Characterization of a spray-modifying agricultural adjuvant using multiple diagnostic techniques

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Abstract
Stewardship of pesticides in crop production requires precise and effective application of agricultural sprays. Tank mix adjuvants are commonly added to pesticide mixtures to modify spray characteristics and improve performance. InterLock is an oil emulsion adjuvant used to reduce fine spray droplets and increase product deposition on plant surfaces. In this study, a variety of imaging-based diagnostic techniques were used to study the atomization process and downstream droplet characterization of an adjuvant spray, validated with laser diffraction sizing measurements. Test conditions represented typical spray application techniques used by many farmers in North America. Separately, InterLock at 0.31% v/v in a water solution, and water alone, were sprayed with a TeeJet AIXR11004 agricultural spray nozzle at 345 kPa. High resolution images were produced by a 29 million pixel PowerView Plus CCD Camera and high speed images were collected with a Phantom v711 CMOS camera. The adjuvant altered the spray pattern and atomization process versus water alone, and ultimately reduced small particle (<150 μm) concentration by 25–50%. The adjuvant solution had a higher average velocity and produced a wider spray angle. These diagnostic methods demonstrate the mechanisms by which a field-realistic nozzle and adjuvant combination that can be used for precision application of crop protection products, enabling farmers to optimize investments and minimize environmental impacts.

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INTRODUCTION

The challenge of understanding spray formation has practical significance for optimizing the use of agricultural products such as pesticides and fertilizers. Many crop protection products are applied in liquid solution to the foliage of crops and weeds. The complex shape of plant canopies, uncontrollable atmospheric conditions, and economic constraints make it challenging for growers to get maximal effect from the products they apply. Some product is invariably lost to the environment due to evaporation and off-target deposition. Off-target movement of spray droplets due to wind is known as spray drift, and is increasingly a focus of regulatory efforts [1]. Spray drift can be reduced by using nozzles, products, and practices that reduce the proportion of the spray made up of fine droplets (50-210 μm) in diameter. However, eliminating fine droplets by simply using an extremely coarse spray comes at the cost of leaf coverage. With fungicides, insecticides, foliar nutrients, and contact-active herbicides, control can be reduced with coarse sprays [2]–[5]. Choosing low-drift spray nozzles is a common way that growers can reduce fine droplets, but every 50% reduction in fine droplets below 5% of the spray volume is correlated with a 100 μm increase in $D_{V0.5}$ [Figure 1].

Another approach for reducing drift potential is to use a spray drift adjuvant, which is a companion product that can be added to the crop protection solution. Oil emulsion adjuvants are one type of product known to reduce fine droplets with minimal change in $D_{V0.5}$ [6]. The exact mechanism by which these adjuvants affect the droplet size distribution is unknown, with perforation of the spray sheet by proposed by many [7], [8], and mediation of the sheet breakup process by a deformable disperse phase (oil emulsion droplets and/or air bubbles) by Qin et al. [9]. Both models recognize the importance oil emulsion droplets providing of inhomogeneities within in the spray, which dramatically alter the spray pattern. Understanding spray sheet formation and finding nozzles, adjuvants, and practices for growers to create precision sprays is critical for stewarding the use of agricultural sprays in the environment. This project built upon previous investigations into multiple measurement techniques for describing flat fan spray formation [10]. Various methods have been used to measure agricultural sprays, but only a few studies have used these methods in combination [11], [12]. This study was conducted in a laboratory that has done extensive testing of agricultural products using laser diffraction. This study builds on prior results by adding several new approaches to examine a low-drift nozzle commonly used by growers for ground applications in the US, in combination with a popular oil emulsion drift control adjuvant that has been applied on 67 million acres in 2014.

**Objective**

1. Characterize the formation and droplet size distributions of two contrasting sprays using a variety of imaging and nonimaging techniques.
2. Provide spray information on a field-realistic nozzle and adjuvant combination that would be used for low-drift application of crop protection products.

**Materials and Methods**

Two contrasting sprays were generated using a TeeJet AIXR11004-VP agricultural spray nozzle (Spraying Systems Co, Wheaton, IL, USA), operated at 345 kPa fluid pressure, delivering a nominal flow rate of 1.5 L min$^{-1}$. This flat-fan spray tip is constructed of ultra-high-molecular-weight polyethylene polymer; it has a nominal spray angle of 110°, and uses a pre-
orifice and air-inlet ports [Figure 2] to produce a “Very Coarse” spray as classified by ASABE S572.1 [13]. One spray was water alone, and the other spray included the agricultural adjuvant, InterLock® (Winfield Solutions, LLC, St. Paul, MN, USA), added at 0.31% m/m. InterLock is composed of modified vegetable oil, polyoxyethylene sorbitan fatty acid ester, and vegetable oil, and forms a microemulsion when mixed into aqueous solution. The two sprays were characterized using five measurement techniques:

1) laser diffraction (LD) droplet size distribution
2) high resolution particle image velocimetry (PIV) of the spray fan
3) spray angle measurement
4) high speed imagery of spray atomization
5) shadowgraphy of individual droplets with size-shape analysis (SSA)

Laser Diffraction
Laser diffraction measurements were conducted with a Sympatec HELOS VARIO-KR system with R7 optics (0.5 to 3500 μm). Data were collected and processed in WINDOX 5.6.2.0 software. Five replicated 30s measurements were taken at the center of the spray, with the mid-point of the laser beam 457 mm downstream of the nozzle orifice. The average volume of droplets <150 μm, volume median diameter (D_{V0.5}), and diameters delineating the spray volume made up of the smallest and largest 10% of droplets (D_{V0.1} and D_{V0.9}, respectively) were calculated. For comparison with other results, the volume within 117 30-μm bins was also calculated.

PIV and Spray Angle Measurement
The sprays were delivered within a glass-walled test chamber, with the spray fan oriented at 90 degrees from the vertical with the broad side perpendicular to the light source and camera. PIV image pairs were collected using a 29 million pixel PowerView Plus interline CCD Camera from TSI Inc., vertically oriented laser sheet produced by a 200 mJ Evergreen Nd:YAG pulsed laser and an acrylic diffuser. Image capture and analysis was completed using the TSI Inc. Insight4G Platform. Images were processed to remove non-uniformities in the back illumination and diminish appearances of off-focus particles. Circularity and diameter were reported within 117 30-μm bins, with the minimum spatial resolution of 66 μm.

RESULTS AND DISCUSSION

Droplet Size and Shape
Laser diffraction results show a decrease in fine droplets with the adjuvant, accompanied by an increase in D_{V0.5}. These results align with previous results with the same treatments from this laboratory.

Table 1. Laser diffraction droplet size distribution of water and an oil emulsion adjuvant solution.

<table>
<thead>
<tr>
<th>Solution</th>
<th>&lt;150 μm (%)</th>
<th>D_{V1.0} (μm)</th>
<th>D_{V0.5} (μm)</th>
<th>D_{V0.9} (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>15.0</td>
<td>126</td>
<td>313</td>
<td>666</td>
</tr>
<tr>
<td>Adjuvant</td>
<td>8.5</td>
<td>160</td>
<td>419</td>
<td>681</td>
</tr>
</tbody>
</table>

Results between SSA and LD differed substantially [Table 3]. The difficulty of comparing temporal and spatial data on agricultural sprays is well-established [12]. The spray fraction relevant for estimating off-target drift potential is the amount of spray <150 μm. The reduction in this drift-prone fraction can be used for regulatory purposes [1], so discrepancies between these measurements are problematic for growers, regulators, and chemical and nozzle manufacturers. However, with both methods, the reduction in small particle concentration <150 μm due to the adjuvant was found to be within the 25 to 50% quartile with this the AIXR11004 nozzle at 345 kPa.
Table 2. Cumulative fraction of fine spray <150 μm produced by water (W) and a drift control adjuvant (ADJ), and percent reduction in fine droplets due to the use of the adjuvant (ΔADJ), measured using size-shape analysis (SSA) and laser diffraction (LD).

<table>
<thead>
<tr>
<th>Method</th>
<th>SSA</th>
<th>LD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solution</td>
<td>W</td>
<td>ADJ</td>
</tr>
<tr>
<td>&lt;150 μm</td>
<td>57.0</td>
<td>36.5</td>
</tr>
<tr>
<td>ΔADJ</td>
<td>-36.0</td>
<td>-43.5</td>
</tr>
</tbody>
</table>

Using super resolution shadowgraphy, 200 images of each spray were captured, with 178,943 water droplets counted and 59,973 adjuvant droplets counted. The smallest measurable droplet was 66 μm. The spray adjuvant reduced the percentage of droplets in the smallest three measurable size classes, with upper boundaries of 90 μm, 120 μm, and 150 μm. The adjuvant increased the proportion of droplets between 150 μm to 778 μm. Above 778 μm the proportion of large droplets for the adjuvant mixture was the same or less than water alone. This is largely consistent with laser diffraction results, in which there was a lower proportion of spray volume comprising droplets below 300 μm with the adjuvant, and a larger volume of spray between 300 to 718 μm. The volume of spray above 718 μm was similar between water and the adjuvant mixture.

Table 3. (SSA) Size-shape analysis and (LD) laser diffraction droplet size distribution within 30 μm bins for water (W) and an oil emulsion adjuvant solution (ADJ).

<table>
<thead>
<tr>
<th>Bin a (μm)</th>
<th>SSA</th>
<th>LD</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>W</td>
<td>ADJ</td>
</tr>
<tr>
<td>30</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>60</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>90</td>
<td>25.4</td>
<td>14.3</td>
</tr>
<tr>
<td>120</td>
<td>19.7</td>
<td>12.2</td>
</tr>
<tr>
<td>150</td>
<td>11.9</td>
<td>10.0</td>
</tr>
<tr>
<td>180</td>
<td>8.5</td>
<td>9.2</td>
</tr>
<tr>
<td>210</td>
<td>5.9</td>
<td>7.5</td>
</tr>
<tr>
<td>240</td>
<td>4.9</td>
<td>6.8</td>
</tr>
<tr>
<td>270</td>
<td>3.9</td>
<td>6.0</td>
</tr>
<tr>
<td>300</td>
<td>3.3</td>
<td>5.4</td>
</tr>
<tr>
<td>330</td>
<td>2.8</td>
<td>4.9</td>
</tr>
</tbody>
</table>

aupper limit of size class bin
bsmallest measurable droplet for SSA was 66 μm

Circularity is a ratio of the diameter of the main axis of the droplet to the minor axis, with a perfectly circular drop having circularity of 1.0. In SSA this can be measured and reported, but in LD, all droplets are assumed to be spherical (and thus circular). A greater proportion of the adjuvant droplets were circular (ratio = 1.0 ± 0.25) than the water droplets, 64% vs. 44% respectively.
Figure 3. Circularity ratio of droplets, with 1.0 representing the major and minor axis equal. Comparing water alone to an oil emulsion adjuvant solution.

Atomization

Disparities in circularity between water and adjuvant may be traced back to the sheet breakup process. With water, the edge of the sheet breakup region is outside of the camera frame, but for the adjuvant, the distance to sheet breakup is reduced and visible within the frame [Figure 6]. With the sheet break up occurring farther downstream of the nozzle for the water case, the effects of the ligament breakup process were more apparent, as the water droplets appeared less circular in comparison with the Interlock solution at the measurement point. This is consistent with one proposed mechanism by which oil emulsions produce coarser sprays, which is that when the breakup region is shifted closer to the nozzle orifice, droplets are formed in a thicker region of the spray sheet, resulting in larger droplets [8], [9].

Spray angle was measured for both sprays, using an edge threshold of 30, with 500 fit points and the first 200 fit points ignored. The measured spray angle for water was 104.5° and for the adjuvant was 114.6° [Figure 5]. With the adjuvant, the spray angle was closer to the nozzle’s nominal spray angle of 110°.

High speed imagery of the sprays showed different patterns of atomization between the two solutions. Water alone broke apart into droplets in a disorderly fashion. The adjuvant solution, in contrast, had relatively even perforations across the spray fan. This more even breakup into droplets is reflected in the smaller span (1)

\[
\text{span} = D_{0.9} - D_{0.1}
\]

of the adjuvant spray (521 μm) than the water spray (540 μm), based on LD values. The most commonly proposed explanation for this phenomenon is the perforation of the spray sheet by oil emulsion particles, which is consistent with Altieri et al. [8]. Other mechanisms, such as the transient elongation of emulsion droplets within the solution, as proposed by Qin et al. [9] could not be addressed by this study.

Spray velocity magnitude was greater with the adjuvant solution than with water alone [Figure 4]. Little research into velocity differences due to formulation, and how that could impact the efficacy of adjuvants in the field has been done. Heidary et al. [14] summarize some of this work and propose that an increase in kinetic energy of the droplets due to their size and velocity may be related to a lower risk of drift.

Conclusions

For farmers, the most cost-effective and environmentally sound approach to pesticide and fertilizer applications is to maximize the amount of product that makes it to the target. Adding the drift control adjuvant to the tank mixture had a number of benefits beyond reduction in fine droplets. The narrow span of the droplet size distribution indicated that more droplets of the desired size were being produced. Across a spray boom with nozzles placed every 50 cm, a wider spray angle improves the coverage across the boom. Using wide-angled nozzles allows the applicator to keep the boom close to the plant canopy, which further reduces risk of drift [14]. The effects of increased spray velocity are not well-understood, but reducing the transit time of the spray droplets onto the target surface may also reduce drift potential and improve plant canopy penetration.

For regulators, this demonstrates the value of drift control adjuvants in the tank mix, but also highlights the methodological challenges of measuring sprays with different instruments.

For crop protection product formulators, oil emulsion adjuvants have been a successful product category. Further investigation is needed to understand the exact mechanism by which these products improve spray characteristics and adjuvant function. Developing the next generation of drift reducing products will hinge upon this understanding.

References


Figure 4. Average velocity field for (A) water alone and (B) an oil emulsion adjuvant solution, demonstrating increased magnitude of droplet velocity across the spray plume with the adjuvant.

Figure 5. Spray angle of (A) water alone, and (B) an oil emulsion adjuvant sprayed at 345 kPa through an AIXR 11004 nozzle tip with nominal spray angle of 110°.
Figure 6. A sequence of still images of (A) water and (B) an oil emulsion adjuvant solution.