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The Effect of Adjuvants at High Spray Pressures for Aerial Applications

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ABSTRACT

Controlling droplet size is a critical part of making any successful agrochemical spray application. This is particularly true for higher-speed aerial applications where secondary atomization from air shear becomes the most dominant factor driving spray droplet size. Previous research has shown that higher spray pressures can result in larger droplet-sized sprays by increasing the exit velocity of the spray liquid from the nozzles, which in turn decreases the differential velocity between the spray liquid and surrounding airstream, reducing secondary breakup. This work explores the effects of higher-than-normal spray pressures on two typical aerial application nozzles in the presence of a formulated herbicide spray solution, with and without additional adjuvants. Generally, the spray solution effects followed trends seen in previous studies, with crop oil-containing adjuvants resulting in the largest droplet-sized sprays and the silicones and polymers the smallest. Increasing spray pressure increased droplet size across all combinations of nozzle, airspeed, and spray solution, without exception. The most promising results from this work showed that for typical high-end application airspeeds, increasing spray pressure from the lowest to highest pressures tested generally resulted in spray classifications increasing at least one

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size coarser. The results from this work demonstrate that larger, faster-flying agricultural aircraft can adopt current methods, with potentially minor equipment adjustments, to generate medium and larger spray qualities and to allow for more efficient applications while meeting agrochemical product label requirements.

Keywords

aerial application, droplet size, droplet size model, adjuvants, spray pressure

Introduction

Droplet size is critical to the efficacy and off-target movement of any agrochemical application. A number of factors affect droplet size from aerial applications—including the type of nozzle selected [1,2], nozzle setup and operation [2–5], and the physical properties of the formulation type and spray mixture used [6–10]. Specific formulation or adjuvant effects (or both) on both droplet size and spray drift have been examined but tend to be limited to either ground application conditions [7,11–13] or to adjuvants tested in the absence of active products [9,14–16]. The influence of formulated products [17–19] and the increased air shear from higher airspeeds [10,20] may mask adjuvant effects. The air shear effect is not solely due to the speed of the surrounding air, rather it is a function of the differential velocity between the surrounding airstream and the liquid exiting the nozzle [21,22]. All of these factors combine to complicate fully understanding the atomization process and developing technologies and methods for maintaining droplet size, particularly at airspeeds associated with larger, faster-flying aircraft.

The authors found that droplet size increased with increasing pressures from 270 to 621 kPa (30 to 90 psig) for flat fan, hollow cone, anvil deflection, and straight stream nozzles [23] in a concurrent airstream up 80 m/s (180 mph). This effect, however, is limited primarily to nozzle orientations such that the liquid exits at, or near, the same directional vector as the concurrent airstream. At larger deflection angles, the liquid velocity is counter to the airflow, which increases the secondary atomization from shearing. With the nozzles tested, and for the orientations where this effect holds, the authors observed no plateauing in the increase in droplet size up to the 621 kPa tested [23]. Unpublished data by the authors demonstrated that this increase continues past the 621 kPa pressure threshold for many nozzles.

As part of examining the spatial bias of laser diffraction measurement systems, Hewitt and Valcore [24] examined the varying effects of concurrent airstream velocities as a means of maintaining homogenous droplet velocities to minimize the spatial bias. As part of this work, airspeeds up to 54 m/s (120 mph) were evaluated using nozzles with exit velocities between 13 and 16 m/s (30 and 35 mph). Their results showed an increase in volume median diameter ($D_{V0.5}$) and a decrease in the percent spray volume comprised of droplets of diameter of 141 µm or less up to airspeeds ranging from 11 and 22 m/s (25 and 50 mph), depending on the nozzle, as a result of the spatial bias [24]. They concluded that concurrent airspeeds between

8 and 11 m/s (18 and 25 mph) minimized the spatial bias with no air shear effects. Earlier work looking at critical droplet diameters that survived in specified airstream velocities concluded that a 1,000-μm droplet would shatter in the presence of a relative critical velocity (differential velocity between the droplet and the surrounding airstream) of 5 m/s (11.5 mph) [25,26]. Similarly, a 500-μm droplet would break up at a relative critical velocity of 8 m/s (18 mph), and a 300-μm droplet would likewise break up faced with a relative critical velocity of 22 m/s (49 mph). As the droplets get smaller, the relative critical velocity at which that droplet survives increases. From both of these sources, we can conclude that the air shear effect depends on the airstream velocity and the size and velocity of the individual particles. To simplify later discussion, we will postulate that, for a composite spray cloud (many droplet diameters and velocities), a critical differential velocity for which air shear comes into play is between approximately 8 and 22 m/s (18 and 50 mph).

The objective of this study was to evaluate the potential of using elevated spray pressures to mitigate air shear effects by increasing nozzle fluid exit velocities under aerial application airspeeds using a formulated active product and adjuvant-based spray solutions.

Materials and Methods

EXPERIMENTAL DESIGN

Two nozzles were evaluated, a 20° and a 40° flat fan, each with a #15 orifice, that were fit into a CP11TT nozzle body (Transland, LLC, Wichita Falls, TX). Throughout the remainder of the text, these nozzles will be referred to as 2015 and 4015 nozzles for the 20° and 40° flat fans, respectively. For each nozzle, the airspeed range evaluated was 62.6 to 80.5 m/s (140 to 180 mph) with the pressures tested ranging from 276 to 827 kPa (40 to 120 psi). The nozzle body orientation in the airstream remained constant, with the body parallel to the airstream during all testing. To characterize spray droplet size across the entire airspeed and spray pressure operational space tested, a response surface model experimental design was used for each nozzle and spray solution [23]. Using SAS's JMP software (Version 11.2, SAS Institute, Cary, NC), a response surface design structure, with spray pressure and airspeed as continuous numeric factors, was established. This resulted in 12 treatments for each nozzle/solution combination (Table 1). Note that Treatments 5, 6, and 7 are identical. This is typical of response surface type designs where the middle of the operational space is critical to overall model reliability. These treatments were not run sequentially, rather they were dispersed among the other treatments.

SPRAY SOLUTIONS EVALUATED

Six spray solutions were evaluated as part of this research. A water plus nonionic surfactant (NIS) spray mixture (0.25 % v/v of 90 % NIS) was the only nonactive spray solution. This solution was included to provide a standardization mark in the data set because this solution is one commonly used by the authors as a “blank” to

TABLE 1 Response surface experimental design treatments used to evaluate each nozzle type/spray solution combination.

Treatment	Pressure kPa (psi)	Airspeed m/s (mph)
1	276 (40)	62.6 (140)
2	276 (40)	71.5 (160)
3	276 (40)	80.5 (180)
4	552 (80)	62.6 (140)
5	552 (80)	71.5 (160)
6	552 (80)	71.5 (160)
7	552 (80)	71.5 (160)
8	552 (80)	71.5 (160)
9	552 (80)	80.5 (180)
10	827 (120)	62.6 (140)
11	827 (120)	71.5 (160)
12	827 (120)	80.5 (180)

mimic typical active spray solutions. The remaining five spray solutions all contained an active product in the form of Roundup® PowerMAX (Gly) (glyphosate, N-phosphonomethylglycine, 48.7 %) at a concentration of 25 ml/L water (1 qt/10 gal). One of the five active product solutions was the Gly-only solution, with the remaining four having an additional spray adjuvant. The adjuvants selected were those used in previous testing by the authors [10]. The six spray solutions used, with naming conventions and mixing rates, are as follows:

- Water plus NIS (90 % NIS at 0.25 % v/v)
- Gly only (25 mL/L water; same for remaining solutions)
- Gly plus methylated seed oil (MSO) (MSO added at 25 mL/L)
- Gly plus crop oil concentrate (COC) (COC added at 25 mL/L)
- Gly plus silicone surfactant (Silicone) (Si added at 0.6 mL/L)
- Gly plus polymer (Polymer) (polymer added at 7.5 mL/L)

Additional details on the adjuvants used are as follows:

- MSO: Methyl soyate, nonylphenol ethoxylate blend (100 %)
- COC: Paraffin base petroleum oil (83 %) and surfactant blend (17 %)
- Si/Silicone: Mixture of 3-(3-hydroxypropyl) heptamethyltrisiloxane, ethoxylated acetate, polyethylene glycol monallyl acetate, polyethylene glycol diacetate (100 %)
- P/Polymer: Polyacrylamide polyvinyl polymer complex (1.3 %) and constituents ineffective as spray adjuvants (98.7 %)

DROPLET SIZE MEASUREMENTS

Droplet sizing measurements were conducted at the U.S. Department of Agriculture (USDA) Agricultural Research Service Aerial Application Technology Research Unit's laboratory located in College Station, Texas. Nozzles were positioned in a high-speed tunnel outlet (45 by 30 cm) with the nozzles positioned at the tunnel exit.

A more detailed description of the high-speed test facility can be found in Fritz and Hoffmann [23]. A Sympatec HELOS laser diffraction system (operated with the manufacturer-denoted R6 lens, 0.5/9–1,750 μm dynamic size range across 32 bins) was positioned downstream of the nozzle such that the area of measurement was 91 cm from the exit of the nozzle. Typically, aerial nozzle testing at this facility is conducted at a measurement distance of 45.7 cm [27], but the extremely high spray pressures tested resulted in ligaments still being present in the spray at this distance, as confirmed by high-speed imagining. To use laser diffraction for droplet sizing required increasing the distance between the nozzle and measurement area to 91 cm to ensure complete atomization. Evaluation of each nozzle/pressure/solution combination consisted of a series of replicated measurements, each of which was one full vertical traverse of the spray plume (at a traverse rate of 6.4 cm/s). Sufficient replications, with a minimum of three, were made to minimize the standard deviations around the means of the $D_{V0.1}$, $D_{V0.5}$, and $D_{V0.9}$ data. Although the American Society of Agricultural and Biological Engineers droplet size classification (DSC) standard (ASAE S572.1) states that a minimum of three replications must be made, it further states that additional replications can be made to meet a desired standard deviation [28]. However, for this work, additional replications were made as needed to meet the U.S. Environmental Protection Agency's (EPA's) Generic Verification Protocol (GVP) for the evaluation of drift reduction technologies specification that standard deviations be within ±5 % of the means [29]. Additionally, the percent volume of the spray contained in droplets of diameter 100 μm ($\%\text{Vol} < 100$ μm) and 141 μm ($\%\text{Vol} < 141$ μm) were also recorded.

DROPLET SIZE CLASSIFICATION

The reference nozzles specified by ASABE S572.1 [28] were evaluated for spray classification purposes using the standard testing methodology established for low-speed, ground nozzle testing conditions [29]. This method places the nozzle on a vertical traverse in a low-speed wind tunnel with a concurrent airflow of 6.7 m/s to minimize the spatial bias with laser diffraction. The nozzle is positioned such that the outlet direction is parallel to the concurrent airflow with the measurement area 30.5 cm downstream of the nozzle outlet. The reference nozzles were obtained from Spraying Systems Co. (Wheaton, IL) and were tested to confirm they met the standard specified flow rates prior to droplet size evaluations. Droplet size measurements were taken for each nozzle at the specified reference pressures (450, 300, 200, 250, 200, and 150 kPa for the 11001, 11003, 11006, 8008, 6510, and 6515 nozzles, respectively) [28]. Similar to the testing of the aerial nozzles, a minimum of three replicated measurements were taken until the resulting standard deviation for each volume diameter was less than 5 % of the means. DSCs were established for each nozzle, pressure, airspeed, and solution combination tested based on the $D_{V0.1}$ and $D_{V0.5}$ values measured as compared to those measured for the reference nozzles as specified by ASABE S572.1 [28]. The DSC thresholds were set using the means plus one standard deviation of $D_{V0.1}$ and $D_{V0.5}$ for each reference nozzle.

DATA PROCESSING

All data processing was conducted using JMP software. A fit model using a standard least squares model was used to look at the main effects of nozzle, solution, airspeed, and pressure. The full response surface models and levels of fit were also determined. The developed models were used to examine the trends in droplet size as a function of spray pressure and airspeed as well as to examine the magnitude of the effect across the entire space.

DROPLET VELOCITY MEASUREMENTS

Measurements of spray exit velocity were made in still air to eliminate the influence of the surrounding high-speed airstream. The 2015 and 4015 nozzles were evaluated for spray exit velocity at three pressures (276, 552, and 827 kPa) using a LaVision ParticleMaster system (Goettingen, Germany) in shadowography mode. A series of paired images, separated by 10 μs, were captured using a high-speed camera with pulsed laser flashes to backlight the droplets. A focused area (19 by 19 mm) was centered on the flat fan spray plane with a depth of field of approximately 3 mm and a minimum resolution of approximately 50 μm. The nozzles were continually traversed such that the entire spray fan spanned the imaging area. For each treatment setup, a minimum of 8,000 to 10,000 spray droplets were sampled and used in the velocity calculations. Droplet velocities were measured at 15 cm from the nozzle. The processing software was set to exclude ligaments from the velocity analysis. Raw data files containing droplet diameter and velocity data for each individual droplet imaged were processed using a custom FORTRAN program (Simply-Fortran™,[4] Version 2.14). Overall mean droplet velocities, as well as the average velocities for droplets below 100 μm and above 400 μm, were determined.

Results

The DSC thresholds used to classify the results of this work are given in Table 2. The percentage spray volume less than 141 μm (%Vol < 141 μm) for the Fine/Medium DSC was 18.1 %, which is the value from which drift reduction metrics are calculated.

The overall average droplet exit velocities increased with pressure for both the 2015 and the 4015 flat fan nozzles, as expected (Table 3). Even with velocity measurements made at 15 cm, droplets began slowing to match the still air, with smaller droplets with less momentum slowing faster than larger ones, resulting in a velocity gradient—as evidenced by the difference in velocity of particles less than 100 μm and those greater than 400 μm.

Droplet size data at each combination of minimum, median, and maximum pressure and airspeed for each nozzle and solution combination are given in Table 4

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[4] Approximatrix, LLC, Cleveland, OH.

TABLE 2 ASABE S572.1 reference nozzle data means (plus one standard deviation) used for DSCs in this study.

Nozzle	DSC	$D_{V0.1}$	$D_{V0.5}$
11001	VF/F	64.9	143.7
11003	F/M	129.4	268.1
11006	M/C	165.0	336.4
8008	C/VC	240.7	517.2

Note: VF/F = very fine/fine; F/M = fine/medium; M/C = medium/coarse; and C/VC = coarse/very coarse.

(for the 2015 nozzle) and Table 5 (for the 4015 nozzle). Model fit testing using a least squares model showed all main effects (nozzle, solution, airspeed, and pressure) were highly significant ($P < 0.0001$) for $D_{V0.1}$, $D_{V0.5}$ and %Vol < 141 µm, as would be expected. General trends by nozzle, solution, and airspeed are discussed here. Given that the objective of this study was to explore the impacts of spray pressure on droplet size, means separation tests by pressure within each nozzle/solution/airspeed grouping were conducted for $D_{V0.1}$, $D_{V0.5}$, and %Vol < 100 µm means. Likely as a result of the precision of the laser diffraction measurement method and the GVP requirement to meet a ±5 % standard deviation to mean, all $D_{V0.1}$ and $D_{V0.5}$ by data within each nozzle/solution/airspeed grouping are significantly different (Tukey's least significant difference [LSD] with $\alpha = 0.05$). The same is true of the %Vol < 100 µm values within each nozzle/solution/airspeed grouping, with very few exceptions.

Generally, the COC, MSO, and water plus NIS solutions resulted in the largest overall droplet size data ($D_{V0.1}$ and $D_{V0.5}$) across the 2015 nozzle and solution combinations tested; however, this trend varied somewhat with airspeed and pressure. At the lowest airspeed and pressure combination, the Polymer and Gly solution resulted in droplet sizes similar to the water plus NIS, Gly only, and Gly plus MSO solutions. As the airspeed increased to the highest level (80.5 m/s), with pressure remaining constant, all solution $D_{V0.5}$ values were within 30 µm of each other as a

TABLE 3 Average spray droplet velocities and diameters at 15 cm for each nozzle and pressure combination evaluated with water only.

Nozzle	Spray Pressure (kPa)	Overall Average Velocity (m/s)	Average Velocity < 100 µm (m/s)	Average Velocity > 400 µm (m/s)
2015	276	16.9	13.4	19.0
	552	18.8	11.2	26.1
	827	26.2	19.3	32.0
4015	276	16.9	14.0	18.3
	552	22.3	16.3	25.9
	827	24.1	16.4	31.1

TABLE 4 Droplet size results and DSC for each solution tested using the 2015 nozzle for the maximum and minimum airspeeds and spray pressures.

Solution	Airspeed (m/s)	$D_{V0.1}$			$D_{V0.5}$			%Vol < 100 µm			DSC		
		276 kPa	552 kPa	827 kPa	276 kPa	552 kPa	827 kPa	276 kPa	552 kPa	827 kPa	276 kPa	552 kPa	827 kPa
Water + NIS	62.6	148c	175b	194a	341c	402b	456a	4.5a	2.8b	2.4b	M	M	C
	71.5	117c	142b	160a	277c	330b	376a	7.5a	4.9b	3.5c	F	M	M
	80.5	90c	113b	129a	222c	267b	305a	11.7a	8.3b	6.0c	F	F	M
Gly	62.6	130c	152b	170a	320c	375b	422a	5.9a	3.9b	3.3b	M	M	C
	71.5	102c	123b	139a	252c	301b	342a	9.7a	6.7b	4.9c	F	F	M
	80.5	80c	99b	113a	203c	245b	280a	14.7a	10.5b	7.8c	F	F	F
Gly + MSO	62.6	143c	182b	218a	316c	389b	451a	4.7a	2.0b	1.2c	M	C	C
	71.5	99c	130b	158a	235c	294b	342a	10.1a	5.7b	3.2c	F	M	M
	80.5	73c	96b	116a	184c	230b	264a	17.5a	11.3b	7.2c	F	F	F
Gly + COC	62.6	160c	201b	240a	348c	419b	492a	3.5a	1.6b	0.9b	M	M	C
	71.5	117c	149b	179a	271c	327b	385a	7.3a	4.2b	2.4c	F	M	C
	80.5	89c	113b	135a	221c	262b	304a	12.3a	8.0b	5.1c	F	F	M
Gly + Silicone	62.6	119c	144b	166a	272c	325b	370a	7.0a	4.2b	3.0c	F	M	C
	71.5	89c	110b	128a	219c	264b	301a	12.4a	8.3b	5.9c	F	F	F
	80.5	69c	86b	100a	179c	216b	245a	18.8a	13.5b	9.8c	F	F	F
Gly + Polymer	62.6	134c	156b	173a	336c	390b	436a	5.7a	3.9b	3.1c	M	M	C
	71.5	106c	125b	140a	272c	319b	357a	9.1a	6.6b	5.1c	F	F	M
	80.5	85c	101b	115a	225c	265b	297a	13.1a	9.9b	7.7c	F	F	F

Note: Means by pressure within each row for each solution/airspeed grouping followed by the same letter are not significantly different (Tukey's LSD with $\alpha = 0.05$); DSC (droplet size classification) column size class abbreviations are as follows: F = fine, M = medium, and C = coarse.

TABLE 5 Droplet size results and DSC for each solution tested using the 4015 nozzle for the maximum and minimum airspeeds and spray pressures.

Solution	Airspeed (m/s)	$D_{V0.1}$			$D_{V0.5}$			%Vol < 100 µm			DSC		
		276 kPa	552 kPa	827 kPa	276 kPa	552 kPa	827 kPa	276 kPa	552 kPa	827 kPa	276 kPa	552 kPa	827 kPa
Water + NIS	62.6	138c	157b	165a	321c	362b	384a	5.2a	3.6b	3.5b	M	M	M
	71.5	111c	131b	140a	262c	303b	326a	8.4a	5.9b	4.8c	F	M	M
	80.5	85c	105b	116a	208c	250b	274a	13.0a	9.5b	7.6c	F	F	F
Gly	62.6	122c	136b	143a	298c	333b	353a	6.9b	5.1b	4.8b	F	M	M
	71.5	98c	113b	121a	240c	276b	297a	10.6a	7.9b	6.7c	F	F	F
	80.5	78c	93b	103a	195c	231b	253a	15.3a	11.7b	9.5c	F	F	F
Gly + MSO	62.6	129c	156b	174a	285c	334b	368a	5.8a	3.0b	2.7b	M	M	C
	71.5	99c	124b	140a	230c	275b	304a	10.5a	6.3b	4.3c	F	F	M
	80.5	70c	92b	106a	175c	215b	239a	18.3a	12.4b	8.9c	F	F	F
Gly + COC	62.6	144c	171b	186a	318c	366b	393a	4.6a	2.5b	2.2b	M	C	C
	71.5	111c	136b	151a	255c	301b	328a	8.3a	5.1b	3.7c	F	M	M
	80.5	84c	108b	122a	202c	248b	273a	13.4a	9.1b	6.5c	F	F	F
Gly + Silicone	62.6	106c	121b	131a	256c	289b	311 a	9.2 a	6.6 b	5.8 b	F	F	M
	71.5	83 c	98 b	109 a	207 c	240 b	262 a	14.2 a	10.4 b	8.4 c	F	F	F
	80.5	66 c	81 b	92 a	171 c	204 b	227 a	19.9 a	14.9 b	11.7 c	F	F	F
Gly + Polymer	62.6	120c	131b	140a	314c	343b	360a	7.2a	5.9b	5.1b	F	M	M
	71.5	99c	109b	117a	270c	298b	313a	10.3a	8.6b	7.4c	F	F	F
	80.5	80c	90b	97a	222c	249b	264a	14.2a	12.1b	10.6c	F	F	F

Note: Means by pressure within each row for each solution/airspeed grouping followed by the same letter are not significantly different (Tukey's LSD with $\alpha = 0.05$); DSC (droplet size classification) column size class abbreviations are as follows: F = fine, M = medium, and C = coarse.

result of the more dominant impact of air shear [10]. At the lowest airspeed (62.6 m/s) and highest pressure (827 kPa), the COC, MSO, and water plus NIS solutions continued to produce the largest droplet-sized sprays, again with the effects being somewhat muted as the airspeed increased to the highest level (80.5 m/s). Although overall droplet sizes tended to be smaller by comparison, the 4015 nozzle results follow much the same trends for solution effect as the 2015 results, as would be expected,.

As previously mentioned, the 4015 nozzle produced smaller droplets than the 2015 under the same conditions (**Table 4** and **Table 5**). This is the result of the greater fan angle (40° versus 20°), which results in a portion of the spray fan being ejected into the airstream at a greater, nonparallel angle. This in turn means a greater relative velocity difference between the spray liquid and the airstream because the outer edges of the fan are traveling at a divergent direction to the airstream. The difference between the two nozzles was greatest at the lower airspeeds but tended to diminish with higher airspeeds.

Although the exit velocities for both nozzles were very similar at the same pressures, the greater spray angle of the 40° nozzle results in a portion of the spray that is at a greater divergent angle to the airstream. For a 20° flat fan, each outer edge of the spray fan is 10° off the concurrent airflow; and similarly, for the 40° flat fan, the outer edges of the spray fan are 20° off the airflow direction. Using simple vector calculations, with the velocity along the outer fan direction as the resultant velocity, V_R along direction angle (ϕ) of 10° and 20°, the velocity of the spray solution in the direction parallel to the airstream is $V_R{*}\cos(\phi)$. It is this velocity that is used to determine the differential velocity. Therefore, for the 20° flat fan, the exit velocity of the spray along the outer edges of the spray fan, in the direction parallel to the airstream, is 0.98 times that resultant velocity. Similarly, for the 40° flat fan, the exit velocity of the spray along the outer edges of the spray fan, in the direction of the airstream, is 0.94 times the resultant velocity. This is equivalent to a 4 % increase in the relative velocity difference at the outer edges of the spray fan for the 40° versus the 20° nozzle, which in turns results in an overall smaller droplet size, as evidenced by the results.

Although solution effects tend to support previous work and are somewhat interesting, more critical to the objective of this work are the effects from increasing spray pressure. Without exception, as spray pressure increased, within any nozzle/solution/airspeed combination, overall droplet size increased—with a resulting decrease in the fraction of fine droplets in the spray. As discussed previously, the increased spray pressures results in higher nozzle exit velocities, which in turn reduces the differential velocity between the liquid and airstream—thereby reducing air shear and droplet shatter. At the lowest airspeed (63 m/s), an increase in spray pressure from 276 to 827 kPa (mean liquid velocities of 17 and 24 to 26 m/s; **Table 3**) decreases the differential velocity from 46 to 38 m/s. Based on a previous discussion postulating that air shear begins to enhance atomization between 8 and 22 m/s, we can see that increasing spray pressure to 827 kPa has the effect of reducing the differential velocity to speeds nearing the upper end of that range.

More critically, and with only a few exceptions, increasing spray pressure within a given nozzle/solution/airspeed combination results in the DSC shifting at least one and, in a few cases, two classes, coarser. This shift from fine to medium or, in some cases, coarse, is crucial to aerial applicators because it will allow them to comply with agrochemical labels as they fly larger and faster aircraft.

IMPACTS ON DRIFT REDUCTION

Improving agrochemical applications and reducing damage due to spray drift are the driving forces behind the EPA's Drift Reduction Technology (DRT) Program [29] and a major goal for the researchers involved in this project. A major component of this program is the evaluation of droplet size of a potential DRT and, by comparison to a standard reference, the ability to rate its potential for reducing drift. As the program currently stands, the reference for comparison is the ASABE S572.1 F/M reference nozzle's %Vol < 141 μm. Following the established methods for evaluating reference nozzles, that value is 18.1 % for our facility. The current proposed DRT rating system assigns star levels depending on the percentage reduction. The levels are:
*>25 % to <50 % reduction
**>50 % to <75 % reduction
***>75 % to <90 % reduction
****>90 % reduction

Using this as a guideline, DRT star ratings were determined for both nozzles at airspeeds of 62.6, 71.5, and 80.5 m/s for spray pressures of 276 and 827 kPa (Table 6 and Table 7).

The DRT star ratings follow trends similar to those of the other droplet size data presented. At the lower spray pressure, a DRT rating is only given to the treatments made using the lowest operational airspeed tested (62.6 m/s [140 mph]). However, at the highest operational pressure, all solutions have at least a one star rating at both the 62.6 and 71.5 m/s airspeeds, with some at two or even three stars. With the 4015 nozzle, there are less star-rated setups, but all solutions have at least a one star at 62.6 m/s airspeed, with several having one or two stars at 71.5 m/s and the PM plus COC having a one star at 80.5 m/s airspeed.

OPERATIONAL CONSIDERATIONS OF HIGHER PRESSURES

The highest spray pressure used in the study cannot be generated by common aerial application equipment and must be used with caution because spray hoses, nozzle bodies, nozzle caps, and gaskets typically utilized may require modification if an applicator configured their aircraft to operate at these higher pressures. Another consideration is that with higher pressures come higher flow rates (Table 8). This would likely require atypical spray boom setups. Increasing pressure from 276 to 827 kPa increased the per nozzle flow rate by approximately 70 %. Because 276 kPa is within the typical spray pressure used by aerial application, a 70 % increase in per nozzle flow rate has significant implications for boom layouts. To illustrate, if we consider a typical application requiring a total spray rate of 9.35 L/ha (3 gpa) using

TABLE 6 DRT star ratings for the 2015 flat fan nozzle at each combination of spray pressure and operation airspeed.

Solution	Airspeed (m/s)	276 kPa		827 kPa	
		%Vol $< 141\,\mu m$	DRT Rating	%Vol $< 141\,\mu m$	DRT Rating
Water + Gly	62.6	9.2	*	5.1	**
	71.5	14.5	-	7.4	**
	80.5	22.1	-	12.0	*
Gly	62.6	11.8	*	7.0	**
	71.5	18.5	-	10.1	*
	80.5	27.0	-	15.1	-
Gly + MSO	62.6	10.2	*	3.2	***
	71.5	19.7	-	7.6	**
	80.5	32.0	-	14.8	-
Gly + COC	62.6	7.7	**	2.5	***
	71.5	14.4	-	5.7	**
	80.5	23.0	-	10.7	*
Gly + Silicone	62.6	14.3	-	7.0	**
	71.5	23.3	-	12.1	*
	80.5	33.9	-	18.9	-
Gly + Polymer	62.6	11.0	*	6.6	**
	71.5	16.6	-	10.0	*
	80.5	23.1	-	14.4	-

an aircraft with an effective swath width of 19.8 m (65 ft) and operating at an airspeed of 62.6 m/s (140 mph), the required total boom flow rate, using Eq 1, is 208 L/min (55 gal/min). If the 2015 nozzle operating at 276 kPa (40 psi) were selected, a minimum of 39 nozzles would be required (boom flow rate/per nozzle flow rate). If the applicator decided to increase the spray pressure to 827 kPa (120 psi) to increase droplet size, the number of nozzles required, using the same 2015 spray nozzle, would be 23 nozzles. This will have a significant impact on the resulting spray pattern, requiring major changes in the spray boom layout. One potential option is to reduce the orifice size, thus reducing flow rate, and although it is expected that the same relative change in droplet size would result, additional testing would be required to confirm this:

$$\text{Boom Flow rate} = 0.006 * \text{SR} * \text{Airspeed} * \text{Swath}$$

where:

Boom Flow rate = total boom flow rate, L/min,
SR = required spray rate of application, L/ha,
Airspeed = aircraft flight speed, kph, and
Swath = effective swath width of application, m.

Note: Constants may be different for units other than those used.

TABLE 7 DRT star ratings for the 4015 flat fan nozzle at each combination of spray pressure and operation airspeed.

Solution	Airspeed (m/s)	276 kPa		827 kPa	
		%Vol $< 141\,\mu m$	DRT Rating	%Vol $< 141\,\mu m$	DRT Rating
Water + NIS	62.6	10.5	*	7.4	**
	71.5	16.2	-	9.9	*
	80.5	24.3	-	14.7	-
Gly	62.6	13.4	*	9.9	*
	71.5	20.0	-	13.2	*
	80.5	28.3	-	18.1	-
Gly + MSO	62.6	12.3	*	6.2	**
	71.5	20.7	-	9.8	*
	80.5	33.9	-	18.2	-
Gly + COC	62.6	9.7	*	5.3	**
	71.5	16.5	-	8.3	**
	80.5	25.5	-	13.5	*
Gly + Silicone	62.6	17.8	-	11.9	*
	71.5	26.1	-	16.4	-
	80.5	36.0	-	22.1	-
Gly + Polymer	62.6	13.3	*	10.3	*
	71.5	18.0	-	13.8	-
	80.5	24.2	-	18.7	-

TABLE 8 Nozzle flow rates by pressure for the 2015 and 4015 flat fan spray nozzles.

Nozzle	Pressure kPa (psi)	Flow Rate L/min (gal/min)
2015	276 (40)	5.36 (1.41)
	552 (80)	7.44 (1.97)
	827 (120)	9.02 (2.38)
4015	276 (40)	5.54 (1.46)
	552 (80)	7.80 (2.06)
	827 (120)	9.46 (2.50)

Conclusions

The use of increased spray pressures was shown to significantly increase spray droplet size for all nozzle/spray solution/airspeed combinations tested. More importantly, DSC was also shown to increase (toward a coarser class), typically resulting in a medium—and in some cases a coarse—spray class, depending on airspeed and solution. All testing was conducted with standard spray nozzle check valves, boom connections, and nozzle bodies, indicating that, other than the pump system on the aircraft, only minor changes in the plumbing system are likely to be required to implement higher pressure sprays. While increasing spray droplet size, nozzle flow rates are also increased, which has potentially significant implications on boom setups required to obtain acceptable spray swath uniformities and coverage when working with higher pressures. Although higher spray pressures do not offer a complete solution to obtaining larger droplets at higher airspeeds, the results herein show that higher pressures will generate a medium spray for a formulated herbicide product at the industry's typical maximum application airspeed of 71.5 m/s (160 mph); and further, that they have the potential to create a medium spray at even higher airspeeds.

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