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Spray Drift Reduction Evaluations of Spray Nozzles Using a Standardized Testing Protocol

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ABSTRACT: The development and testing of drift reduction technologies (DRTs) have come to the forefront of application research in the past few years in the United States. DRTs can be spray nozzles, sprayer modifications, spray delivery assistance, spray property modifiers (adjuvants), and/or landscape modifications. A protocol for testing DRTs in high speed wind tunnels has been previously reported and was expanded to test spray nozzles. This manuscript reports on the initial implementation of the DRT program for conducting DRT evaluations of three spray nozzles under high speed conditions (i.e.,45–65 m/s (100–140 mph)), which are relevant to the aerial application of crop production and protection materials. The spray nozzles were evaluated in the USDA-Agriculture Research Service High Speed Wind Tunnel facility. The droplet size of each of the nozzles with different airspeeds, spray pressures, and orientation was measured with a Sympatec Helos laser diffraction instrument. The droplet size spectra for each test were input in a spray dispersion model (AGDISP), which calculates the downwind drift expected from a typical aerial application scenario. As compared to the reference nozzle, the three spray nozzles reduced spray drift by 70–84 % as compared to the reference nozzle. The nozzles generated spray droplets with volume median diameters 60–80 μm larger than the reference nozzle. One of the aerial application industry's best management practices (BMPs) is to not spray directly on the downwind edge of a field. The spray swath near this edge is moved upwind (i.e., offset) by 1/2 to 1 swath width. When this BMP was combined with the drift reductions from the spray nozzles, the amount of drift reduction was slightly increased; however, application efficiencies increased to 93–96 %. These results demonstrate the possibility of combining multiple drift reduction techniques and technologies to greatly reduce spray drift.

KEYWORDS: drift, DRT, drift reduction technology, droplet sizing, spray droplet size

Introduction

The development and testing of drift reduction technologies (DRTs) have come to the forefront of application research in the past few years in the United States. The need to develop a testing program for measuring DRTs was recognized by the EPA in 2004 [1]. DRTs can be spray nozzles, sprayer modifications, spray delivery assistance, spray property modifiers (adjuvants), and/or landscape modifications. The DRT program is an EPA-led program to "achieve improved environmental and human health protection through drift reduction by accelerating the acceptance and use of improved and cost-effective application technologies" [2]. The first step in implementing the DRT program is to develop a set of protocols, standard operating procedures, and data quality assurance steps so that the results from any trials or research conducted are scientifically valid and repeatable; data quality and protection must also be maintained throughout the study [3,4].

Computer models for predicting spray deposition and dispersal have been developed over the last 30 years [5,6]. AGDISP is the model that is currently being used in the field of aerial application [7,8]. AGDISP is a near-wake model that "solves a Lagrangian system of equations for the position and position variance of spray material released from each nozzle on an aircraft" [9]. This model has been used to predict deposition and drift from aerial spray nozzles [10,11].

Best management practices (BMPs) are common industry practices that are used to apply agrochemicals to optimize swath deposition while minimizing off-target movement. For aerial applications, common

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BMPs are identification of sensitive areas around a field to be sprayed, modification of spray applications to account for changes in wind speed and direction, proper equipment setup to optimize agrochemical delivery [12], and other professional practices all directed at making the most effective spray application. One common BMP is the use of a swath offset to minimize off-target deposition when an application is made near a downwind field edge. This practice involves moving a spray swath some distance upwind of a downwind field edge while spraying in a crosswind [13].

The objective of this work is to evaluate the DRT testing program for aerial applications under high airspeeds (i.e., >100 km/h (~ 60 mph), which is typical for these type of crop production and protection material applications. The testing protocols rely on established professional standards, such as ASTM E361-01, Standard Methods for Testing Hydraulic Spray Nozzles Used in Agriculture [14]; ASAE S572, Standard Spray Nozzle Classification by Droplet Spectra [15]; ASAE S561.1, Standard Procedure for Measuring Drift Deposits from Ground, Orchard and Aerial Sprayers [16]; and peer- and EPA-reviewed protocols [17,18].

The measure of performance for the DRTs (nozzles) for high speed wind tunnels will be derived from droplet size distribution measurements. These values will be used by EPA to model deposition from 0 to 10 m downwind of a field edge. The basic experimental design will be to measure the droplet size spectrum under targeted test conditions with the test nozzles operating at specified spray pressures and airspeeds. The measured droplet size spectrum of the DRT system and the reference nozzle, along with the established test condition bounds, will be used to predict deposition downwind of an aerially applied swath using a spray drift model such as AGDISP [11,19].

Materials and Methods

This testing will gather information and data for evaluating the applicability of the pesticide spray DRT protocol for successfully testing commercially ready pesticide spray DRT nozzles. All high speed tests were conducted in the USDA-Agriculture Research Service (ARS) wind tunnel located in College Station, TX. The specific operating conditions used during the testing are documented in the following section. The procedure discussed in this work follow the quality assurance developed to evaluate the performance of the DRT and document the test conditions.

Three test nozzles and a reference nozzle were tested using the pesticide spray DRT protocol. The three test nozzles were a ULD 120-04 nozzle (Hypro, New Brighton, MN), an AI-110 VS nozzle (Teejet Technologies, Wheaton, IL), and a CP11TT 40° flat fan nozzle with a #08 orifice (CP Products Inc., Mesa, AZ). The nozzle used to define the fine/medium boundary in the American Society of Agriculture and Biological Engineers (ASABE) standard was selected as the reference nozzle [18]. Specifically, this reference nozzle was a Spraying Systems 110° flat fan nozzle with an #03 orifice operated at 300 kPa (43 psi). The testing nomenclatures for the nozzles tested were

- N1: Hypro ULD 120–04,
- N2: Teejet AI 11003 VS, and
- N3: CP11TT 4008.

Spray Solutions

All nozzle evaluations were made using a spray solutions containing water with 0.25 % volume/volume (v/v) of a 90 % nonionic surfactant (NIS) (R-11, Wilbur-Ellis Co., San Antonio, TX). The water plus NIS solution was used because it is a good simulant of most water-based insecticide sprays [20,21] and allows the sprayers to be tested without exposing the personnel involved with this study to insecticides.

Droplet Size Measurements

A Sympatec Helos laser diffraction droplet sizing system (Sympatec Inc., Clausthal, Germany) was used to measure the droplet size downwind of the tested nozzles. The Helos system utilizes a 623 nm He–Ne laser and was fitted with a lens (denoted by manufacturer as R7) with a dynamic size range of 0.5–3500 μm, which is 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. The laser was horizontally positioned so that the beam was in the center of the wind tunnel outlet.

FIG. 1—*Sympatec system positioned on both side of the high speed tunnel with the tunnel outlet on the right side of the picture.*

Droplet size measurements included volume median diameter ($D_{V0.5}$) and $D_{V0.1}$ and $D_{V0.9}$. $D_{V0.5}$ is the droplet diameter (μm) where 50 % of the spray volume or mass is contained in droplets of lesser diameter. $D_{V0.1}$ and $D_{V0.9}$ values, which describe the proportion of the spray volume (10 % and 90 %, respectively) contained in droplets of a specified size or less. The percent volume less than 200 μm, which is an indicator of the "driftable" portion of a spray, was also computed along with the relative span (RS) (Eq 1), which is a dimensionless measure of the spread of the droplet sizes in the spray

$$\mathrm{RS} = \frac{D_{V0.9} - D_{V0.1}}{D_{V0.5}} \tag{1}$$

All measurements were conducted at the USDA-ARS wind tunnel site in College Station (Fig. 1). Three replications were conducted for each combination of air speed, spray nozzle, spray solution, and/or nozzle orientation. In order to meet the data quality indicator guidelines, the measured volume median diameter ($D_{V0.5}$) and $D_{V0.1}$ and $D_{V0.9}$ (the droplet diameter bounding the upper and lower 10 % fractions of the spray) should vary by less than ±3 %. A replication comprised of traversing the entire spray plume through the Sympatec Helos laser beam nozzle at a distance of 61 cm (24 in.) from the laser beam of the droplet measurement system. Tests were performed within the guidelines provided by ASTM E1260-05, Standard Test Method for Determining Liquid Drop Size Characteristics in a Spray Using Optical Non-imaging Light-Scattering Instruments [22].

AGDISP Model Setup and Inputs

Computer models are typically very sensitive to the input variables, and AGDISP is not different. AGDISP Ver. 8.21 was used in the modeling scenarios with the following inputs standard across all scenarios reported in this manuscript:

- Aircraft: Air Tractor AT-401 with 20 m (66 ft) swath width;
- Application scenario: 3.5 m (11.5 ft) release height with ten spray applications moving upwind; and
- Meteorological conditions: Wind speed, 2.2 m/s (5 mph) @ 90° (crosswind); temperature, 26.6°C (80°F); and relative humidity, 70 %.

More detailed explanations of the inputs into the AGDISP model have been reported in the literature [11,19].

Based on the droplet size measurements from each of the nozzle evaluations, the corresponding droplet size data were input into the model, and a simulation run was made with the AGDISP model. One of the default settings in the AGDISP model is a swath offset of 0. The effects of changing this offset from 0 to 1/2 swath offset were modeled. As noted previously, the practice of using 1/2 to 1 full swath offset is a common BMP that aerial applicators use during spray applications.

TABLE 1—*Drift reduction classification for the LERAP and ISO system based on percentage reduction of candidate system as compared to reference system.*

Drift reduction, %[a]	$25 \leq 50$	$50 \leq 75$	$75 \leq 90$	$90 \leq 95$	$95 \leq 99$	≥ 99
LERAP drift classification	*	**	***	***	***	***
ISO drift classification	F	E	D	C	B	A

[a] Drift reduction is the percentage of drift reduction achieved by a technology as compared to a standard reference.

Drift Reduction Ratings from ISO and LERAP Standards—The two most commonly used drift reduction classification systems are the Local Environmental Risk Assessment for Pesticide (LERAP) and the International Standards Organization (ISO) systems. The LERAP system [23] uses a system of stars (no stars to ***) to denote the level of drift reduction that a given technology provides as compared to a reference system [24]. The rating to determine the size of the spray buffer mitigation the applicator can use with a given spray technology. The ISO drift reduction standard [25] defines the six drift reduction classes ranked alphabetically (A–F), with the A class having the greatest percentage reduction and the F class the least (Table 1). The ISO classification is also used as a method to mitigate the size of a no-spray buffer area. Unlike the ISO classification system, the LERAP method groups systems with a 75 % reduction or greater into a single classification group.

Statistical Analyses—No attempt was made to statistically separate the droplet size means from the four nozzles in these tests. The measurements were taken as input into the AGDISP model. The modeling data were also not statistically separated since the modeling results for a given set of inputs are always the same.

Results

The droplet size measurements for the reference and three test nozzles are shown in Table 2. As expected, the droplet size decreased for each of the nozzles as the airspeed in the wind tunnel increased from 53 to 63 m/s. The droplet sizes also increased with N1 and N2 when the spray pressure was increased from 207 to 413 kPa. These data were used in all of the subsequent AGDISP modeling work.

Modeling Application Efficiency

After running AGDISP using the droplet size measurements for the different testing scenarios (nozzle, pressure, and airspeed), the modeling outputs were recorded. Application efficiency is the amount of spray material, expressed as a percentage of spray released from the simulated aircraft, which deposits in the field or targeted area. For all of the simulations, downwind deposition out to 10 m was modeled. This is

TABLE 2—*Droplet size data from nozzle evaluation tests.*

Nozzle	Airspeed m/s (mph)	Spray Pressure kPa (psi)	$D_{V0.5}$ [a] (μm)	RS[b]	%<200 μm [c]
Reference	53 (120)	350 (42)	210.7	1.13	45.6
	63 (140)	350 (42)	183.5	1.13	57.9
N1	53 (120)	207 (30)	276.7	1.06	25.9
		413 (60)	290.1	1.04	22.3
	63 (140)	207 (30)	214.5	1.13	44.1
		413 (60)	228.6	1.11	39.0
N2	53 (120)	207 (30)	275.9	1.07	26.5
		413 (60)	291.0	1.07	23.1
	63 (140)	207 (30)	223.2	1.12	40.9
		413 (60)	234.2	1.10	37.1
N3	53 (120)	275 (40)	308.5	1.03	21.1
	63 (140)	275 (40)	261.1	1.10	30.2

[a] $D_{V0.5}$=volume median diameter.

[b] Relative span=$[D_{V0.9}-D_{V0.1}]/D_{V0.5}$.

[c] %<200 μm=percentage of spray volume comprised of droplets less than 200 μm in diameter.

TABLE 3—*Modeled application efficiency, downwind deposition, and airborne drift from the four nozzle tests at airspeeds of 53 m/s (120 mph).*

Nozzle	Pressure kPa (psi)	Application Efficiency, Percent of Applied	Downwind Deposition (%)	Airborne Drift (%)
Reference	350 (43)	86.74	11.75	1.51
N1	207 (30)	90.34	9.34	0.33
	413 (60)	90.76	8.97	0.27
N2	207 (30)	90.21	9.35	0.45
	413 (60)	90.67	9.03	0.30
N3	275 (40)	91.16	8.61	0.24

representative of the spray deposition from the edge of the swath to a distance 10 m downwind. The airborne drift at 10 m represents the portion of the spray volume that remains in the air at this distance. If different distances were selected, the numerical values would change, but the trends would remain the same.

The modeled outputs for airspeed tests of 53 and 63 m/s are presented in Tables 3 and 4, respectively. The reference nozzle generated an application efficiency of 86.7 % with 1.5 % of the spray in the air 10 m from the field boundary in the 53 m/s modeling runs. The three nozzles (N1, N2, and N3) tested all had improved application efficiencies and large decreases in airborne drift as compared to the reference nozzle. In the 63 m/s tests, the reference nozzle had an application efficiency of 84.6 % and 2.45 % of the spray was still airborne at 10 m. The three nozzles tested all had improved application efficiencies and decreases in airborne drift.

Drift Reduction from Nozzles

Drift reduction is defined as the reduction in the airborne portion of the spray as compared to a reference (ISO standard). The test nozzles reduced airborne spray drift by 70–84 % in the 53 m/s airstreams and from 41 % to 74 % in the 63 m/s airstream tests (Table 5). At lower airspeed, the tested nozzles received E and D ratings based on the ISO drift classification scheme and ** and *** based on the LERAP scheme (Table 5). At 63 m/s, the test nozzles received F and E ratings based on the ISO drift classification scheme and * and ** based on the LERAP scheme.

Effects of Swath Offset on Application Efficiency and Drift Reduction

All of the scenarios that were modeled to produce the results in Tables 3 and 4 were rerun with a 1/2 swath offset except the reference nozzle settings. A 1/2 swath offset was the equivalent of making a spray application 10 m further upwind from the field edge. For both of the airspeeds, the three nozzles combined with a 1/2 swath offset resulted in application efficiencies between 93 % and 97 % (Tables 6 and 7) and only minor changes in the airborne drift percentages. The offset results in more material depositing in the field, which is why aerial applicators have adopted this practice. After running the same drift reduction calculations with the swath offset included, the only scenario that resulted in a change in drift classification was N3 at 53 m/s, which improved from an E to a D on the ISO drift classification system but did not change under the LERAP scheme.

TABLE 4—*Modeled application efficiency, downwind deposition, and airborne drift from the four nozzle tests at airspeeds of 63 m/s (140 mph) airstream.*

Nozzle	Pressure kPa (psi)	Application Efficiency, Percent of Applied	Downwind Deposition (%)	Airborne Drift (%)
Reference	350 (43)	84.63	12.91	2.45
N1	207 (30)	87.19	11.36	1.45
	413 (60)	88.13	10.70	1.18
N2	207 (30)	87.84	10.85	1.32
	413 (60)	88.58	10.47	0.952
N3	275 (40)	89.7	9.67	0.629

TABLE 5—*Drift reductions from three spray nozzles as compared to a reference nozzle with corresponding ISO and LERAP drift reduction ratings.*

Nozzle	Pressure kPa (psi)	Drift Reduction (%)	ISO Drift Ratings	LERAP Drift Ratings
53 m/s airspeed				
N1	207 (30)	78.4	D	***
	413 (60)	82.3	D	***
N2	207 (30)	70.3	E	**
	413 (60)	80.3	D	***
N3	275 (40)	84.3	D	***
63 m/s airspeed				
N1	207 (30)	40.8	F	*
	413 (60)	51.8	E	**
N2	207 (30)	46.1	F	*
	413 (60)	61.1	E	**
N3	275 (40)	74.3	E	**

Conclusions

This work examined a drift reduction testing protocol comparing three different nozzles to a reference nozzle. Additionally, an industry BMP of offsetting near field edge spray swaths was examined. The techniques and procedures for determining the nozzle effects on spray droplet size under high speed air-sheer showed distinct differences between the nozzles tested and the reference nozzle. Using the AGDISP model, these droplet size results were translated to estimates of downwind deposition and airborne drift as a means of comparing the relative efficiencies of each nozzle as compared to the reference nozzle under different airspeeds and pressures. When compared to the reference nozzle, the results showed that the following.

TABLE 6—*Modeled application efficiency, downwind deposition, and airborne drift from three nozzle tests in a 53 m/s (120 mph) airstream combined with a 1/2 swath offset.*

Nozzle	Pressure kPa (psi)	Application Efficiency, Percent of Applied	Downwind Deposition (%)	Airborne Drift (%)
Reference[a]	350 (43)	86.74	11.75	1.51
N1	207 (30)	96.14	3.54	0.322
	413 (60)	96.57	3.17	0.261
N2	207 (30)	96.02	3.55	0.437
	413 (60)	96.47	3.24	0.293
N3	275 (40)	96.95	2.82	0.227

[a] Reference modeling results were not run with a swath offset.

TABLE 7—*Modeled application efficiency, downwind deposition, and airborne drift from three nozzle tests in a 63 m/s (140 mph) airstream combined with a 1/2 swath offset.*

Nozzle	Pressure kPa (psi)	Application Efficiency, Percent of Applied	Downwind Deposition (%)	Airborne Drift (%)
Reference	350 (43)	84.63	12.91	2.45
N1	207 (30)	93	5.59	1.41
	413 (60)	93.95	4.9	1.14
N2	207 (30)	93.66	5.06	1.28
	413 (60)	94.41	4.66	0.93
N3	275 (40)	95.56	3.84	0.60

- The three spray nozzles reduced spray drift potential by 40–84 % due mainly to the larger $D_{V0.5}$ values, which were 30–80 μm larger than the $D_{V0.5}$ for the reference nozzle.
- After modeling the aerial application industry's BMPs of 1/2 swath offset, the results showed further increases in drift reduction and large increases in application efficiency with application efficiencies ranging from 93 % to 97 %.
- The combination of multiple drift reduction techniques/technologies can greatly reduce spray drift.

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