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Effects of Formulated Glyphosate and Adjuvant Tank Mixes on Atomization from Aerial Application Flat Fan Nozzles

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ABSTRACT: This study was designed to determine if the present USDA-ARS spray-nozzle models, which were based on spray solutions of water plus non-ionic surfactant, could be used to estimate spray droplet-size data for different spray formulations through use of experimentally determined correction factors. Twelve spray-solution treatments were evaluated, ten of which contained a formulated glyphosate product and nine of these contained an additional tank-mix adjuvant. Droplet-size testing was conducted across multiple operational points (nozzle-orifice size, nozzle orientation, spray pressure, and airspeed), in a high-speed wind tunnel, which corresponds to the response surface experimental model used to develop the present spray-nozzle models. The hypothesis that the different treatment solutions would respond linearly across a range of operational parameters and that a correction factor from relative to water plus non-ionic surfactant solution was proven false. When compared to water or the water plus non-ionic surfactant, the changes in atomization across the operation spectrum of the nozzle were not consistent and varied by formulation. Attempts to apply regression fits for a correction factor based on solution physical properties were not successful. With the formulated glyphosate tank mix used, none of the adjuvants tested, except the polymer, showed significant changes in droplet size under the high air shear regime. Whereas there is likely a need

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to develop formulated product-specific atomization models, the further addition of adjuvants do not significantly change the atomization characteristics, and, as such, should not require a unique spray-nozzle model.

KEYWORDS: active formulation, physical properties, spray atomization, aerial sprays

Introduction

The most critical concern for any agricultural spray applicator is to maximize the amount of product that deposits on the intended target with optimal and uniform coverage to provide complete control of the targeted pest, while at the same time minimizing the amount of product that deposits anywhere else. Based on the analysis of a number of aerial field trials, the Spray Drift Task Force concluded that droplet spectra, wind speed, application release height, and effective boom length were the predominate factors influencing downwind spray movement [1]. Of these, droplet spectra plays the dominant role, with the other factors merely influencing where and to what degree the applied spray droplets move. In most cases, agrochemical product labels specify a required application droplet size. This specification may either be by a droplet-size class [2] or a specific droplet diameter. Regardless of which method is used, an applicator is required, by law, to insure that all elements of their individual spray system are configured to meet the labeled specification. To guide applicators in this setup process, there are a number of resources, including spray-nozzle models and spray-nozzle size and classification tables available; however, most are limited in scope, as discussed in following.

One of the most critical decisions applicators make when trying to achieve a specific droplet spectrum is the choice of spray nozzle. Spray nozzles used for aerial systems typically include hydraulic nozzles. These can include flat fans, hollow cones, straight streams, air induction, and electrostatic nozzles. Additionally, nozzles, such as rotary atomizers, may introduce additional atomization energy beyond the air shear effect. Droplet size from hydraulic nozzles can be controlled by changes in nozzle type [3,4], spray pressure [4,5], and nozzle orientation [4,6]. Rotary-atomizer droplet size can be influenced by changes in spray pressure, flow rate, and rotational speed [7–9]. Influencing droplet size for both of these types of nozzles is airspeed, [4–7,9] formulation type, and physical properties (viscosity, extensional viscosity, and surface tension) [1,3,6,10–16]. For a selection of hydraulic nozzle that had significant market penetration, Kirk [17] developed a series of models that allowed users to input the nozzle type and configuration along with spray pressure and airspeed to predict the resulting droplet size [18]. These models were organized into a spreadsheet format that allowed users to quickly and easily change the operational configurations to obtain multiple droplet-size predictions. This allowed for an easy method of targeting nozzle and operational parameter setups that conform to a given application and pesticide-use label. Similarly, a database of droplet-size data for rotary atomizers was developed for a range of sprayer settings and application airspeeds, as well as several different spray formulations [9].

One of the shortcomings of both the nozzle models and database was the use of limited spray treatment solutions. Only water with a non-ionic surfactant was used in the development of the models by Kirk [17], and only water, water plus a seed oil, water plus a polyacrylamide, and pure product (no dilution) were used for the rotary-atomizer database. There have been a number of efforts at compiling databases [19,20] and developing new methods of correlating previously measured data to allow for predictions of droplet size both by solution and for nozzle setups not measured [21]. However, even with the very limited success of these efforts, the agricultural spray-application industry is still in need of more information and resources on the atomization characteristics of active product spray formulations, particularly when spray adjuvants are added.

The objective of this work was to determine if the present USDA-ARS spray-nozzle models, which are based on water plus non-ionic surfactant spray solutions, could be used to estimate spray droplet-size data for real-world tank mixtures (active product with and without additional adjuvants) through the use of experimentally determined correction factors. In addition, atomization characteristics of multiple adjuvant classes in the presence of a formulated active product were examined.

Methods

The initial hypothesis of this work was that correction factors based on individual spray solutions with unique physical properties could be developed to correct the presently available USDA-ARS spray-nozzle models [17]. This would prevent the need to develop additional unique models for each real-world tank mix used by the aerial application industry. The experimental design for these models follows the Box and Behnken [18] multi-factor experimental design for a rotatable second-order design characterizing four variables at three levels resulting in 27 unique operational points that can be used to characterize the response surface. The details of this design and resulting analysis and response relationships are further describe by Kirk [17]. Given that these 27 unique points define the response surface, the hypothesis was that droplet size for test solutions of different physical properties compared to the test solution, for which the models were developed, would change uniformly across all points. In other words, the response surfaces defined by the two spray solutions are uniformly offset to each other, such that the response surface defined using water only could be adjusted to mimic the response surface of the test solution using a linear correction factor. To determine the validity of this hypothesis, ten unique spray formulations consisting of an active ingredient and spray adjuvant were evaluated for droplet size across the 27 operational points defined by the Box and Behnken design and were compared to data from the same 27 operation points for water and water plus surfactant spray solutions. The specific details of the nozzles, spray solutions, and droplet measurement protocols are described below.

Spray Solutions

Twelve spray solutions were evaluated as part of this study. Two of the spray solutions did not contain active ingredient; one was water alone the other was water plus a 90 % non-ionic surfactant (0.25 % vol./vol.). The remaining ten solutions contained Roundup PowerMAX (glyphosate, N-glycine, 48.7 %) (PM) (Monsanto Company, St. Louis, MO) at a rate of 25 ml/l water (1 qt/10 gal). Nine of the ten PM solutions had an additional adjuvant added (see Appendix for additional details on each of these adjuvants). For each solution, 189 l (50 gal) was mixed in a recirculating spray tank. All treatments and mixing rates are shown in Table 1.

Nozzle and Airspeed Operational Settings

The nozzle selected was a 40-degree flat fan orifice nozzle (CP Products, Inc., Tempe, AZ). The four variables included nozzle-orifice size, nozzle orientation, spray pressure, and airspeed. For each variable, the three levels used

TABLE 1—*Treatment number with PowerMAX and spray adjuvant types and mixing rates for 189 L (50 gal) of spray solution.*

Treatment Number	PowerMAX (PM) Mixing Rate (L)	Adjuvant Type and Mixing Rate (Volume of Adjuvant Added)
1	None	None
2	None	90 % non-ionic surfactant (NIS) (473 ml)
3	4.73	None
4	4.73	90 % non-ionic surfactant (NIS) (473 ml)
5	4.73	Methylated seed oil (MSO) (4.73 L)
6	4.73	High surfactant oil concentrate (HSOC) (4.73 L)
7	4.73	Crop oil concentrate (COC) (4.73 L)
8	4.73	Oil/surfactant blend (O/S) (591 ml)
9	4.73	Invert emulsion (IE) (1.18 L, premixed w/ PM)
10	4.73	Micro emulsion (ME) (591 ml)
11	4.73	Silicone (Si) (118 ml)
12	4.73	Petroleum polymer (PP) (1.42 L)

TABLE 2—*Treatment operational parameters tested in the high-speed wind tunnel to measure droplet size for 12 treatment solutions (Table 1).*

Treatment	Orifice Size	Deflection Angle	Spray Pressure (kPa/psi)	Airspeed (kph/mph)
1	30	90	276/40	257/160
2	4	90	276/40	257/160
3	30	0	276/40	257/160
4	4	0	276/40	257/160
5	15	45	414/60	322/200
6	15	45	138/20	322/200
7	15	45	414/60	193/120
8	15	45	138/20	193/120
9	15	45	276/40	257/160
10	30	45	276/40	322/200
11	4	45	276/40	322/200
12	30	45	276/40	193/120
13	4	45	276/40	193/120
14	15	90	414/60	257/160
15	15	0	414/60	257/160
16	15	90	138/20	257/160
17	15	0	138/20	257/160
18	15	45	276/40	257/160
19	30	45	414/60	257/160
20	4	45	414/60	257/160
21	30	45	138/20	257/160
22	4	45	138/20	257/160
23	15	90	276/40	322/200
24	15	0	276/40	322/200
25	15	90	276/40	193/120
26	15	0	276/40	193/120
27	15	45	276/40	257/160

included a maximum, minimum, and median value. The three levels for nozzle orifice were 4, 15, and 30. These three orifice tips were fit into a rotatable turret (CP-11TT, CP Products, Tempe, AZ) allowing for quick changes to the nozzle size. Similarly, nozzle orientation levels included 0, 45, and 90 degrees, which were set using a swivel attachment (CP-03 swivel, CP Products, Tempe, AZ). Spray-pressure levels included 138, 276, and 414 kPa (20, 40, and 60 psi). Airspeed levels included 193, 257, and 322 kph (120, 160, and 200 mph). The resulting 27 nozzle treatments are shown in Table 2.

High-Speed Wind-Tunnel Testing

Atomization testing was conducted in the United States Dept. of Agriculture, Agricultural Research Service (USDA-ARS) Aerial Application Technology

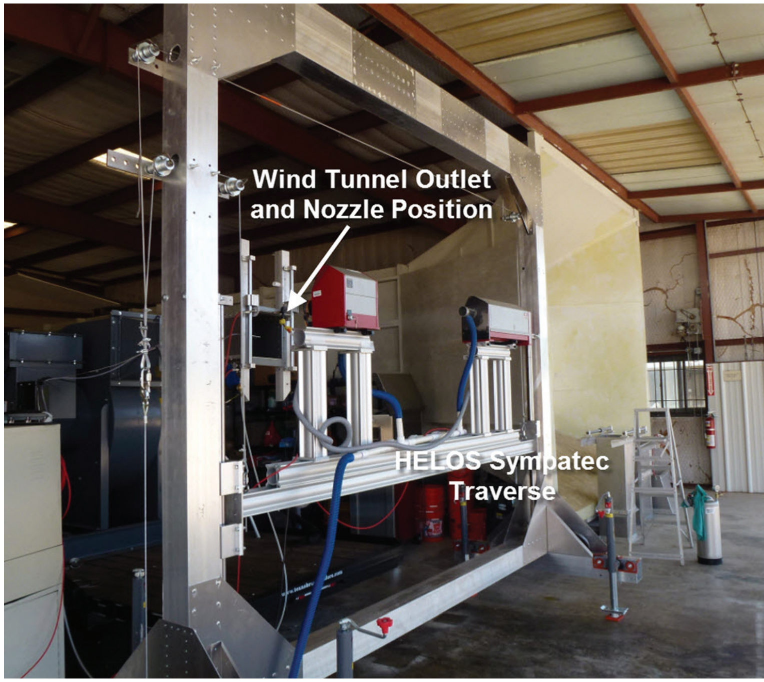

FIG. 1—*Wind tunnel and HELOS Sympatec traverse setup.*

high-speed wind-tunnel facility. The tunnel has an outlet section of 0.3 m × 0.3 m (1 ft × 1 ft) and a plumbed spray section mounted on a vertical linear traverse (Fig. 1) with an operational airspeed range from 6.7 to 98 m/s (15 to 220 mph). Spray nozzles were mounted on the boom similar to how they would be configured on an aircraft. The boom was plumbed to a pressurized spray container from which spray pressure was adjusted and maintained.

Droplet-size measurements were made using a Sympatec HELOS laser diffraction droplet-sizing system (Sympatec Inc., Clausthal, Germany), which was positioned approximately 1.2 m downstream of the spray-nozzle outlet to insure full atomization of the spray. A minimum of three replicated measurements were made for each treatment, where one replication was a complete vertical traverse of the laser through the spray plume. After the replicated measurements for each treatment were completed, droplet-size statistics were determined for the $D_{V0.1}$, $D_{V0.5}$, and $D_{V0.9}$, which are the droplet diameters (μm) for which 10 %, 50 %, and 90 %, respectively, of the total spray volume is contained in droplets of equal or lesser size.

Low-Speed Wind-Tunnel Testing

Additional lower airspeed atomization testing was conducted for treatment solutions 2–8 and 10–12 in the USDA-ARS Aerial Application Technology low-speed wind-tunnel facility. The low-speed tunnel setup is similar to the high-speed tunnel except that the low-speed tunnel has a larger outlet section of 1.2 m × 1.2 m (4 ft × 4 ft) with a plumbed spray section mounted vertically on a linear traverse and centered across the exit. The tunnel has an operational airspeed range from 0 to 8 m/s (0 to 18 mph). Spray nozzles were mounted on the vertical traverse and plumbed to a pressurized spray container from which spray pressure was adjusted and maintained. The same Sympatec HELOS system, as used in the high-speed tunnel testing, was positioned 1.8 m downstream of tunnel and centered vertically on the outlet. All droplet-size testing was conducted with a 11004VS flat fan nozzle (Spraying Systems, Wheaton, IL) at 276 kPa (40 psi) with a tunnel airspeed of 3.6 m/s (8 mph). The same replication protocol and droplet-size data as described in the high-speed wind-tunnel section were applied.

Physical Property Measurements

For each treatment solution dynamic surface tension, shear viscosity, and extensional viscosity were measured. Dynamic surface tension was measured at 20 ms using a SensaDyne Surface Tensiometer 6000 (Chem-Dyne Research Corp., Mesa, AZ), which employs the maximum bubble pressure method. Shear viscosity was measured with a Brookfield Synchro-Lectric Viscometer (Model LVT, Brookfield Engineering, Middleboro, MA) using a UL adapter 0.1–100 cps range. More details on the dynamic surface tension and shear viscosity measurement techniques are described by Hoffmann et al. [22]. Both the dynamic surface tension and shear viscosities measurements were replicated three times with the spray solutions at the same temperature as the droplet sizing work was conducted. Extensional viscosity was measured at a separate laboratory (Huntsman, The Woodlands, TX) following ASTM E2408 [23]. All extensional viscosity measurements were replicated five times with solutions at 22°C. Treatment 9 was not evaluated for extensional viscosity as a result of material shortage.

Data Analysis

To examine the validity of the hypothesis that a linear correction factor could be established, comparisons were made between each active product treatment solution (Table 1 Treatments 3–12) and the two "blank" treatment solutions (Table 1 Treatments 1 and 2). These comparisons were made at each of the 27 treatments points that define the response surface (Table 2). Ratios were calculated by dividing the $D_{V0.1}$, $D_{V0.5}$, and $D_{V0.9}$ data at each operational treatment point for each of the treatment solutions by the corresponding data for the water and water plus NIS solutions and expressed as a percentage. Percentages greater than 100 % meant that the droplet-size measurement was greater than

TABLE 3—*Physical property data (means ± standard deviations) for each treatment solution.*

Trt	Active Ingredient	Adjuvant	Temperature of Solution (celsius)	Dynamic Surface Tension (N/m @ 20 ms)[a]	Shear Viscosity (cp)[a]	Relative Extensional Viscosity[a]
1	None	None	30.0	0.071 ± 0.00a	0.42 ± 0.0e	1.000 ± 0.0a
2	None	NIS	29.6	0.052 ± 0.22b	0.44 ± 0.0d	1.063 ± 0.009bc
3	PM	None	31.7	0.044 ± 1.29def	0.44 ± 0.0d	1.036 ± 0.014a
4	PM	NIS	31.5	0.044 ± 0.43ef	0.44 ± 0.0d	1.080 ± 0.008c
5	PM	MSO	33.6	0.044 ± 0.19f	0.49 ± 0.0b	1.079 ± 0.016bc
6	PM	HSOC	30.3	0.046 ± 0.19de	0.52 ± 0.0a	1.092 ± 0.015bc
7	PM	COC	30.1	0.048 ± 0.31d	0.47 ± 0.01bc	1.083 ± 0.003b
8	PM	O/S	32.3	0.048 ± 0.31d	0.44 ± 0.0d	1.071 ± 0.011b
9	PM	IE	34.5	0.044 ± 0.56f	0.46 ± 0.01c	nr
10	PM	ME	34.2	0.049 ± 0.69bc	0.42 ± 0.0e	1.041 ± 0.012c
11	PM	Si	35.0	0.047 ± 0.52d	0.49 ± 0.0e	1.056 ± 0.008c
12	PM	PP	31.6	0.049 ± 0.69c	0.51 ± 0.01a	1.050 ± 0.013c

Note: The surface tension data for the water only treatment (T1) was obtained from Ref 33. PM = PowerMax.

[a]Means within each column followed by the same letter(s) are not significantly different as determined using Dunnett's T3, $\alpha = 0.05$.

the water plus NIS solution. The means and standard deviations across the 27 treatments points for each treatment solution were determined and means separations determined using the general linear model and Dunnett's T3 (to account for unequal variances) at $\alpha = 0.5$, using SYSTAT (ver. 13.00.05, SYSTAT Software, Inc., Chicago, IL). The means and standard deviations for all of the physical property data were also determined and means separations determined using the general linear model and Dunnett's T3 (to account for unequal variances) at $\alpha = 0.5$ using SYSTAT.

Results and Discussion

Physical Properties

The dynamic surface tensions, shear viscosities, and relative extensional viscosities of the different solutions tested are given in Table 3.

The physical properties of the treatments solutions varied little, with few significant differences. The addition of a tank-mix adjuvant or PM caused the surface tension to drop from 0.071 (with water) to 0.052 N/m or less. More significant overlap of the means was observed in the shear viscosities for solutions with tank-mix adjuvants and PM, as compared to water. When compared to the PowerMax (PM) only solution (Trt 3) the addition of silicone, petroleum

TABLE 4—*Ratio of measured droplet size for each treatment solution relative to water only.*

	$D_{V0.1}$ [a]				$D_{V0.5}$ [a]				$D_{V0.9}$ [a]			
Treatment	Mean		SD		Mean		SD		Mean		SD	
2 - NIS only	0.91	±	0.11	b	0.92	±	0.10	c	0.92	±	0.09	c
3 - PM only	0.84	±	0.08	a	0.87	±	0.08	bc	0.91	±	0.08	c
4 - PM + NIS	0.82	±	0.08	a	0.85	±	0.08	abc	0.88	±	0.08	c
5 - PM + MSO	0.81	±	0.10	a	0.78	±	0.08	a	0.78	±	0.08	a
6 - PM + HSOC	0.84	±	0.12	a	0.85	±	0.11	abc	0.87	±	0.10	bc
7 - PM + COC	0.88	±	0.07	a	0.87	±	0.05	bc	0.85	±	0.06	abc
8 - PM + O/S	0.87	±	0.08	a	0.83	±	0.07	ab	0.80	±	0.06	ab
9 - PM + IE	0.83	±	0.13	a	0.80	±	0.11	ab	0.79	±	0.09	ab
10 - PM + ME	0.84	±	0.11	a	0.83	±	0.10	abc	0.83	±	0.09	abc
11 - PM + Si	0.83	±	0.09	a	0.85	±	0.09	abc	0.87	±	0.85	bc
12 - PM + PP	0.87	±	0.10	a	0.89	±	0.10	bc	0.88	±	0.09	c

Note: Data represents the means of the results from the 27 operational treatment points.
[a]Means within each column followed by the same letter(s) are not significantly different as determined using Dunnett's T3, $\alpha = 0.05$.

polymer or oil concentrates increased the shear viscosity and surface tensions. The addition of the emulsions (invert and micro) and the non-ionic surfactant resulted in negligible changes to shear viscosities and surface tensions compared to PM only solution (Trt 3). All adjuvants increased the relative extensional viscosities compared to the PM only (Trt 3). The non-ionic surfactant (Trt 4) and the oils (Trt 5–8) provided the greatest increase in extensional viscosity.

Droplet-Size Data

The calculated ratios of droplet-size data for the different treatment solutions relative to water only or water plus NIS are shown in Tables 4 and 5, respectively. Additionally, the maximum and minimum ratios for each solution and droplet-size parameter are given in Table 6. Attempts to fit regression (single and multiple variables) to these ratios based on operational settings and physical property measurements did not result in any significant correlations. One possible reason for this was the non-linear change between operational parameters for the treatment solutions when compared to water or water plus NIS. In other words, when compared to the water or water plus NIS, the other treatment solutions showed varying changes in droplet size across the range of operational treatments (Table 2). For example, for operational treatment 20 (Table 2—40-degree flat fan, number 4 orifice, 45° orientation, 414 kPa, and 257 kph) the water plus PM solution $D_{V0.5}$ was 89 % of the water plus NIS value, whereas for operational treatment number 4 (Table 2—same as number 20 but

TABLE 5—*Ratio of measured droplet size for each treatment solution relative to water plus NIS.*

	$D_{V0.1}$[a]				$D_{V0.5}$[a]				$D_{V0.9}$[a]			
Treatment	Mean		SD		Mean		SD		Mean		SD	
3 - PM only	0.93	±	0.08	a	0.95	±	0.06	b	0.99	±	0.08	e
4 - PM + NIS	0.91	±	0.08	a	0.93	±	0.07	b	0.96	±	0.08	de
5 - PM + MSO	0.89	±	0.09	a	0.85	±	0.07	a	0.86	±	0.07	a
6 - PM + HSOC	0.92	±	0.07	a	0.93	±	0.06	b	0.95	±	0.08	cde
7 - PM + COC	0.97	±	0.10	a	0.95	±	0.08	b	0.93	±	0.07	bcde
8 - PM + O/S	0.97	±	0.10	a	0.91	±	0.08	ab	0.88	±	0.09	abc
9 - PM + IE	0.91	±	0.10	a	0.87	±	0.08	a	0.87	±	0.07	ab
10 - PM + ME	0.93	±	0.10	a	0.91	±	0.08	ab	0.91	±	0.08	abcd
11 - PM + Si	0.91	±	0.07	a	0.93	±	0.07	b	0.96	±	0.09	cde
12 - PM + PP	0.96	±	0.08	a	0.97	±	0.07	b	0.97	±	0.07	de

Note: Data represents the means of the results from the 27 operational treatment points.
[a]Means within each column followed by the same letter(s) are not significantly different as determined using Dunnett's T3, $\alpha = 0.05$.

0° deflection and 276 kPa) the water plus PM $D_{V0.5}$ was 120 % of the water plus NIS value. Within each treatment solution the percentages varied with the operational treatment number.

Generally the solutions containing PM resulted in droplet-size statistics that were 15–20 % less than what was found with water only (Table 4) and 5–10 % less than that found with water plus NIS (Table 5). The data shows little to no separation between the PM solutions, regardless of the additional adjuvant type added. This is not too surprising given that the physical properties of the different PM spray solutions were not dramatically different (Table 3). As indicated by the standard deviations (Tables 4 and 5) and range of ratios (Table 6), the ratios were not consistent, and in most cases for a given solution not always indicative of a decrease in droplet size, i.e., ratios greater than 1 (Table 6). For example, comparing treatment solution number three (water plus PM) to number 2 (water plus NIS) across all 27 operational treatment points, the water plus PM solution resulted in $D_{V0.5}$ values that ranged from 88 to 119 % of those measured for the water plus NIS. These results illustrate that the water only and the water plus NIS test solutions do not provide an adequate mimic for the PM and PM plus additional adjuvant solutions. There is a need for either a correction factor for the current models or unique models for the different spray solutions.

Larger differences in spray droplet size between the different spray solutions of PM and PM plus additional adjuvant were anticipated. To determine if high wind shear was the cause of limited adjuvant effect, all treatment solution

TABLE 6—*Maximum and minimum ratios of measured droplet size for each treatment solution relative to water only and water plus NIS.*

	$D_{V0.1}$		$D_{V0.5}$		$D_{V0.9}$	
Treatment	MIN	MAX	MIN	MAX	MIN	MAX
Based on comparisons to water only solution						
2 - NIS only	0.62	1.31	0.66	1.33	0.68	1.23
3 - PM only	0.71	1.10	0.77	1.16	0.77	1.13
4 - PM + NIS	0.70	1.13	0.74	1.19	0.70	1.16
5 - PM + MSO	0.68	1.24	0.70	1.17	0.67	1.13
6 - PM + HSOC	0.71	1.36	0.74	1.33	0.72	1.24
7 - PM + COC	0.72	1.07	0.78	1.01	0.66	0.99
8 - PM + O/S	0.70	1.17	0.73	1.21	0.72	1.17
9 - PM + IE	0.58	1.34	0.58	1.26	0.62	1.15
10 - PM + ME	0.73	1.31	0.73	1.27	0.71	1.21
11 - PM + Si	0.73	1.19	0.75	1.07	0.66	0.97
12 - PM + PP	0.72	1.19	0.74	1.20	0.74	1.09
Based on comparisons to water + NIS solution						
3 - PM only	0.83	1.25	0.88	1.19	0.89	1.25
4 - PM + NIS	0.80	1.24	0.86	1.23	0.82	1.25
5 - PM + MSO	0.81	1.27	0.81	1.16	0.78	1.15
6 - PM + HSOC	0.81	1.16	0.85	1.19	0.84	1.24
7 - PM + COC	0.82	1.43	0.76	1.29	0.77	1.26
8 - PM + O/S	0.84	1.20	0.85	1.20	0.82	1.23
9 - PM + IE	0.66	1.29	0.68	1.16	0.71	1.11
10 - PM + ME	0.84	1.33	0.84	1.23	0.83	1.24
11 - PM + Si	0.89	1.38	0.81	1.25	0.78	1.26
12 - PM + PP	0.85	1.28	0.86	1.18	0.86	1.12

Note: Data represents the max and min of the results from the 27 operational treatment points.

except exception of water only and the invert emulsion were evaluated for droplet size in the low speed tunnel using a 11 004VS flat fan nozzle (this nozzle is the ASABE Fine to Medium Reference Nozzle [2]). Results of the low speed wind tunnel were contrasted with droplet-size data for each of the solutions from the 4015 flat fan nozzle at 0 degrees deflection, 276 kPa, with and airspeed of 54 m/s (120 mph) from the high speed wind tunnel. The high speed operational point was selected such that orientation was not a factor in atomization and the results would be representative of an aerial flat fan with air shear (Table 7).

Each treatment solution shows a different trend, as compared to the water plus NIS, comparing the droplet-size data at 3.6 m/s to that at 54 m/s. All PM and PM plus adjuvant treatments solutions resulted in significant decreases in overall droplet size as compared to the water plus NIS under high airspeed

TABLE 7—*Comparison of droplet-size data between spray solutions under high and low speed air shear conditions.*

	$D_{V0.1}$[a]				$D_{V0.5}$[a]				$D_{V0.9}$[a]			
Treatment Solution	Mean		SD		Mean		SD		Mean		SD	
4015 flat fan at 54 m/s												
2 - Water + NIS	152.9	±	0.5	a	351.0	±	1.4	a	584.4	±	6.2	a
3 - PM Only	128.8	±	1.6	d	316.8	±	3.4	cd	562.6	±	8.5	ab
4 - PM + NIS	124.4	±	3.3	d	307.5	±	4.5	cde	532.6	±	4.1	b
5 - PM + MSO	133.5	±	0.6	d	298.5	±	2.0	e	493.0	±	4.1	d
6 - PM + HSOC	138.0	±	0.3	bcd	319.3	±	1.8	c	527.3	±	5.2	bc
7 - PM + COC	148.3	±	1.8	ab	338.1	±	2.0	b	562.8	±	8.6	ab
8 - PM + S/O	140.8	±	1.5	bc	315.5	±	5.2	cde	518.9	±	13.1	bcd
10 - PM + ME	137.7	±	1.1	d	300.0	±	1.3	de	486.9	±	4.1	d
11 - PM + Si	132.9	±	3.3	d	302.7	±	1.3	de	495.1	±	2.1	d
12 - PM + PP	132.5	±	2.6	d	306.8	±	1.9	de	508.8	±	3.2	cd
11004VS flat fan at 3.6 m/s												
2 - Water + NIS	120.9	±	2.1	e	269.8	±	8.9	d	490.0	±	5.3	c
3 - PM Only	121.9	±	1.5	e	270.8	±	3.4	d	492.2	±	12.0	c
4 - PM + NIS	152.9	±	2.1	cd	336.9	±	4.3	b	583.5	±	6.1	ab
5 - PM + MSO	154.0	±	4.5	bc	310.1	±	3.8	c	508.0	±	7.0	c
6 - PM + HSOC	124.7	±	3.1	e	274.8	±	3.7	d	483.0	±	11.6	c
7 - PM + COC	161.6	±	0.6	bc	324.0	±	0.4	bc	515.9	±	3.7	c
8 - PM + S/O	153.9	±	1.0	cd	311.4	±	3.4	c	520.1	±	13.3	bc
10 - PM + ME	189.2	±	2.7	a	385.7	±	6.2	a	624.2	±	13.9	ab
11 - PM + Si	114.8	±	2.5	e	264.0	±	4.5	d	485.2	±	11.2	c
12 - PM + PP	125.2	±	4.9	de	279.5	±	3.1	d	517.4	±	12.7	c

[a]Means within each column, for each nozzle, followed by the same letter(s) are not significantly different as determined using Dunnett's T3, $\alpha = 0.05$.

(54 m/s) conditions. There was very little significant change in the $D_{V0.1}$ and $D_{V0.5}$ data resulting from the addition of additional adjuvant to the water plus PM mixture for the high-speed wind tunnel data. However, under the low air-speed (3.6 m/s) conditions only a few of the adjuvants (NIS, MSO, COC, S/O and ME) resulted in significant increases in droplet size as compared to the water plus NIS and water plus PM.

Conclusions

The work presented in this manuscript attempted to use physical properties of a spray solution to characterize the overall complex nature of the atomization process. When looking at the low speed atomization data (Table 7), the addition of the spray adjuvants tended to increase droplet size whereas in the high-speed airstream droplet size tended to decrease (Table 7). The physical properties of the different treatment solutions measured as part of this work did not correlate to the observed changes in droplet size. The primary difference in the atomization process between high- and low-speed tunnels is the degree of secondary atomization. As the droplets formed near the exit of a nozzle operating within a high-speed airstream encounter the high-speed air, if the physical forces within the droplet are less than the energy imparted by the airstream, they will shatter [24,25]. When the formulated glyphosate product had additional adjuvants added, the changes (either increase or decrease) in droplet size in both the high- and low-speed tunnels were negligible. These differences tended to be more muted in the high speed atomization data than the low speed, likely as a result of the dominance of the high speed air shear and secondary atomization. It is also conjectured that the additional adjuvant effect, in terms of change in droplet size, is further muted as a result of the adjuvant package already included with the formulated product.

These results indicate that whereas there is likely a need to develop multiple atomization models for individual formulated active products, the new product specific models could potentially suffice to represent the majority of spray formulations using that specific product. The addition of further tank-mix adjuvants generally did not result in significant changes to droplet-size characteristics across the operational treatment ranges tested. However, there are cases, such as the petroleum polymer, where significant differences result. These products would need either additional models or guidance on correcting existing modeled droplet-size data. Given the unlimited combinations of formulated products, tank-mix adjuvants, and spray nozzles available, developing droplet sizing operational guidance across the full array of operational settings is not an option. The authors suggest that product specific models would be developed initially followed by limited screening of additional adjuvants, in terms of measuring droplet size at selected operational points, to determine if additional spray models would be needed.

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APPENDIX

Non-ionic surfactant:	
- Alkyphenol ethoxylate, butyl alchohol, dimethylpolysiloxane	90 %
- Constituents ineffective as spray adjuvants	10 %
Methylated seed oil:	
- Methyl soyate, nonylphenol ethoxylate blend	100 %
High surfactant oil concentrate:	
- Paraffin base oil, sorbitol fatty acid alkoxylates, alkyl ethoxylates	98 %
- Constituents ineffective as spray adjuvants	2 %
Crop oil concentrate:	
- Paraffin base petroleum oil	83 %
- Surfactant blend	17 %
Oil/Surfactant blend:	
- Ethylated seed oil; 3-(3-hydroxypropyl)-heptamethyltrisiloxane, ethoxylated acetate; polyoxyethylene dioleate; polyol alkyl ethoxylate	100 %
Invert emulsion:	
- Modified vegetable oil, aliphatic mineral oil, amine salts of organic acids, aromatic acid	100 %
Micro emulsion:	
- Modified seed oils, amine salts of organic acids, and organic acid	100 %
Silicone:	
- A Mixture of 3-(3-Hydroxypropyl) heptamethyltrisiloxane, ethoxylated acetate, polyethylene glycol monallyl acetate, polyethylene glycol diacetate	100 %
Petroleum polymer:	
- Polyacrylamide polyvinyl polymer complex	1.3 %
- Constituents ineffective as spray adjuvants	98.7 %

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