# AIRSPEED AND ORIFICE SIZE AFFECT SPRAY DROPLET SPECTRA FROM AN AERIAL ELECTROSTATIC NOZZLE FOR ROTARY-WING APPLICATIONS

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*The aerial electrostatic spraying system patented by the U.S. Department of Agriculture–Agricultural Research Service (USDA-ARS) is a unique aerial application system that inductively charges spray droplets for the purpose of increasing deposition and efficacy. While this system has many potential benefits, no published data exist that describe how changes in airspeed or nozzle orifice size affect the droplet spectra of charged sprays at rotary-wing airspeeds. This study quantified these effects in a controlled wind tunnel at airspeeds from 80 to 177 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 generally produced smaller spray droplets for all nozzle orifices tested, as quantified by standard spray droplet parameters. Generally, a decrease in nozzle orifice size increased the fineness of the spray droplet spectra at all airspeeds but also increased the charge-to-mass ratio of the spray, which can improve spray deposition. The results from this study will help aerial applicators better understand how changes in rotary-wing airspeeds and nozzle orifice size affect droplet size from aerial electrostatic nozzles.*

**KEY WORDS:** *electrostatic charging, helicopter, aerial application, aerial spraying, agricultural aviation, laser diffraction*

## 1. INTRODUCTION

Recent increases in fuel prices have forced many aerial applicators to consider alternative agricultural 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), may provide such a benefit. Many aerial applicators around the world currently use this system; however, no known data exist that describe its spray quality at rotary-wing airspeeds and associated nozzle orifice sizes. Rotary-wing electrostatic aerial applicators need knowledge of operational spray parameters to help them decide the best application airspeed and nozzle spray tip for the job. Over the past several decades, much foundational work has been conducted to better understand electrical atomization and electrostatic charging of spray particles for agricultural spray applications (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 have 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, 1998; Giles et al., 1992; 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 at higher, fixed-wing airspeeds with water-sensitive papers has been reported (Fritz et al., 2007; Martin et al., 2007; Latheef et al., 2009). 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 was the subject of this study.

### 1.1 Objectives

The focus of this study was to evaluate the performance of the redesigned Spectrum aerial electrostatic nozzle (Spectrum Electrostatic Sprayers, Houston, Texas), which is referred to here as the Brazilian aerial electrostatic nozzle. The objectives of the study were as follows:

1. To quantify the effects of typical rotary-wing airspeeds and nozzle orifice sizes on the atomization of charged spray from the Brazilian aerial electrostatic nozzle in a controlled wind tunnel.

2. To quantify the electrostatic performance characteristics (charge-to-mass ratio, $Q/M$) of the nozzle for each of the test orifices and at each test airspeed/flow rate.

## 2. MATERIALS AND METHODS

### 2.1 Electrostatic Nozzle Setup

All spray tests were conducted with the Brazilian electrostatic nozzle (Spectrum Electrostatic Sprayers, Houston, Texas). The nozzle was mounted to a test section of a slipstream 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, New York). 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, Wisconsin) was connected to a custom-designed, electrically isolated, Faraday cage, to measure the return spray current through the system to ground (Fig. 2).

#### *2.1.1 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

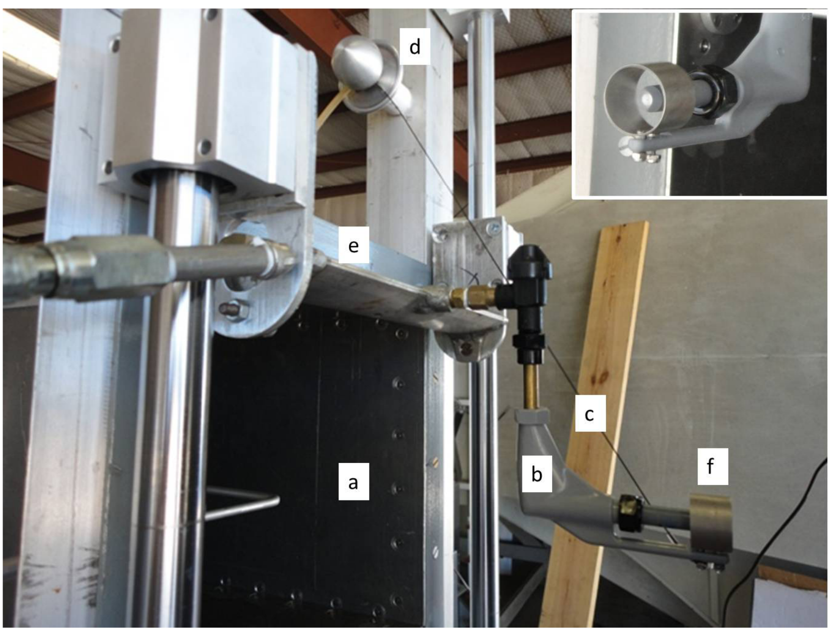


**FIG. 1:** Wind tunnel setup for the study showing: (a) wind tunnel outlet, (b) aerial electrostatic nozzle, (c) high-voltage conductor, (d) power junction, (e) test section of slipstream boom, and (f) charging electrode (inset: spray tip within the charging ring).


**FIG. 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, (d) computer system for processing data, and (e) high-voltage power supply.

of 24–346 km/h. The nozzle was tested at airspeeds of 80–177 km/h, and nozzle orifice diameters of 1.04–1.32 mm (TXVK-4, TXVK-6, and TXVK-8 spray tips; Spraying Systems Co., Wheaton, Illinois) were chosen for this study because they are specifically suited to rotary-wing aircraft. A 50-mesh screen filter with a 138-kPa integrated check valve was used with the TXVK-4 and TXVK-6 spray tips while a 24-mesh screen filter with a 138-kPa integrated check valve was used with the TXVK-8 spray tip. This practice is common because the smaller mesh size used on the TXVK-4 and TXVK-6 helps reduce nozzle plugging of these smaller orifices from foreign materials. All spray testing was completed at 517 kPa using a spray solution of water plus a non-ionic surfactant [0.25% volume-to-volume (v/v) ratio; R-11, Wilbur-Ellis, Devine, Texas] dispensed from an 18.9-L pressure pot (Model 29749PS, Sharpsville Container, Sharpsville, Pennsylvania). 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 measurement range of 0.1–875 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.

### *2.1.2 Charge-to-Mass Ratio Determination*

The 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:

$$\frac{Q}{M} = \frac{I}{\dot{M}_L} \tag{1}$$

where $Q/M$ = charge-to-mass ratio (mC/kg); $I$ = measured return spray current (μA); and $\dot{M}_L$ = liquid mass flow rate (g/s). The spray current with a charging voltage of +6000 V was measured for 60 s with the microammeter previously described. The 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, California). These measurements were replicated three times and the flow rates were averaged for the three replicates.

## 2.2 Statistical Analyses

To test the significance of the airspeed and nozzle orifice size on the spray droplet spectrum parameters, both the airspeed and nozzle orifice size were treated as fixed effects. The Statistical Analysis System, General Linear Model (PROC GLM, SAS Institute, Cary, North Carolina) was used to perform the analyses of variance and to test the significance of each effect at the $\alpha = 0.05$ level of significance according to Duncan's multiple range test. 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.

For each of the graphs in the results section, statistically significant separation of means are indicated by a combination of upper and lower case letters. The upper case letters represent differences in the dependent variable between nozzle orifice sizes and the lower case letters represent differences between airspeeds. For instance, if the droplet size for the TXVK-4 nozzle orifice at 130 km/h is statistically different than that of the TXVK-6 nozzle orifice at the same airspeed, the TXVK-4 data point might have an upper case A next to it on the graph and the TXVK-6 data point might have an upper case B next to it. In addition, for a given nozzle orifice size, if the droplet size at 110 km/h is statistically different than at 130 km/h, the data point at 110km/h might be lower case a, whereas the data point at 130 km/h might be lower case b. Putting these two statistically significant indicators together, a data point may be labeled Aa and another may be labeled Ba. If these points are at a particular airspeed for different nozzle orifice sizes, the labels would indicate a significant difference between the two points (i.e., A versus B). However, if these two points are for a particular nozzle orifice size but at different airspeeds, the labels would indicate no significant difference between the two points, since both are designated with a lower case a. This method of indicating statistical separation of means is very useful when two different dependent variables are jointly considered.

## 3. RESULTS AND DISCUSSION

### 3.1 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 ($Q/M$) ratios with magnitudes on the order of 1.0 mC/kg or greater 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 magnitude of the average $Q/M$ ratio reaches a value of about 1.0 mC/kg. The $Q/M$ ratios for the Brazilian aerial electrostatic nozzle were determined for various orifice sizes and rotary-wing airspeeds at a charging voltage of +6000 V. The results are presented in Table 1. Overall, as the orifice size decreased, the $Q/M$ ratio increased ($P < 0.0001$). This is expected as a lower mass of spray flows through the nozzle with smaller orifices at the same charging voltage. In addition, for all orifice sizes, as airspeeds increased so did the $Q/M$ ratios ($P < 0.0001$). This is likely attributed to a reduction in droplet size (and mass) at higher airspeeds due to increased air shear while the droplets still maintain the same charge. A reduction in nozzle orifice size also increased the $Q/M$ ratio for all airspeeds ($P < 0.0001$). The higher $Q/M$ ratios are desirable because they will favor increased deposition of the spray onto plant targets. Thus, higher application airspeeds would be desirable and should increase spray deposition. It is also important to realize that in an aerial application system, the spray is typically released 2–4 m above the plant canopy. As the droplets fall from their release point to their target, depending primarily upon temperature and relative humidity, they will lose mass due to evaporation. This will increase the $Q/M$ ratio of the droplets at the time of impact, resulting in $Q/M$ ratios higher than those listed in Table 1.

**TABLE 1:** Spray charge-to-mass ratio (mC/kg) from a Brazilian aerial electrostatic nozzle at rotary-wing airspeeds with +6000 V applied voltage

| **Nozzle** | **Flow Rate (g/s)** | **Airspeed (km/h)** | | | |
|---|---|---|---|---|---|
| | | **80** | **113** | **145** | **177** |
| TXVK-4 | 4.94 | –0.648 Aa | –0.850 Ab | –0.972 Ac | –1.114 Ad |
| TXVK-6 | 7.01 | –0.500 Ba | –0.714 Bb | –0.828 Bc | –0.928 Bd |
| TXVK-8 | 8.87 | –0.394 Ca | –0.575 Cb | –0.789 Cc | –0.845 Cd |

Note: The spray solution was water plus 0.25% v/v non-ionic surfactant. Means followed by the same letter are not significantly different based on Duncan's multiple range test with $\alpha = 0.05$. Differences within a column are designated by an upper case letter; differences within a row are designated by a lower case letter.

## 3.2 Spray Atomization

The spray droplet spectra data from the Brazilian aerial electrostatic nozzle tested at various rotary-wing airspeeds and nozzle orifice sizes are presented below. The first parameter of interest was $D_{v0.1}$, which is the droplet diameter where 10% of the spray volume is contained in droplets smaller than this value (Fig. 3). Figure 3 shows that both the airspeed and nozzle orifice size affected $D_{v0.1}$. Overall, as the airspeed increased, $D_{v0.1}$ generally decreased for all nozzle orifice sizes. The common exception to this was at 80 km/h, where each of the nozzle tips yielded a smaller $D_{v0.1}$ than at 113 km/h. This interesting anomaly at 80 km/h is not consistent with the results found at higher airspeeds (Martin and Carlton, 2013), where the trend was generally a consistent decrease of $D_{v0.1}$ with increasing airspeed. This could be an artifact of using a spatial sampling system (laser diffraction) because relative droplet velocity profiles will affect the reported data. Additionally, at all airspeeds, $D_{v0.1}$ increased as the nozzle orifice size increased from TXVK-4 to TXVK-6. However, the opposite trend was seen when switching from the TXVK-6 to the TXVK-8 spray tip, which yielded a lower $D_{v0.1}$ than TXVK-6 at all airspeeds. It is possible that the larger droplets produced by the TXVK-8 nozzle underwent secondary atomization due to air shear, resulting in lower $D_{v0.1}$ values than the TXVK-6 nozzle.

Another parameter of interest was $D_{v0.5}$, or the volume median diameter (VMD), which is the droplet diameter where 50% of the spray volume is contained in droplets

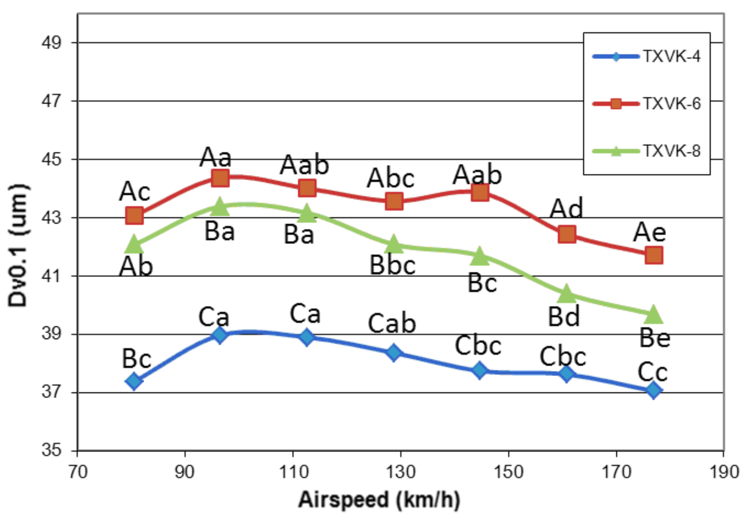


**FIG. 3:** Effect of rotary-wing airspeed and nozzle orifice size on $D_{v0.1}$ from the Brazilian aerial electrostatic nozzle. Means followed by the same letter are not significantly different based on Duncan's multiple range test with $\alpha$ = 0.05. Differences between spray tips at a given airspeed are designated by an upper case letter; differences between airspeeds for a given spray tip are designated by a lower case letter.

smaller than this value. Again, from this parameter it can be seen that the VMD of the spray generally decreased with increasing airspeed for all nozzle orifices except for the TXVK-8 nozzle at 80 km/h (Fig. 4). In addition, overall, as the nozzle orifice size increased, the VMD also increased, except for the TXVK-8 nozzle at 80 km/h, which had a smaller VMD than the TXVK-6 nozzle at the same airspeed (121.14 versus 124.51 μm). Interestingly, the VMD values for the TXVK-4 orifice were much lower than those for the TXVK-6 or TXVK-8 orifice at all airspeeds. The VMD values for TXVK-6 and TXVK-8 were virtually identical for airspeeds below 129 km/h, and only nominally different from 129 to 177 km/h. The overall trend for the VMD as a function of airspeed and orifice size agrees with previously published fixed-wing data for the same nozzle (Martin and Carlton, 2013).

Analysis of $D_{v0.9}$, 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 generally resulted in a decrease in $D_{v0.9}$ of the spray for all orifice sizes, with stronger trends as the airspeed increased (Fig. 5). Additionally, an increase in nozzle orifice size generally resulted in an increase in $D_{v0.9}$ for all airspeeds. Significant differences between $D_{v0.9}$ of the TXVK-6 and TXVK-8 orifices were only seen above 113 km/h, whereas $D_{v0.9}$ of TXVK-4 was much smaller than both the TXVK-6 and

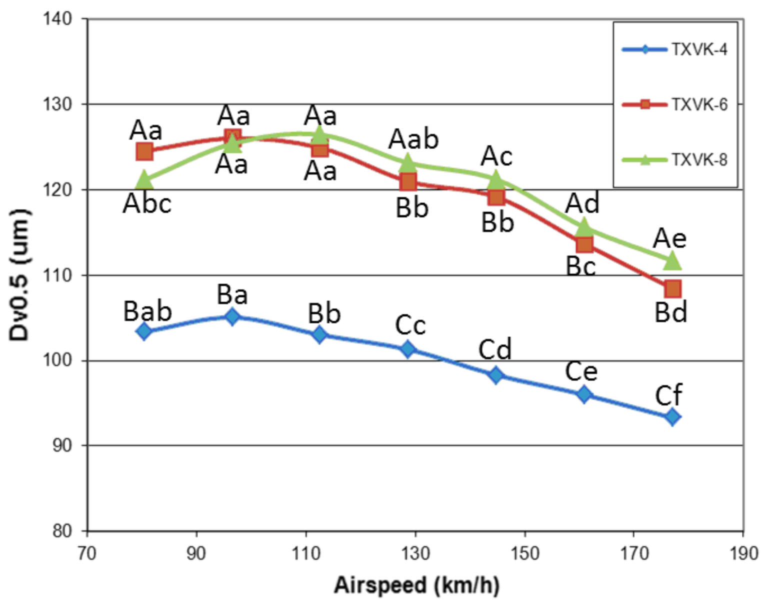


**FIG. 4:** Effect of airspeed and nozzle orifice size on $D_{v0.5}$ from the Brazilian aerial electrostatic nozzle. Means followed by the same letter are not significantly different based on Duncan's multiple range test with $\alpha = 0.05$. Differences between spray tips at a given airspeed are designated by an upper case letter; differences between airspeeds for a given spray tip are designated by a lower case letter.

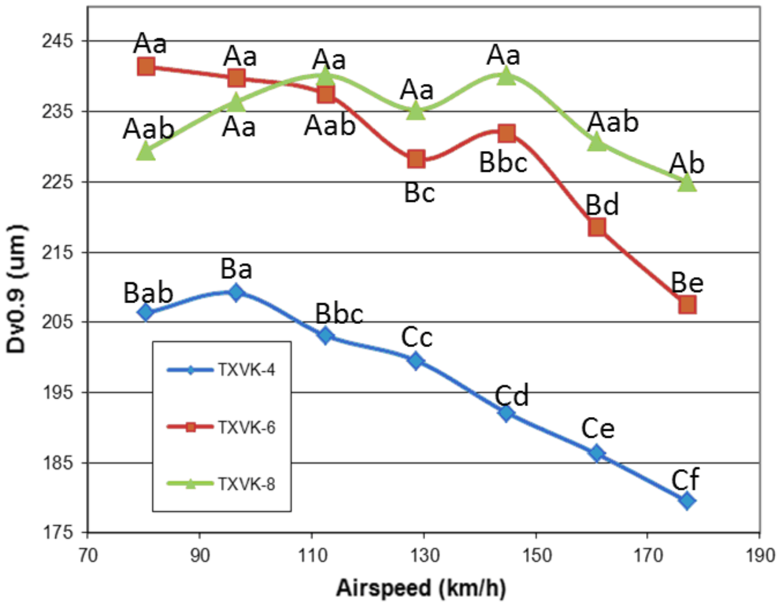


**FIG. 5:** Effect of airspeed and nozzle orifice size on $D_{v0.9}$ from the Brazilian aerial electrostatic nozzle. Means followed by the same letter are not significantly different based on Duncan's multiple range test with α = 0.05. Differences between spray tips at a given airspeed are designated by an upper case letter; differences between airspeeds for a given spray tip are designated by a lower case letter.

TXVK-8 orifices at all airspeeds. These results for $D_{v0.9}$ are consistent with previously published results for this nozzle at higher airspeeds (Martin and Carlton, 2013).

The relative span (RS) of a spray is defined as

$$\text{RS} = \frac{(D_{v0.9} - D_{v0.1})}{D_{v0.5}} \tag{2}$$

For aerial spray applications, a lower RS is usually desirable because the range of droplet sizes is minimized. However, a lower RS 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 RS may be desired. In this study, the RS of the spray did not follow a consistent pattern (Fig. 6). For the TXVK-4 orifice, the RS generally decreased as the airspeed increased, for all airspeeds. The opposite trend resulted from the TXVK-8 orifice because it remained unchanged for airspeeds between 80 and 129 km/h; however, it generally increased at airspeeds between 145 and 177 km/h. The airspeed had very little effect on the RS of the TXVK-6 orifice. Above 129 km/h, the RS resulting from the TXVK-8 nozzle was much greater than that of the TXVK-4 or TXVK-6 orifice.

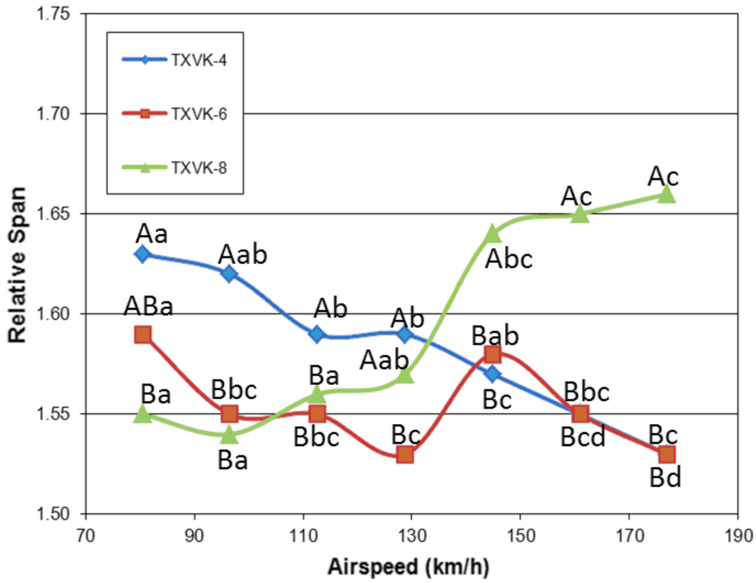


**FIG. 6:** Effect of airspeed and nozzle orifice size on the RS from the Brazilian aerial electrostatic nozzle. Means followed by the same letter are not significantly different based on Duncan's multiple range test with $\alpha = 0.05$. Differences between spray tips at a given airspeed are designated by an upper case letter; differences between airspeeds for a given spray tip are designated by a lower case letter.

One of the most important spray droplet spectra parameters for determining the potential driftability of a spray is the percent of the spray volume that is contained in fines. This fraction of the spray is usually reported as the percentage of the spray volume that contains 100–200 μm droplets or less (Yates et al., 1976; Miller, 1993; Hoffmann and Kirk, 2005; Fritz et al., 2010; Martin and Carlton, 2013). In this study, we report the percent volume of the spray that contains droplets of 100 μm or less, which shall henceforth be referred to as percent fines. From Fig. 7, it can be seen that the percent fines generally increased as the airspeed increased for all nozzle orifices with the exception of the TXVK-4 orifice at 80 km/h, where the percent fines at this point were slightly higher than at 97 km/h. Also, as the nozzle orifice size increased from the TXVK-4 nozzle orifice to the TXVK-6 orifice, the percent fines decreased. However, there was no difference in percent fines between the TXVK-6 and TXVK-8 orifices, except at 177 km/h, where the TXVK-6 orifice resulted in a slightly higher percentage of fines (45.14 versus 44.11%). The overall trend of a general increase in percent fines with decreasing orifice size and increasing airspeed is consistent with previous research at higher airspeeds (Martin and Carlton, 2013). 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 when drift is a concern. With

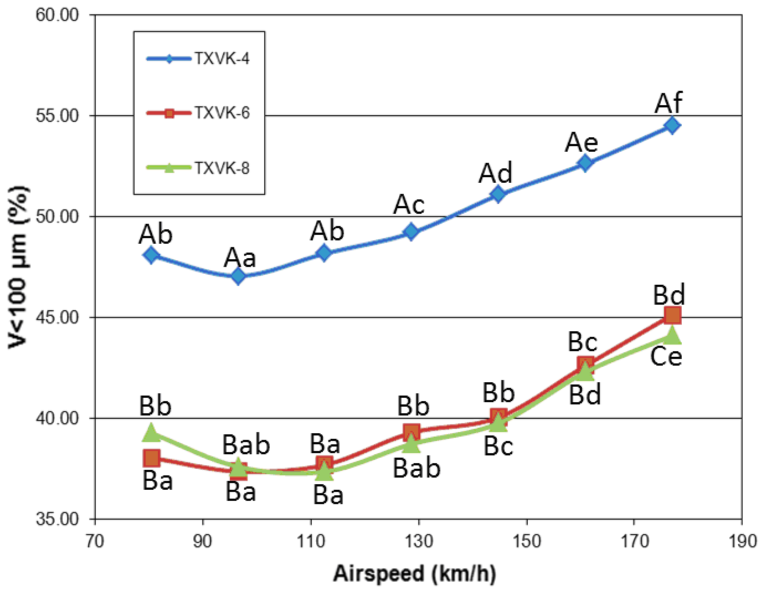


**FIG. 7:** Effect of airspeed and nozzle orifice size on percent fines (percent of the spray volume that is contained in spray droplets of 100 µm or less) from the Brazilian aerial electrostatic nozzle. Means followed by the same letter are not significantly different based on Duncan's multiple range test with $\alpha = 0.05$. Differences between spray tips at a given airspeed are designated by an upper case letter; differences between airspeeds for a given spray tip are designated by a lower case letter.

electrostatic nozzles, the smaller the droplet, the higher is 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 the droplet and target would be the determining factor whether deposition or drift occurs.

## 4. CONCLUSIONS

This study quantified the effects of typical rotary-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 from 97 to 177 km/h generally produced smaller spray droplets for all nozzle orifices tested. Additionally, an increase in nozzle orifice size generally increased the VMD and $D_{v0.9}$ but reduced the percent fines (% volume $<$ 100 µm) at all airspeeds. Increases in airspeed and reductions in nozzle orifice size also increased the $Q/M$ ratio of the resulting spray, which should increase deposition on plant targets. These results agree well with previously reported data for aerial electrostatic droplet spectra using the same nozzle at higher, fixed-wing airspeeds (Martin and Carlton, 2013). While it is currently difficult to correlate the results of this study with actual in-field deposition, how these charged sprays influence efficacy, or 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, quantify spray drift and deposition from electrostatically charged sprays under field conditions, and compare the performance of a newly designed aerial electrostatic nozzle to the current nozzle.

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