray tests were conducted with the Brazilian electrostatic nozzle (Spectrum Electrostatic Sprayers, Houston, Tex.). The nozzle was mounted to a test section of a slip-stream boom at the outlet of a high-speed wind tunnel (fig. 1), positioned in the center of the outlet. A high-voltage conductor connected the electrostatic nozzle electrode to a power junction, which also was connected to a high-voltage power supply (Universal Voltronics Corp., White Plains, N.Y.). The power supply was grounded to the frame of the wind tunnel and adjusted to provide a positive voltage of 6000 V to the electrode ring and induce a negative charge on the spray. The positive terminal of a DC microammeter (Simpson, Lac du Flambeau, Wis.) was connected to a custom-designed, electrically isolated, Faraday cage, to measure the return spray current through the system to ground (fig. 2).

Atomization Testing

The atomization tests were conducted in the USDA-ARS Aerial Application Technology high speed wind tunnel in College Station, Texas, which has an operational range of 24 to 346 km/h. The nozzle was tested at airspeeds of 177 to 306 km/h and at nozzle orifice diameters of 1.19 to 1.70 mm (TXVK-6, 8, 10, and 12 spray tips, Spraying Systems Co., Wheaton, Ill.). A 50-mesh screen filter with a 138-kPa integrated check valve was used with the TXVK-6 spray tip while a 24-mesh screen filter with a 138-kPa integrated check valve was used with the TXVK-8, 10, and 12 spray tips. All spray testing was completed at 517 kPa using a spray solution of water plus a non-ionic surfactant (0.25% v/v, R-11, Wilbur-Ellis, Devine, Tex.) dispensed from a 18.9-L pressure pot (Model 29749PS, Sharpsville Container, Sharpsville, Pa.). Droplet size measurements were made using a Sympatec Helium-Neon Laser Optical System (HELOS) (Clausthal-Zellerfeld, Germany) laser diffraction instrument with an R5 lens, a 13-mm beam diameter, and a measurement range of 0.1 to 875 µm. The nozzle was positioned 53 cm from the laser beam and 79 cm from the mouth of the Faraday cage. Pressure was first applied to the nozzle until steady state plume conditions were achieved and then analyzed with the laser for 10 s. A minimum of three replicated measurements was made for each treatment.

Charge-to-Mass Ratio Determination

Charge-to-mass ratio of the spray was calculated for each of the spray tips at each of the tested airspeeds according to the following equation:

$$\frac{Q}{M} = \frac{I}{\dot{M}_L} \quad (1)$$

where

Q/M = charge-to-mass ratio (mC/kg)

I = measured return spray current (µA)

$\dot{M}_L$ = liquid mass flow rate (g/s)

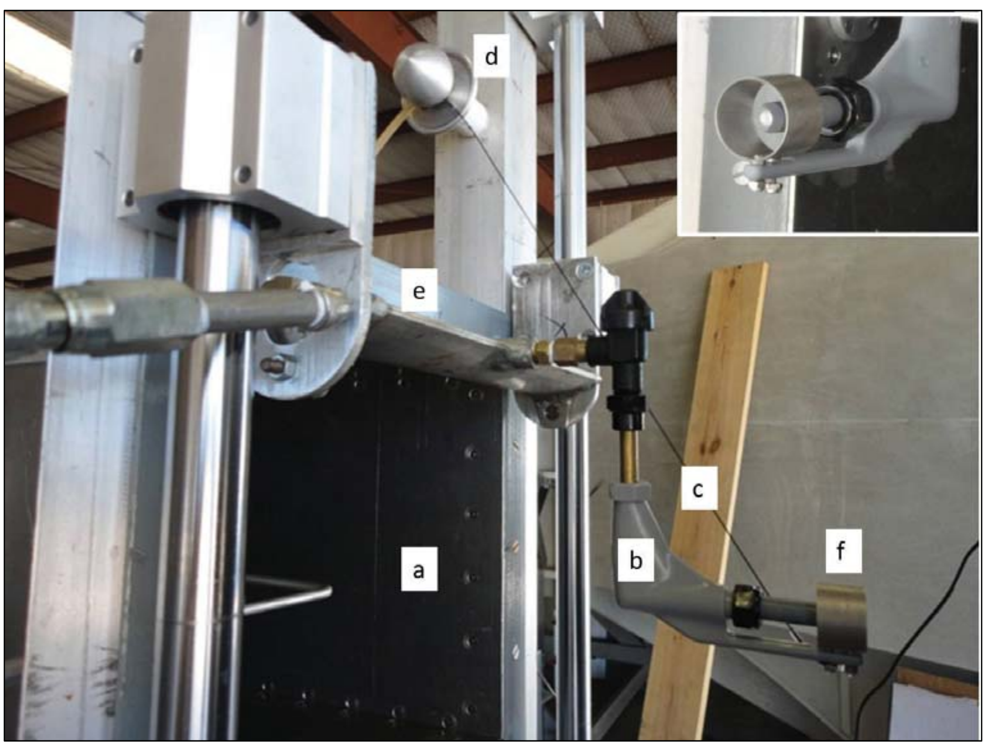

Figure 1. Wind tunnel setup for study showing: (a) wind tunnel outlet, (b) aerial electrostatic nozzle, (c) high voltage conductor, (d) power junction, (e) test section of slip-stream boom, and (f) charging electrode. Inset: Spray tip within the charging ring.

Figure 2. Study setup showing: (a) aerial electrostatic nozzle, (b) laser diffraction instrument for measuring droplet size, (c) Faraday cage for capturing and returning spray current, and (d) computer system for processing data. Inset: (e) High-voltage power supply.

The spray current with a charging voltage of +6000 V was measured for 60 s with the microammeter previously described. Spray mass flow rate was determined by collecting spray discharge from the nozzle for each tip size at 517 kPa for 60 s. The collected spray was then weighed on a tared and calibrated electronic digital balance (Model SK-5001WP, A&D Engineering, Inc., San Jose, Calif.). These measurements were replicated three times and the flow rates averaged for the three replicates.

Statistical Analyses

To test the significance of airspeed and nozzle orifice size on spray droplet spectrum parameters, both airspeed and nozzle orifice size were treated as fixed effects. The Statistical Analysis System, General Linear Model (PROC GLM, SAS Institute, Cary, N.C.) was used to perform the analyses of variance to test the significance of each effect at the α=0.05 level of significance. If the probability of significance (*p*-value) was less than 0.05 or less than 0.01, the effect was determined to be significant or highly significant, respectively.

Results and Discussion

Charge-to-Mass Ratio

One of the most important parameters for determining electrostatic spray nozzle performance is the charge-to-mass ratio. Charge-to-mass ratios (Q/M) on the order of 1.0 mC/kg have been found necessary to achieve enhanced spray deposition from electrostatic ground sprayers (Law and Lane, 1981). Specifically, the electric field within a falling electrostatically-charged spray plume does not reach sufficient driving force to enhance deposition until the average Q/M ratio reaches a value of about 1.0 mC/kg. The charge-to-mass ratios for the Brazilian aerial electrostatic nozzle were determined for various nozzle tip sizes and fixed-wing airspeeds at a charging voltage of +6000 V. The results are presented in table 1. Overall, as orifice size increased, the charge-to-mass ratios decreased. This is expected as a greater mass of spray flows through the nozzle with the larger orifices at the same charging voltage. In addition, for all orifices, as airspeed increased, so did the charge-to-mass ratio. This is likely attributed to a reduction in droplet size at higher airspeeds due to increased air sheer and is consistent with previous findings (Yates et al., 1985). Overall, the charge-to-mass ratios are low compared to some electrostatic ground sprayers that have been reported to produce Q/M ratios in the range of -5 to -8 mC/kg (Law and Scherm, 2005). In addition, many of the Q/M ratio values reported in table 1 are either below or on the verge of the 1.0-mC/kg target for good deposition. However, it is important to realize that in an aerial application system, the spray is typically released 2 to 4 m above the plant canopy. During this fall time, depending primarily upon temperature and relative humidity, the droplets will lose mass due to evaporation which will increase the charge-to-mass ratio of the droplets at the time of impact, resulting in Q/M ratios higher than those listed in table 1.

Spray Atomization

The spray droplet spectra data from the Brazilian aerial electrostatic nozzle tested at various fixed-wing airspeeds and nozzle orifice sizes are presented below. The first parameter of interest was the $D_{v0.1}$, which is the droplet

Table 1. Spray charge-to-mass ratio (mC/kg) from a Brazilian aerial electrostatic nozzle at different airspeeds with a +6000 V applied voltage. Spray solution was water plus 0.25% v/v non-ionic surfactant.

Nozzle	Flow Rate (g/s)	Airspeed (km/h)[a] 177	209	241	274	306
TXVK-6	7.01	-0.928 Aa	-1.070 Ab	-1.242 Ac	-1.428 Ad	-1.628 Ae
TXVK-8	8.87	-0.845 Ba	-0.958 Bb	-1.127 Bc	-1.240 Bd	-1.420 Be
TXVK-10	13.46	-0.595 Ca	-0.691 Cb	-0.781 Cc	-0.892 Cd	-1.004 Ce
TXVK-12	14.13	-0.495 Da	-0.622 Db	-0.686 Dc	-0.792 Dc	-0.892 De

[a] Means followed by the same letter are not significantly different based on Duncan's Multiple Range test with α = 0.05. Differences within a column are designated by a capital letter, within a row by a lowercase letter.

diameter where 10% of the spray volume is contained in droplets smaller than this value (fig. 3). This figure shows that both airspeed and nozzle orifice size affected the $D_{v0.1}$. As airspeed increased, $D_{v0.1}$ decreased for all nozzle spray tips. As nozzle orifice size increased, $D_{v0.1}$ also increased for all airspeeds except for the TXVK-6 spray tip, which yielded a higher $D_{v0.1}$ than the TXVK-8 for all airspeeds, and was greater than the TXVK-10 at 274 km/h. The reason for this exception is unknown. It is possible that the larger droplets produced by the TXVK-8 nozzle underwent secondary atomization, resulting in a lower $D_{v0.1}$ than the TXVK-6 nozzle.

Another parameter of interest was the $D_{v0.5}$, or Volume Median Diameter (VMD), which is the droplet diameter where 50% of the spray volume is contained in droplets smaller than this value. Again, from this parameter it can be seen that the VMD of the spray decreased with increasing airspeed for all nozzle orifices (fig. 4). In addition, overall, as nozzle orifice size increased, the VMD also increased. Above 209 km/h, however, the TXVK-6 tip resulted in larger VMDs than the TXVK-8. Although large differences exist between nozzle orifices at lower airspeeds, at airspeeds above 274 km/h (170 mph), the droplet spectrum curves tend to converge. This is most likely due to secondary atomization of the larger droplets produced by the larger orifice nozzles. These results compare well to a previous field study where the authors reported a VMD of 94 µm from a 9.4-L ha^{-1} aerial electrostatic application at 209 km/h and 483 kPa with a TXVK-8 spray tip (Martin et al., 2007). A VMD of 100 µm for those same application parameters is reported in this study.

Analysis of the $D_{v0.9}$, which is the droplet diameter where 90% of the spray volume is contained in droplets smaller than this value, indicated a similar trend where increases in airspeed resulted in a decrease in the $D_{v0.9}$ of the spray for all orifice sizes (fig. 5). Additionally, an increase in nozzle orifice size resulted in an increase in the $D_{v0.9}$ for all airspeeds. Differences between small and large orifices seem to virtually disappear as airspeeds exceed 274 km/h (170 mph). Again, this is most likely due to secondary atomization of the larger droplets produced by the larger orifices due to air sheer.

The relative span of a spray is defined as:

$$RS = \frac{(D_{v0.9} - D_{v0.1})}{D_{v0.5}} \quad (1)$$

For aerial spray applications, a lower relative span is usually desirable, as the range of droplet sizes is minimized. However, a lower relative span is only advantageous if the most efficacious droplet spectrum is known for the target pest. When the required droplet spectrum is not known or if multiple pests are targeted, each with a different optimum droplet spectrum, a larger relative span may be desired. For this study, the relative span of the spray decreased with increased airspeed for all

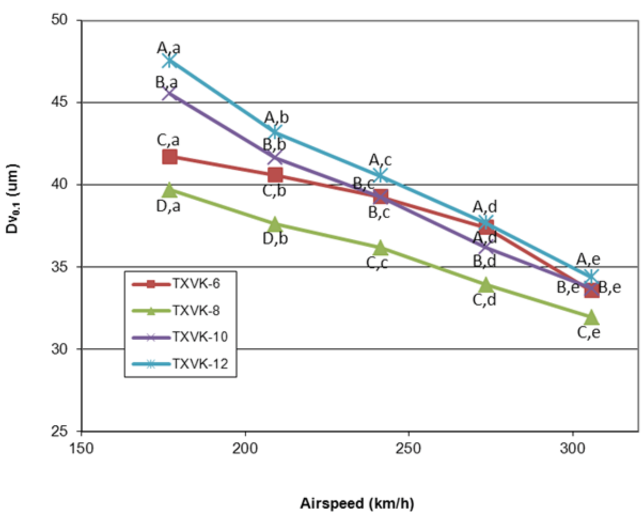

Figure 3. Effect of airspeed and nozzle orifice size on $D_{v0.1}$ from the Brazilian aerial electrostatic nozzle. Means followed by the same letter are not significantly different based on Duncan's Multiple Range test with α = 0.05. Differences between spray tips at a given airspeed are designated by a capital letter; between airspeeds for a given spray tip by a lowercase letter.

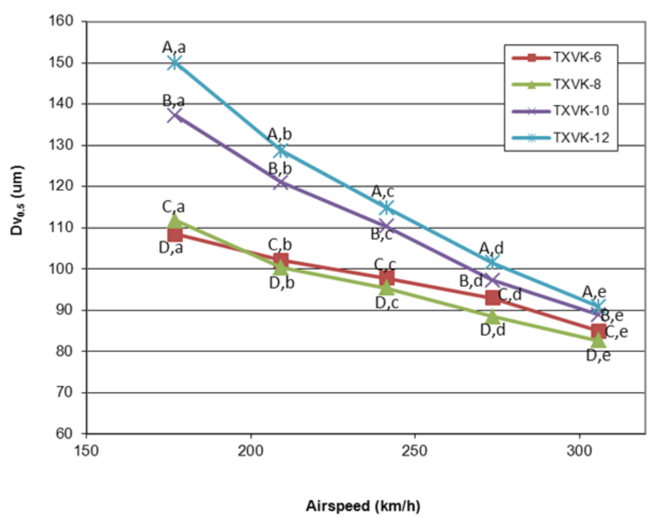

Figure 4. Effect of airspeed and nozzle orifice size on $D_{v0.5}$ from the Brazilian aerial electrostatic nozzle. Means followed by the same letter are not significantly different based on Duncan's Multiple Range test with α = 0.05. Differences between spray tips at a given airspeed are designated by a capital letter; between airspeeds for a given spray tip by a lowercase letter.

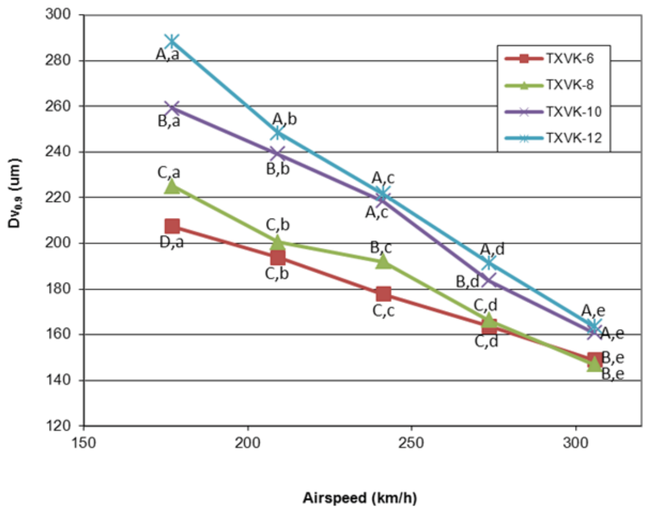

Figure 5. Effect of airspeed and nozzle orifice size on $D_{v0.9}$ from the Brazilian aerial electrostatic nozzle. Means followed by the same letter are not significantly different based on Duncan's Multiple Range test with α = 0.05. Differences between spray tips at a given airspeed are designated by a capital letter; between airspeeds for a given spray tip by a lowercase letter.

nozzle orifices but one (fig. 6). The relative span of the TXVK-10 spray tip increased with airspeed up to 210 km/h, and then decreased as airspeed continued to increase. This can be attributed to the lower relative $D_{v0.9}$ for theTXVK-10 versus the TXVK-12 for airspeeds below 210 km/h. The relative difference between the TXVK-10 and the TXVK-12 for both $D_{v0.1}$ and $D_{v0.5}$ was steady and consistent. However, the $D_{v0.9}$ for the TXVK-10 was much lower than the TXVK-12 at 177 km/h. This resulted in a lower relative span at that airspeed.

One of the most important spray droplet spectra parameters for determining the potential driftability of a spray is the percent of the spray volume which is contained in spray droplets of 100 µm or less (%V<100 µm). From figure 7, it can be seen that the percent fines increased as airspeed increased for all nozzle orifices. Also, as the nozzle orifice size increased, the volume of spray less than 100 µm decreased. For a conventional aerial nozzle, anything over about 10% driftable fines would be of great concern because the spray would have the drift potential of a medium or finer spray whereas coarse sprays are usually preferable where drift is a concern (*ASABE Standards,* 2009). With electrostatic nozzles, the smaller the droplet, the higher the charge-to-mass ratio, and thus, the greater the attraction between droplet and target. Depending on the height above canopy at the time of application, the result will be either deposition of the spray onto the plant surface or off-target movement of the spray due to wind. The distance between droplet and target would be the critical factor determining whether deposition or drift occurs.

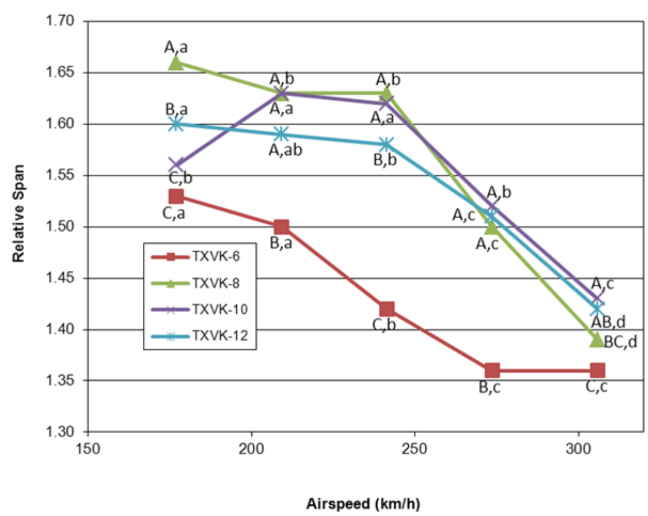

Figure 6. Effect of airspeed and nozzle orifice size on the relative span from the Brazilian aerial electrostatic nozzle. Means followed by the same letter are not significantly different based on Duncan's Multiple Range test with α = 0.05. Differences between spray tips at a given airspeed are designated by a capital letter; between airspeeds for a given spray tip by a lowercase letter.

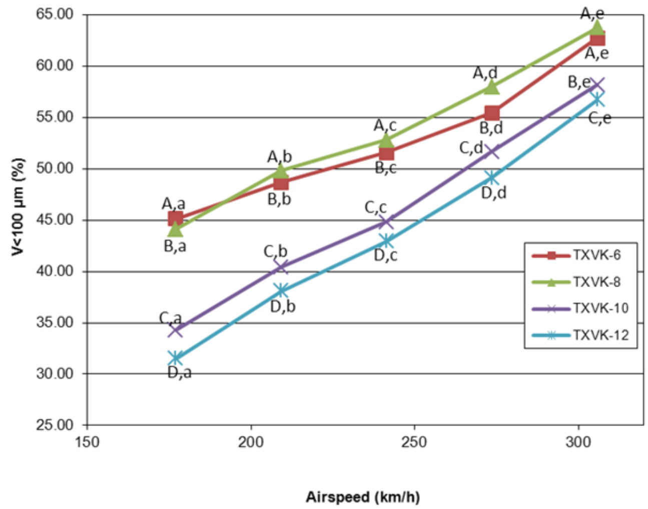

Figure 7. Effect of airspeed and nozzle orifice size on the percent of the spray volume that is contained in spray droplets of 100 µm or less from the Brazilian aerial electrostatic nozzle. Means followed by the same letter are not significantly different based on Duncan's Multiple Range test with α = 0.05. Differences between spray tips at a given airspeed are designated by a capital letter; between airspeeds for a given spray tip by a lowercase letter.

These results from this study are consistent with previous research. Latheef et al. (2008) conducted field research with the original Spectrum aerial electrostatic nozzles but with a spray tip smaller than the TXVK-6 (flowrate = 3.6 g/s) charged to ± 5000 V at 193 km/h, 4.7 L ha^{-1} and 483 kPa and reported a VMD of 95 µm and a %V<100 µm of 53%. These results compare well to an interpolated VMD of 105 µm and %V<100 µm of 47% for the larger TXVK-6 at the reported airspeed.

Conclusion

This study quantified the effects of typical fixed-wing airspeeds and nozzle orifice sizes on the atomization of charged spray from a Brazilian aerial electrostatic nozzle in a controlled high-speed wind tunnel. Without exception, increases in airspeed produced smaller spray droplets for all nozzle orifices tested. With very few exceptions, an increase in nozzle orifice size increased the spray droplet spectra at all airspeeds. These results are in good agreement with previously reported aerial electrostatic droplet spectra data from field studies using water sensitive papers. While the results of this work are currently difficult to interpret and apply because of an overall lack of understanding of how electrostatically-charged aerial sprays deposit under "real-world" conditions, how these charged sprays influence efficacy and the potential for these small-droplet sprays to drift, they lay the groundwork for future research to improve this understanding. Future research should investigate the effects of airspeed and nozzle orifice size on the chargeability of different spray formulations, investigate spray nozzle atomization characteristics at rotary-wing airspeeds and quantify spray drift from electrostatically-charged sprays under field conditions.

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