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LABORATORY AND FULL BOOM-BASED INVESTIGATION OF NOZZLE SETUP ERROR EFFECTS ON FLOW, PRESSURE, AND SPRAY PATTERN DISTRIBUTION

S. H. Forney, J. D. Luck, M. F. Kocher, S. K. Pitla

ABSTRACT. *Pesticide application is an integral part of crop production, and ground-based agricultural boom sprayers are used extensively to apply pesticides to the crop canopy or soil surface across millions of acres in the United States. Efficient application is necessary to minimize costs and limit adverse environmental impacts. The goals of this study were to provide quantified measurements on the effects of nozzle setup errors on spray pattern uniformity and evaluate how laboratory patternator-based simulations would compare to measurements on a full spray boom. More specific objectives were to determine the effects of factors such as nozzle lateral angle, nozzle spacing, nozzle replacement, and nozzle pitch angle on spray pattern distribution and evaluate a simulation approach to predict the effects of single nozzle boom setup errors on full boom system pattern uniformity. Laboratory and sprayer-based tests were devised to quantify the impact of nozzle setup and operational errors on spray pattern uniformity, boom pressure, and nozzle flow rates. Results indicated that small variations in boom setup or nozzle operation (i.e., pressure or flow) can cause significant errors in spray nozzle distribution which may not be completely detectable by measuring spray pattern alone. Simulations using laboratory data from setup or operational errors reflected similar changes (differences less than 2.6%) in spray pattern CV as full boom data with similar setup errors. These findings were significant in that it may be possible to model errors within full boom spray distributions based on smaller laboratory-collected datasets.*

Keywords. *Equipment, Equipment for crop protection, Patternator, Spray pattern distribution, Spraying.*

Pesticides, including herbicides, insecticides, and fungicides used to limit yield loss in crops are an integral part of crop production in U.S. agriculture. In the United States over 285 million acres were treated for weeds, grass, or brush, and over 100 million acres were treated to control insects, according to the 2012 census of agriculture (USDA, 2012). In 2014, U.S. producers spent over $15.8 billion on pesticide inputs (USDA, 2016). As pesticides are used to treat such large areas, and contribute to such a large portion of input costs, accurate application must be achieved to minimize wasted product.

The fate of agrochemicals (e.g., pesticides and nutrients) has raised concerns regarding risks to human and environmental health. Pesticides pose a threat to humans when encountered in drinking water (Younes and Galal-Gorchev, 2000). Excess nutrients in runoff from crop land can enter aquatic ecosystems, increasing the abundance of algae and aquatic plants (Smith et al., 1999), leading to eutrophication. Responsible and efficient application of agrochemicals is important to minimize negative impacts from chemicals not reaching the target pests or crops. Agricultural field sprayers are designed to accurately apply pesticides, fertilizers, and other agrochemicals to the crop canopy, soil surface, or targeted weeds. Proper chemical application requires correct mixing of chemicals, calibration, and selection and setup of that equipment (Grisso et al., 1988). Individual nozzle spray pattern quality has been shown to decrease with orifice wear (Ozkan et al., 1992). Field operation factors such as boom height, boom roll angle, and boom pitch angle have been investigated (Azimi et al., 1985); however, individual nozzle setup errors and nozzle mounting geometry have not been studied. Therefore, further research regarding the effects of individual nozzle setup errors on sprayer uniformity would be useful.

A field survey of 140 pesticide applicators conducted in Nebraska found that only one in three liquid pesticide applicators had applied chemicals within 5% of the intended rate (Grisso et al., 1988). Proper application of pesticides is primarily dependent on the operator and his or her competence in equipment selection, calibration, and chemical mixing (Grisso et al., 1988). Successful spray application requires that the proper amount of chemical is applied uniformly from the spray boom to the crop or soil surface. Thus, maintaining accurate nozzle flow rates and uniform spray pattern is critical to proper application. If operators understood how boom setup factors influenced spray uniformity (i.e., nozzle flow and spray pattern), they would be better equipped to monitor and correct issues as they developed in the field.

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While more challenging than measuring nozzle flow rates, spray pattern testing has been conducted for many years using patternators to evaluate single or multiple nozzle distributions, commonly measured as the coefficient of variation (CV). The effects of orifice wear demonstrated the early use of patternators to quantify nozzle spray pattern performance (i.e., CV) (Ozkan et al., 1992). To minimize human error, computerized spray pattern collection systems have been developed, however, early versions had problems with vibration at some operating conditions (Ozkan and Ackerman, 1992). Luck et al. (2016) built a patternator using digital liquid level sensor technology, capable of measuring spray pattern CVs (in 25 mm increments) and pressure data simultaneously.

Studies have been conducted in the past to quantify the effects that field operation factors might have on pattern uniformity. Mawer and Miller (1989) studied the effects of boom roll and boom height on spray pattern CV. The findings concluded that boom roll angles as small as one degree could affect the spray pattern CV. A simulation (Mawer and Miller, 1989) and results from a single nozzle (Azimi et al., 1985) showed that spray pattern CV decreased with increased height. Pressure testing of a single nozzle showed decreased spray pattern CV with increased pressure, with the exception of cone and flooding nozzles which showed less improvement with increased pressure (Azimi et al., 1985). Tilt angle (which involved rotating one nozzle) away from the direction of travel was shown to decrease CV, but the investigators warned this may leave spray droplets more susceptible to drift (Azimi et al., 1985). While most studies have focused on how operation (i.e., boom height, tilt, roll, and pressure) of a single nozzle may affect spray uniformity, little has been done to quantify how setup factors of an individual nozzle among a boom of properly mounted nozzles might contribute to the spray distribution of the system. For instance, a single nozzle tilted laterally or fore or aft may have a negative impact on the spray pattern. In practice, plastic wet boom tubing tends to warp over time which creates a lateral angle shift in nozzles along that portion of the boom. The effects of improper nozzle spacings within a boom section on pattern uniformity have also not been previously reported.

The goals of this study were to provide quantified measurements on the effects of nozzle setup errors on spray pattern uniformity and evaluate how laboratory patternator data would compare to measurements on a full spray boom. More specific objectives were: 1) to determine the effects from factors such as nozzle lateral angle, nozzle spacing, nozzle replacement, and nozzle pitch angle on spray pattern distribution, 2) to evaluate a simulation approach to predict the effects of single nozzle boom setup errors on full boom system pattern uniformity, and 3) to assess the sensitivity of full boom operational measurements (e.g., flow, pressure, and spray pattern) for predicting any distribution errors.

MATERIALS AND METHODS

Spray pattern distribution, boom pressure, and nozzle flow rates were collected on an indoor patternator, as outlined by Luck et al. (2016), to quantify how nozzle setup errors impacted spray pattern distributions. The patternator was constructed per ASTM standard E641-01 (ASTM, 2006) and was capable of simultaneously recording a 76 cm width of spray pattern distribution in 25 mm increments and pressure data at the nozzle. To quantify the CV, the patternator measured the amount of time to fill a fixed volume (166 mL) for each 25 mm division. As each individual tube was filled, a liquid-level sensor (102101, Honeywell Inc., Morris Plains, N.J.) triggered a virtual instrument (VI) in LabVIEW (National Instruments Corporation, Austin, Tex.) and flow rate for each 25 mm division was automatically recorded.

The VI then created a spreadsheet and provided a quantitative and visual depiction of the spray pattern. Spray pattern quality was quantified by CV, as calculated by equation 1 (Ozkan et al., 1992). CV is a standardized measure of the dispersion of data points, and when applied to spray patterns it measures how evenly nozzle effluent is distributed. Higher CVs indicate a poor or uneven spray distribution while lower CVs indicate improved uniformity.

$$CV(\%) = (100\%)\cdot\frac{\sqrt{\frac{\sum_{i=1}^{n}(x_i-\bar{x})^2}{n-1}}}{\frac{\sum_{i=1}^{n}x_i}{n}} \tag{1}$$

where

x_i = flow rate (fixed volume divided by the time to fill tubes) of i^{th} sample across spray pattern width ($mL \cdot min^{-1}$),

$\bar{x}$ = mean flow rate ($mL \cdot min^{-1}$) to fill tubes across pattern width,

n = number of collection tubes.

Tests using the indoor patternator system took place at the University of Nebraska-Lincoln, free of wind or other environmental conditions. Nozzles used during this study were stainless steel extended range (XR and XRC) flat fan nozzles and stainless steel air-injected extended range (AIXR) flat fan nozzles of orifice sizes 01, 03, and 05 manufactured by TeeJet (TeeJet Technologies, Wheaton, Ill.), (TeeJet Technologies, 2015). These nozzles were chosen because they are commonly used in pesticide application in the United States.

A standard nozzle setup configuration was used for height and spacing settings above the indoor and outdoor patternator. These settings were based off of the manufacturer-recommended values obtained from the literature (TeeJet Technologies, 2015). For the purposes of this study, 80° nozzles (e.g., XR 8001, XR8003, XR8005, and XRC8003) were placed at a height of 75 cm with a spacing of 50 cm. The 110° nozzles (e.g., XR11003 and AIXR11003) were placed at a height of 50 cm with a spacing of 50 cm.

NOZZLE LATERAL ANGLE TEST

The nozzle lateral angle test setup consisted of five nozzles mounted above the indoor patternator in a dry boom configuration. A system is considered a dry boom configuration if the support mechanism and spray solution delivery mechanism are separate, whereas in a wet boom configuration the support mechanism also delivers the spray solution (Klein, 2004). Spray pattern data were collected in two 76 cm sets to the left and right of the center nozzle, and they were combined to make one 152 cm dataset at each angle setting. Three replicates of 152 cm spray pattern data were collected for each treatment. Spray distribution measurements were recorded as the center nozzle was rotated in a clockwise direction about a horizontal axis perpendicular to the boom in 2° increments from 0° to 8° (fig. 1) while the surrounding nozzles kept their original orientation (spraying vertically downward). The nozzle was rotated by loosening a bolt on the custom-made mounting bracket, adjusting the nozzle angle (measured with an angle gauge), then tightening the bolt to hold the test nozzle in position.

Tests were run first with TeeJet XR8003 nozzles, then XR8005 nozzles at a system pressure of 207 kPa which was set via a pressure relief valve (23120, TeeJet Technologies, Wheaton, Ill.). Additional tests were recorded using XR11003 and AIXR11003 nozzles; XR11003 nozzles were tested at a system pressure of 207 kPa while the AIXR11003 nozzles were tested at 207 and 345 kPa. It should be noted that the AIXR nozzles were operated at two different pressures because their operating pressure range is typically higher than that of the XR nozzles (TeeJet Technologies, 2015). Nozzle spacing, boom height, and system pressure remained unchanged as the center nozzle lateral angle was adjusted during these tests. Test results were analyzed for significant differences using a general mixed model (GLIMMIX) in SAS v9.4 to run a Least Significant Means (LSM) test (SAS Institute Inc., 2013) with an alpha level of 0.05. The LSM test was setup using the lateral angle settings as treatments to determine which lateral angle settings produced significantly different spray pattern distributions.

NOZZLE SPACING TEST

To test for the effects of improper nozzle spacings, six XR8003 nozzles were mounted above the indoor patternator surface and operated at 207 kPa, as well as six AIXR11003 nozzles operated at 345 kPa. Nozzles were assigned numbers one through six from left to right, and nozzle number three was offset in 25 mm increments to the right (fig. 2). Pattern data were collected for nozzle number three with offset values of 0, 25, 50, 75, 100, and 125 mm. All other nozzles remained in the same location for each test. The patternator was positioned to collect two sets of 76 cm of pattern data which were combined to make one 152 cm dataset centered beneath the original location of the third nozzle. Three replications of spray pattern data were taken for each offset value. A LSM test, with an alpha of 0.05, was used to determine differences among the mean spray pattern CV for the nozzle offset values.

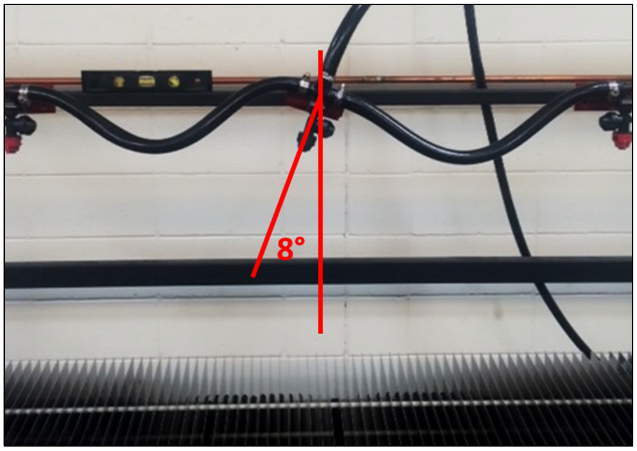

Figure 1. Nozzle lateral angle test with center test nozzle set to 8°.

NOZZLE REPLACEMENT TEST

To test the effect due to an incorrect nozzle placed within the spray boom, six XR8003 nozzles were mounted above the indoor spray patternator surface and operated at a pressure of 207 kPa. Three replicate spray pattern measurements (152 cm centered below the third nozzle) were made with this nozzle configuration. To test the effect due to either an incorrect, plugged, or worn nozzle, the third nozzle (from left) was replaced with an XR8001 and then an XR8005 nozzle. Three replications of spray pattern data were collected with both nozzle replacements. Boom pressure was monitored with calibrated pressure transducers (PX309-100G5V, Omegadyne, Inc., Sunbury, Ohio) and used as the independent variable. The pressure transducers produced a 0 to 5 V DC output directly proportional to a 0 to 690 kPa pressure range. Flow rate data were manually collected for each of the six spray nozzles during each test using a graduated cylinder with graduations in increments of 2 mL and a stopwatch. To estimate effects on spray pattern uniformity or nozzle flow rates from these changes, the spray pattern CVs from the tests with XR8001 and XR8005 replacement nozzles were compared to CVs from the XR8003 nozzles.

NOZZLE PITCH ANGLE TEST

To evaluate effects of nozzle pitch angle on pattern uniformity, five XR11003 nozzles were mounted above the indoor spray patternator and operated at a system pressure of 276 kPa. The center nozzle was rotated in the direction of (fore), and against the direction of (aft) travel of a sprayer in 4° increments from 0° to 24° first clockwise, then counterclockwise, when the boom was viewed from the right side (fig. 3). The other four nozzles remained pointed vertically downward above the patternator. Three replications of data were recorded for each nozzle angle setting. A LSM test with an alpha value of 0.05 was used to determine significant differences among the CVs produced by the nozzle settings.

COMPARISON OF LABORATORY SIMULATED PATTERN DATA VERSUS FULL BOOM FIELD PATTERN TEST

Spray pattern data from one replicate of the laboratory patternator tests (152 cm widths) were extrapolated to simulate the full boom of a sprayer. Eighteen sets of baseline XR8003 spray pattern and boom pressure data were placed side by side to simulate a 27.4 m spray boom. One set of reference spray pattern data (152 cm) was then removed and replaced with 152 cm of spray pattern data from the nozzle replacement test (i.e., the XR8003 and XR8005 nozzle replacements). These tests were conducted to quantify the effect of a single nozzle setup error on a full boom width. The

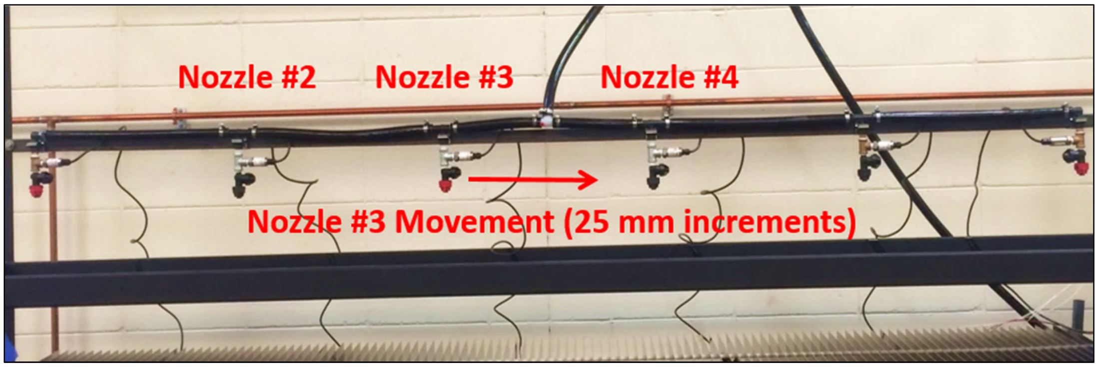

Figure 2. Nozzle spacing test with nozzle three, as shown, moved in 25 mm increments to the right.

25 mm patternator collection width increments were grouped into 100 mm increments by averaging flow rates from four successive 25 mm collection tubes. This grouping of the baseline XR8003 data and lateral angle test data were necessary to compare with the full boom sprayer pattern data which was collected in 100 mm widths.

To document the full boom plumbing layout, measurements (1.51 mm graduations) were taken between successive nozzle bodies. A common point in the middle of each nozzle body (top of the arrow in fig. 4) was used as a reference point for these measurements. For this spray boom the recommended spacing was 50 cm. Distances between successive tips were also measured using the same method. Assuming the lateral angle originated at the QJ360C nozzle body center rotation point (fig. 4), the nozzle tip spacing deviation and the distance from the center of rotation to the nozzle tip could be used to calculate the nozzle lateral angle. A simulation spray pattern was created using lateral angle test results from the indoor patternator corresponding to rotation angles measured from nozzle body and tip spacings on the full boom. Four sets of 8° and four sets of 4° lateral angle test indoor pattern distribution data were inserted into the baseline full boom simulation to create a modified baseline simulation to account for nozzle tip and spacing deviations.

Spray pattern, boom subsection pressure, nozzle pressure, and nozzle flow rate data were collected on a full boom sprayer for comparison with the full boom simulations. An Apache AS1020 self-propelled sprayer with a 27.4 m boom (54 XRC8003 nozzles at 50 cm spacing) was used in conjunction with a mobile patternator (Sprayertest 1000, Herbst pflanzenschutztechnik, Hirschbach, Germany) to collect spray pattern data. These data were collected outdoors early in the morning to minimize wind effects. The Herbst Sprayertest 1000 (fig. 5) is a mobile patternator in which the user places a track underneath the spray boom and installs the spray pattern collection cart on the track. The cart used 100 mm collection troughs to collect spray pattern data by collecting one patternator width (1 m) at a time.

The spray pattern collection cart utilized control software to enter the start and end positions along the boom. The spray pattern collection cart moved to the start location (centerline of the first nozzle) and then automatically recorded spray pattern measurement data along the track beneath the boom. Individual spray pattern cart measurements were recorded the centerline of the last nozzle was reached at which time a composite spray pattern (mL/min^{-1}) was generated for the boom and exported to an Excel document.

Boom subsection pressure data were collected using electronic pressure transducers (Omega Engineering PX309-100G5V) installed inline within the boom hose (fig. 6) and individual nozzle pressure readings were collected via a manual pressure gauge fitted to a nozzle body connector (fig. 6). The output signal from the electronic pressure transducers was recorded to a.txt file at 1 Hz using a microcontroller (Arduino Mega 2560, Arduino LLC, Ivrea, Italy). The

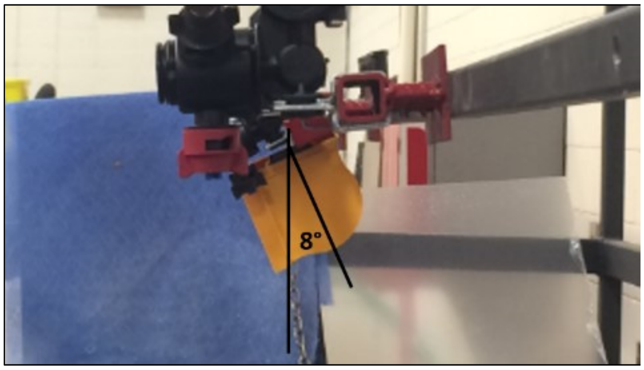

Figure 3. Nozzle pitch angle test with nozzle rotated 8° counterclockwise (fore) from vertical.

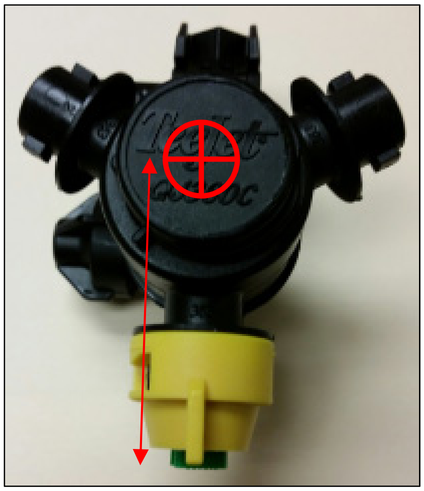

Figure 4. TeeJet QJ360C nozzle bodies used on Apache sprayer during outdoor boom tests. The distance from nozzle tip to center of rotation, as shown by red arrow, is 60 mm. Center of rotation is approximated by a red cross.

Figure 5. Herbst Sprayertest 1000 on tracks placed below Apache AS1020 sprayer, with the spray pattern collection device installed on the end of the tracks (foreground of picture).

manual pressure gauge (PGS-35L-100, Omegadyne, Inc., Sunbury, Ohio) had a minimum graduation increment of 6.9 kPa (1 psi) for recording pressure readings (fig. 6). A diagram of the spray boom is illustrated in figure 7 showing locations of the pressure transducers. Individual nozzle flow rates were collected using a 250 mL graduated cylinder (graduations in increments of 2 mL) and a stopwatch. Three replicates of flow rate measurements were taken at each nozzle across the boom during the tests. CV values were calculated for each of these parameters to quantify variation before and after the nozzles were replaced.

The baseline test of full boom pattern data utilized XRC8003 nozzles with the boom positioned 75 cm above the surface of the Sprayertest 1000. The operating pressure was set to 207 kPa on the Raven in-cab monitor. The nozzle at position #20 (numbered from left to right), in the fourth boom subsection (fig. 7) was replaced with an XR8001 and then an XR8005 nozzle for the two subsequent nozzle replacement tests. Three replicates of pattern and pressure data (both manual and automated pressure sensor data) were collected along with flow rate data.

The modified baseline full boom simulation was further revised to include a laboratory patternator section of data from the XR8001 and XR8005 nozzle replacement tests. The 152 cm sections of patternator data (grouped into 100 mm collection widths) from both tests were inserted in approximately the same location as nozzle #20 (on the full boom) into the modified baseline simulation. Subsequent comparisons were made between the full boom CVs between both the simulated distributions and the actual tests where XR8001 and XR8005 nozzles were inserted into the full boom.

RESULTS AND DISCUSSION

NOZZLE LATERAL ANGLE TEST

Figure 8 shows the spray pattern distribution from a nozzle lateral angle test baseline (0° nozzle lateral angle) replicate which yielded a CV of 4.1%. The x-axis shows each 25 mm patternator collection width (numbered 1 to 60 as a position identifier). The center nozzle was positioned between volume divisions 30 and 31. Figure 8 illustrates the flow rate per collection volume (25 mm widths per container) across the 152 cm collection width. Figure 9 illustrates the spray pattern change when the test nozzle (nozzle #3) was rotated 8° to the left. The spray pattern shown in figure 9 with an 8° clockwise nozzle lateral angle yielded a CV of 15.4% and was visibly worse than that of the baseline group shown in figure 8.

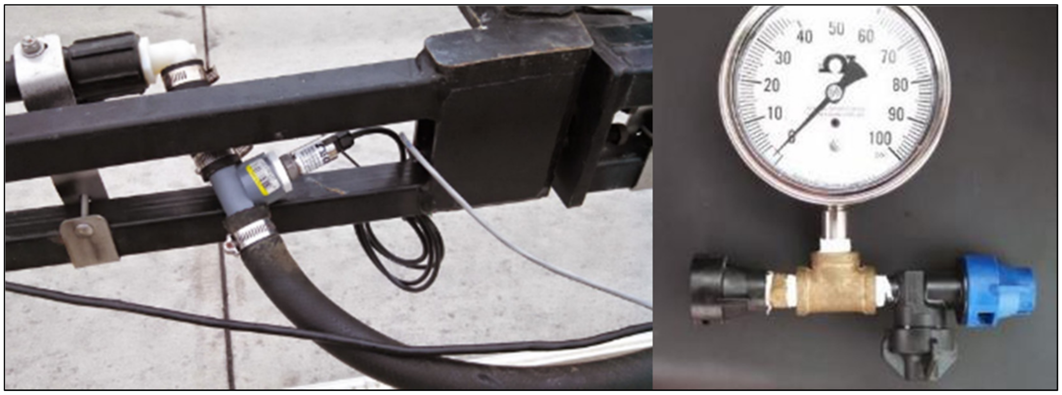

Figure 6. Omega pressure transducer plumbed in line with boom subsection supply line (left) and manual pressure gauge (right).

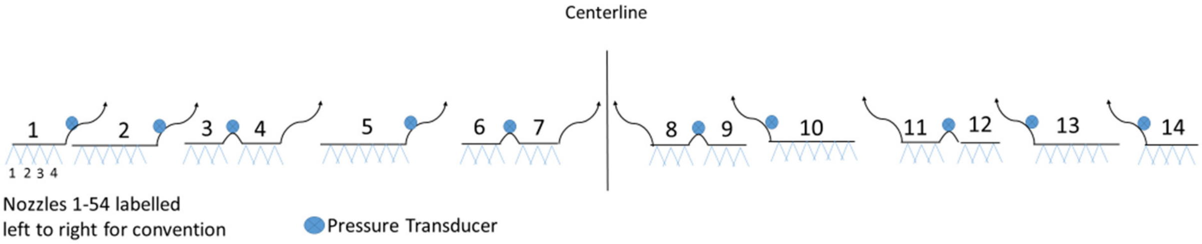

Figure 7. Boom setup diagram of Apache AS 1020 showing boom subsections and pressure transducer placement.

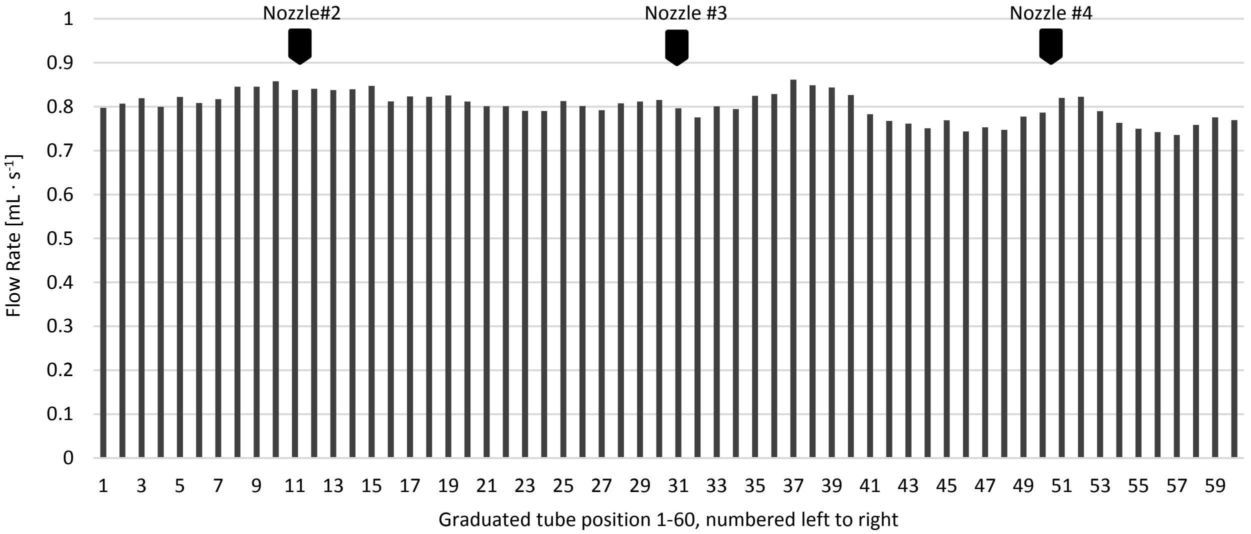

Figure 8. Spray pattern from nozzle lateral angle test in flow rate versus position with 0° of nozzle lateral angle rotation using XR8003 nozzles (75 cm height, 50 cm spacing, 207 kPa).

The baseline CV (i.e., 0° center nozzle lateral angle for XR8003 nozzles, 75 cm height, 50 cm spacing, and operating at 207 kPa), averaged 4.2%. The baseline CV with XR8005 nozzles averaged 5.1%. The threshold for a desirable pattern CV was considered at or below 10% (Azimi et al., 1985; Ozkan et al., 1992). As the lateral angle rotation of the center nozzle increased, the CVs also tended to increase (table 1). The results for the 80° nozzles (XR8003 and XR8005) showed that CV values approached or exceeded 10% as the nozzle angle reached 4°. With a nozzle lateral angle of 8°, the CV for both 80° nozzles exceeded 15%, which would be considered unacceptable (Ozkan et al., 1992). Statistical analysis revealed that each 2° increment in nozzle lateral angle significantly ($p \leq 0.05$) increased the average spray pattern CV for XR8003 and XR8005 nozzles (table 1). The nozzle lateral angle test data for the 110° nozzles is also summarized in table 1. The baseline CV for the XR11003 averaged 6.5% while baseline CVs for the AIXR11003 nozzles at 207 and 345 kPa were 10% and 4.5%, respectively. The data in table 1 indicate that pattern uniformity of flat fan nozzles with 110° spray angles was less susceptible to lateral angle changes than the 80° nozzles. The narrower nozzle fan angles and higher boom heights, of 80° nozzles compared to 110° nozzles, likely contributed to the larger CVs as lateral angle increased. As expected, the pattern of the AIXR11003 nozzles at 207 kPa was poor due to low operating pressure.

NOZZLE SPACING TEST

Results from the nozzle spacing test showed that changing the center XR8003 nozzle position (spacing) by as much as nearly one-fourth of the initial spacing did not raise the

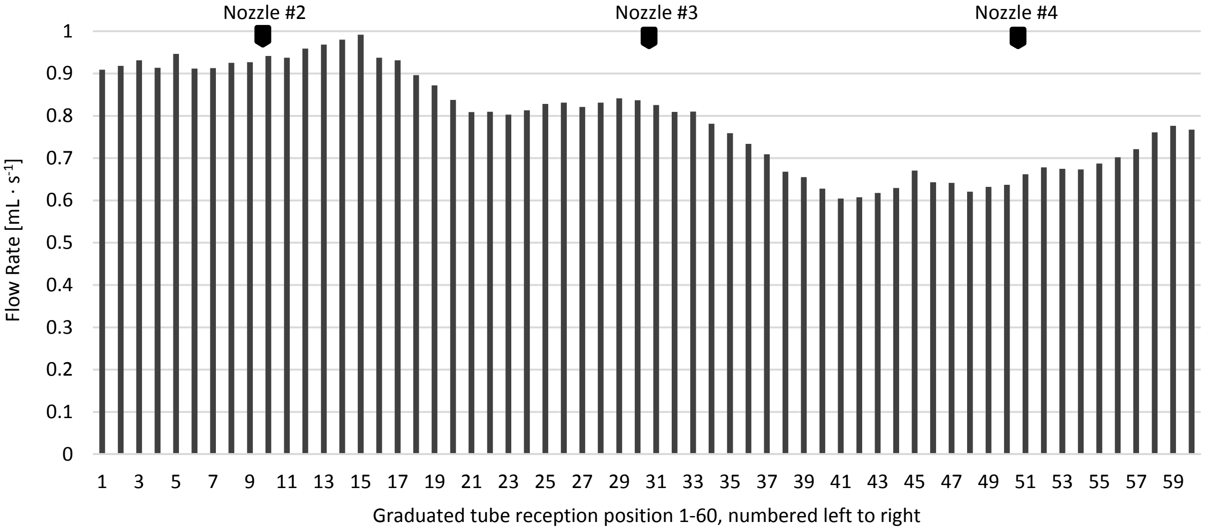

Figure 9. Spray pattern from nozzle lateral angle test in flow rate vs. position where nozzle #3 was rotated 8° clockwise using XR8003 nozzles (75 cm height, 50 cm spacing, 207 kPa).

Table 1. Summary of nozzle lateral angle test CV results for five nozzles.[a]

Center Nozzle Lateral Angle	XR8003 [75 cm height at 207 kPa] (%)	XR8005 [75 cm height at 207 kPa] (%)	XR11003 [50 cm height at 207 kPa] (%)	AIXR11003 [50 cm height at 207 kPa] (%)	AIXR11003 [50 cm height at 345 kPa] (%)
0°	4.2^{a}	5.1^{a}	6.5^{a}	10.0^{a}	4.5^{a}
2°	5.3^{b}	8.0^{b}	6.6^{a}	9.9^{a}	4.9^{a}
4°	9.9^{c}	11.1^{c}	7.2^{a}	10.2^{b}	6.0^{b}
6°	11.5^{d}	12.7^{d}	7.5^{a}	10.9^{b}	6.2^{b}
8°	15.6^{e}	18.1^{e}	7.9^{a}	11.5^{c}	8.4^{c}

[a] Within each nozzle, mean CVs with same letter are not significantly different ($p \le 0.05$). Mean CVs between nozzles was not tested for significance.

CV above the 10% threshold (table 2). As shown in table 2, baseline CVs for both 80° and 110° nozzles at a 50 cm spacing were established at 3.8% and 4.9%, respectively. As nozzle #3 was moved to the right in 25 mm increments, the spray pattern CV values increased. Considerable deviations in nozzle spacing >100 mm) occurred before undesirable pattern CVs (i.e., greater than 10%) were noticed with these nozzle configurations. There was no significant change from the initial 50 cm spacing CV until the nozzle was moved 50 mm to the right (table 2) for either 80° or 110° nozzles. Each subsequent increment of movement to the right produced an increase in CV for both nozzles, however, the spray pattern CVs did not exceed 10% until the center nozzle was positioned 125 mm to the right. These results indicate that the spray pattern for 80° and 110° nozzles did not change significantly and were therefore quite tolerant of nozzle spacing deviations.

NOZZLE REPLACEMENT TEST

Baseline data were collected using six XR8003 nozzles at 207 kPa which produced an average spray pattern CV of 4.1% with individual replicates as low as 3.9%. Spray pattern CVs increased to 18.9% and 8.4% when the original XR8003 nozzle at position #3 was replaced with an XR8001 and then an XR8005 nozzle, respectively (table 3). Flow rate changes (measured in % change from the 16.7 mL s^{-1} baseline of all XR8003 nozzles) from the replacement tests were much larger than changes in the spray pattern CV. When the XR8001 nozzle replaced the XR8003 nozzle, the spray pattern CV increased by 14.8% while the test nozzle flow rate decreased by 66%. The XR8005 replacement resulted in a 4.3% increase in spray pattern CV while the flow rate increased by 70% relative to the XR8003 nozzle flow rate. In the case of the XR8005 nozzle, the spray pattern CVs never exceeded the 10% unacceptable threshold for such a change in measured flow rate.

NOZZLE PITCH ANGLE TEST

Table 4 summarizes the results for the nozzle pitch angle test. The baseline spray pattern CV prior to the pitch angle rotation forward of vertical averaged 5.0%. The spray pattern CV remained at 5.6% for the 4°, 8°, and 12° fore rotations and averaged 7.1% at 24° of fore rotation. The baseline spray pattern CV prior to aft rotation averaged 4.9%. The spray pattern CV gradually increased up to 8.9% at 24° of nozzle pitch angle rotation aft of vertical. This shows that fore/aft rotation of the middle of the three nozzles up to 24° from vertical did not increase spray pattern CV above the maximum desirable CV limit of 10%. The discrepancy in CV change in fore versus aft for similar angle changes may be due to the slope of the patternator collection.

COMPARISON OF LABORATORY SIMULATED PATTERN DATA VERSUS FULL BOOM FIELD PATTERN TEST

Figure 10 shows an extrapolation to a 27.4 m spray boom based on the measurements made with the 25 mm indoor patternator data from the XR8003 nozzles, resulting in a CV of 3.8%. This represented a well-balanced boom with adequate flow and positioning from all nozzles and served as a reference for comparison with the full boom pattern test. To simulate the effect of having a nozzle obstruction in the 27.4 m boom simulation 152 cm of pattern data were replaced with 152 cm of data from the nozzle replacement test using an XR8001 nozzle. This change increased the simulated boom CV to 7.6% from 3.8%. The simulated full boom CV was much lower than the resulting CV from the 152 cm patternator CV with an XR8001 in one nozzle position

Table 2. Summary of nozzle spacing test CVs as nozzle #3 moved to the right in 25 mm increments from original 50 cm spacing.[a]

Nozzle #3 Offset (mm)	XR8003 CV (%)	AIXR11003 CV (%)
0	3.8^{a}	4.9^{a}
25	4.7^{a}	4.8^{a}
50	6.2^{b}	5.5^{b}
75	7.7^{c}	6.8^{c}
100	8.0^{c}	9.4^{d}
125	11.1^{d}	11.4^{e}

[a] Mean CVs with same letter are not significantly different ($p \le 0.05$).

Table 4. Summary of nozzle pitch angle test with XR11003 nozzles rotated about a horizontal axis parallel to the boom.

Center Nozzle Pitch Angle	Spray Pattern CV[a] Fore of vertical (%)	Spray Pattern CV[a] Aft of vertical (%)
0°	5.0^{a}	4.9^{a}
4°	5.6^{a,b}	4.8^{a}
8°	5.6^{a,b}	5.6^{b}
12°	5.6^{a,b}	6.5^{c}
16°	5.9^{b}	7.5^{d}
24°	7.1^{c}	8.9^{e}

[a] Mean CVs with same letter are not significantly different ($p \le 0.05$).

Table 3. Summary of average spray pattern CV, flow rate changes and pressure from nozzle replacement test.

Nozzle at Position #3	Average (of three replicates) Spray Pattern CV (%)	Nozzle #3 Flow Rate (mL s^{-1})	Flow Deviation of Center Nozzle from XR8003 (%)	Average Boom Pressure (kPa)
XR8001	18.9	5.6	- 66	209.1
XR8003	4.1	16.6	-	209.8
XR8005	8.4	28.0	+ 70	205.6

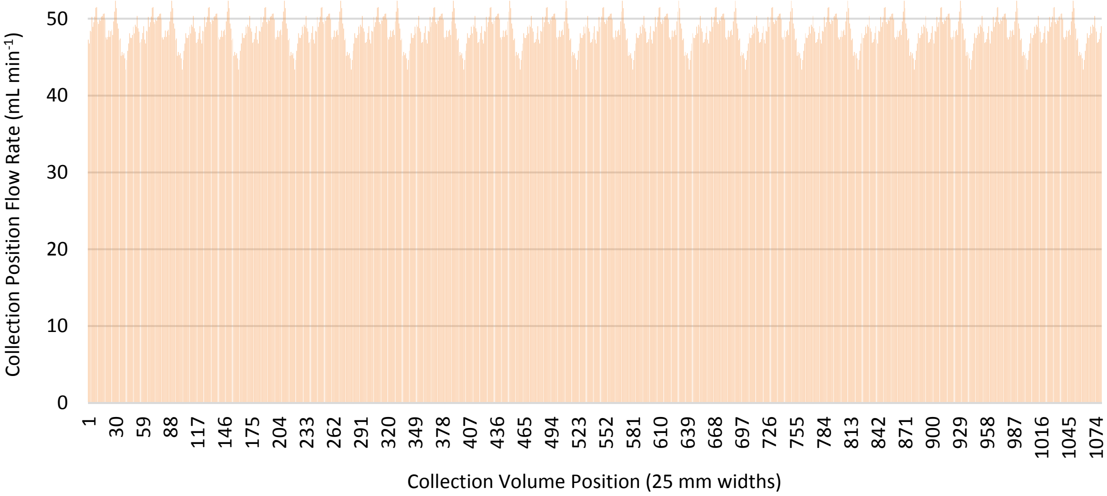

Figure 10. Simulation of 27.4 m boom of XR8003 nozzles using 152 cm spray pattern data (CV 3.8%).

(18.9%) as illustrated in table 3. This showed that CV is much more sensitive when calculated from three nozzles as opposed to a full boom consisting of 54 nozzles. Similar simulations performed using the XR8005 replacement nozzle data resulted in a CV of 7.3% which represented an increase from the 3.9% baseline CV full boom simulation of XR8003 nozzles.

Table 5 contains CV estimates from lateral angle test in both 25 mm collection width increments and 100 mm averaged collection widths. The effect from collection width was minimal with the largest difference in CV being 0.2% for 0° and 8° (table 5). This showed that the simulation data could be converted from 25 to 100 mm collection widths with negligible affects to the CV values.

Figure 11 shows the results of the 100 mm collection tube averaging when applied to the baseline simulation with XR8003 nozzles. The conversion demonstrated only a slight decrease (0.4%) in average spray pattern CV as compared to the 27.4 m boom simulation with 25 mm collection widths (fig. 10). Therefore, the data averaged into 100 mm collection widths was considered suitable for comparison to the full boom data.

The baseline spray pattern data collected from the full boom sprayer using the Sprayertest 1000 is shown in figure 12. A summary of the boom pressure, flow rates, and spray pattern results from the sprayer can also be found in table 6. Flow rate data from all nozzles were compared to the average flow across the boom and found to be within 5% from the average flow rate. Thus, initial nozzle flow rate CVs (prior to nozzle replacement) were fairly consistent and low. The baseline performance data for the sprayer resulted in a pattern CV of 11.0% which was much higher than anticipated for the system. Manual pressure readings at each nozzle showed little variation, in fact, for the XR8005 nozzle, no pressure deviation was noticed with the manual pressure gauge. When the nozzle at position #20 was changed from the XRC8003 to the XR8001 and XR8005 nozzles, changes were apparent in the pattern and flow rate data. In both cases, there were small increases in overall spray boom CV, while much larger changes were noticed in nozzle flow rate CV values for the entire boom. Variations in pressure among nozzles or boom sections were negligible.

The discrepancy noticed between the simulated 27.4 m boom baseline (3.4% CV) and the data collected from the mobile patternator (11% CV) was higher than expected. The reference pattern data CV was initially higher than the simulated data, thus was less susceptible to changes, and pattern variations had a smaller impact. The simulation started with a much lower baseline CV, therefore, any variation introduced would likely cause a larger increase in CV. To explain the high initial CV of the full boom spray pattern, some factors were considered which may have contributed to the spray pattern uniformity. Because few issues were noticed with boom pressure and flow measurements during baseline tests, nozzle spacing measurements were observed to determine if they may have affected the high pattern CV measured (11%). Summing the 53 nozzle body spacing or the 53 nozzle tip spacing measurements revealed an error of only +5 cm in total boom width in either case. Figure 13 shows a histogram of nozzle body spacing and nozzle tip deviations (in mm) from the manufacturer-recommended spacing of 50 cm. Of the total 53 spaces between nozzle bodies along the boom, 32 deviated by less than ±5 mm. Fourteen spacing deviations varied between ±5 to 10 mm while another six nozzle bodies spacing deviations exceeded ±10 mm. Only one spacing measurement indicated a deviation greater than 20 mm, which measured 48.6 mm.

Table 5. Spray pattern CVs results from 25 mm nozzle lateral angle test averaged into 100 mm collection widths.

Nozzle #3 Lateral Angle Rotation (°)	Spray Pattern CV for 25 mm Collection Width	Spray Pattern CV for 100 mm Collection Width
0	4.1%	3.9%
2	5.3%	5.2%
4	9.6%	9.7%
6	11.3%	11.3%
8	15.2%	15.4%

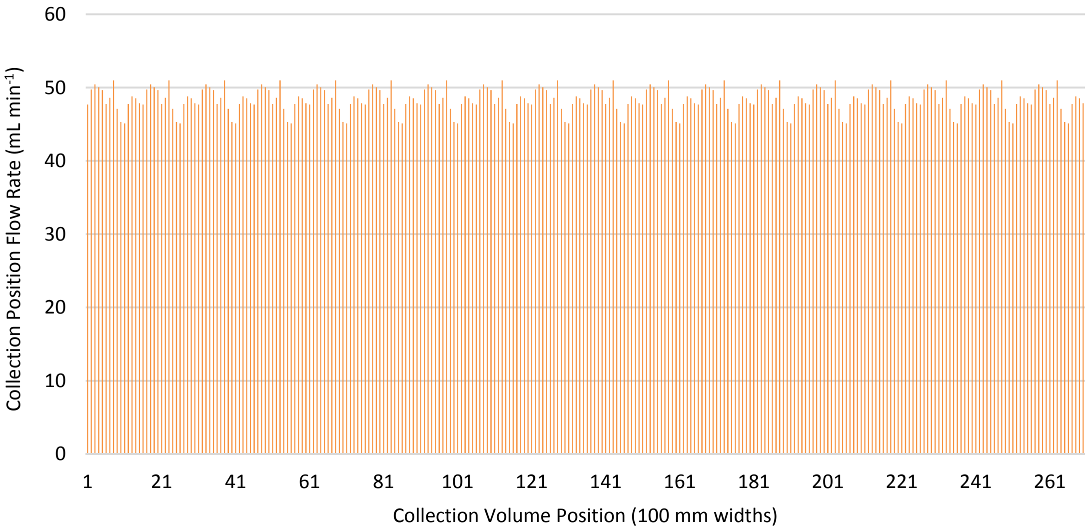

Figure 11. Simulation of 27.4 m boom of XR8003 nozzles using 152 cm spray patternator data (25 mm collection width) grouped into 100 mm collection widths (CV 3.4%).

Based on the information contained in table 1, the differences in nozzle body spacings that exceeded 20 mm could have affected spray pattern CV in that area up to 1%. The effect of the smaller deviations that were measured may be determined with further study as the minimum deviation tested with the indoor patternator was 25 mm. Based on the data in figure 13, nozzle spacing likely had little negative impact on the full boom spray pattern CV values.

The data in figure 13 also summarize similar data from the nozzle tip spacing measurements. While this information does not provide an absolute deviation in lateral angle from vertical, it does provide insight into the nozzle to nozzle variation. The analysis of nozzle body spacing and nozzle tip spacing provide evidence that multiple nozzles could have exceeded a lateral angle deviation of 10° from vertical. Considering the data contained in table 1, these angles could have contributed to spray pattern errors across the boom. The result of adding nozzle body and tip variations into the initial baseline simulation can be seen in figure 14, referred to as the modified reference pattern simulation.

Table 6. Summary of spray pattern, nozzle pressure, boom section pressure and nozzle flow rate CVs for nozzle #20 replacement tests.

Test Setup	Average Spray Pattern CV (%)	Average Nozzle Pressure CV (%)	Average Boom Section Pressure CV (%)	Average Nozzle Flow Rate CV (%)
Baseline	11.0	1.9	1.0	1.4
w/ XR8001	13.3	2.7	0.8	9.1
w/ XR8005	12.3	-	0.8	8.5

Figure 15 represents the full boom modified reference pattern simulation data after a subsection of indoor patternator data from the XR8001 replacement test had been added at the nozzle #20 location. Here, the reduced flow rate at that location is clearly visible compared to the modified baseline

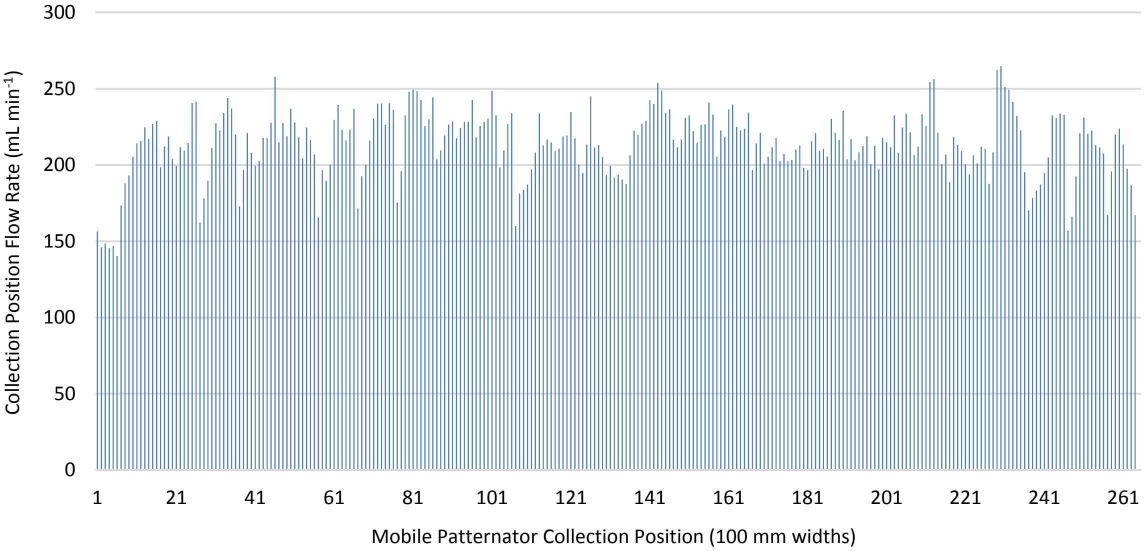

Figure 12. Mobile spray patternator output for baseline full boom data collection (11% CV).

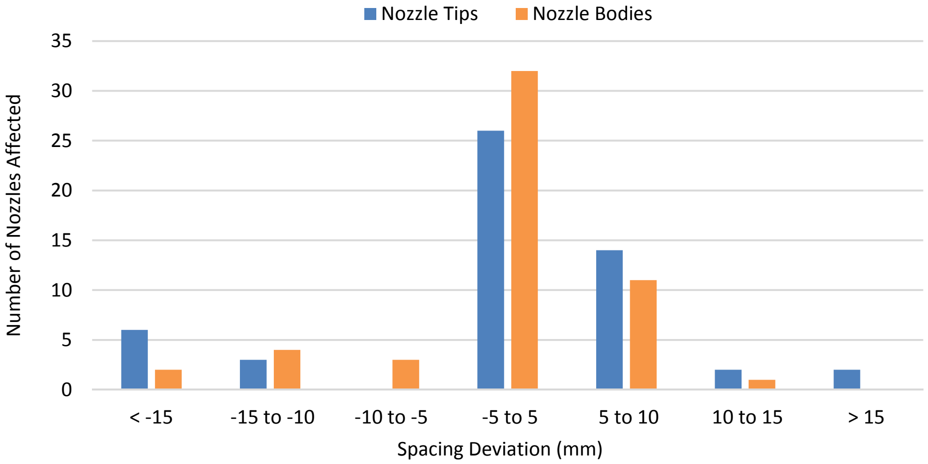

Figure 13. Number of nozzle bodies and nozzle tips at various spacing deviations (mm) from recommended spacing of 50 cm.

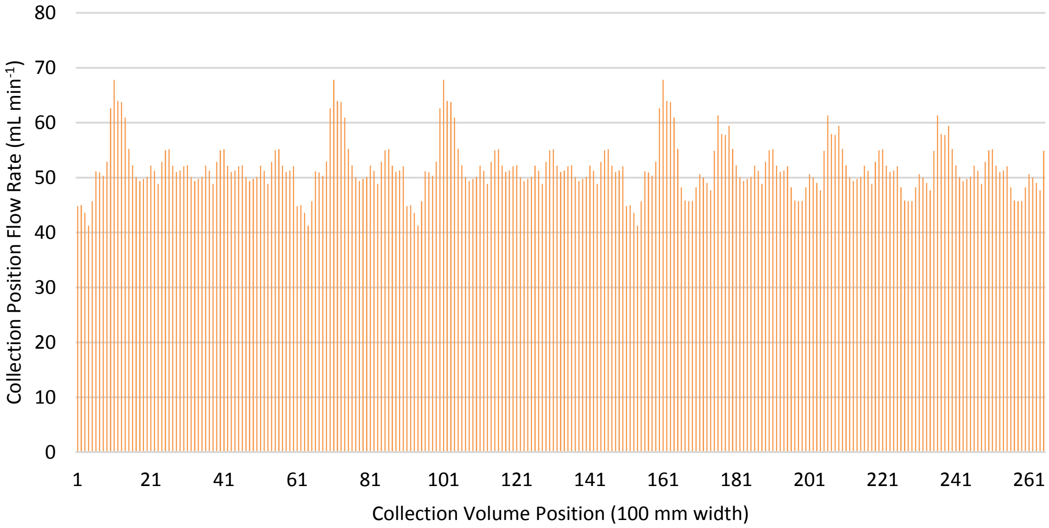

Figure 14. Modified reference pattern simulation of 27.4 m boom for the XR8003 laboratory nozzle data (CV 9.4%).

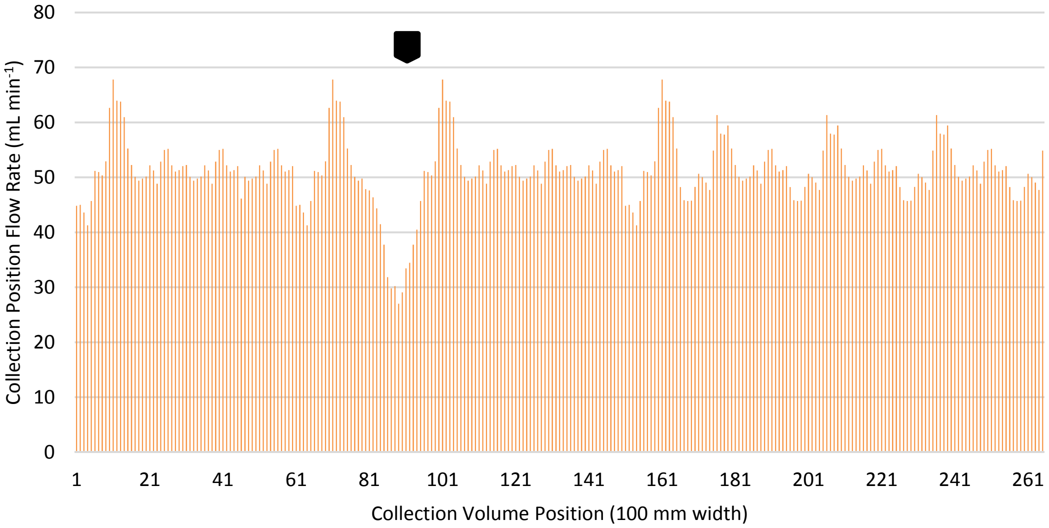

Figure 15. Simulated 27.4 m full boom scenario (CV 12.0%) created from patternator for XR8003 nozzles with one subsection of XR8001 spray pattern data inserted, position indicated with arrow.

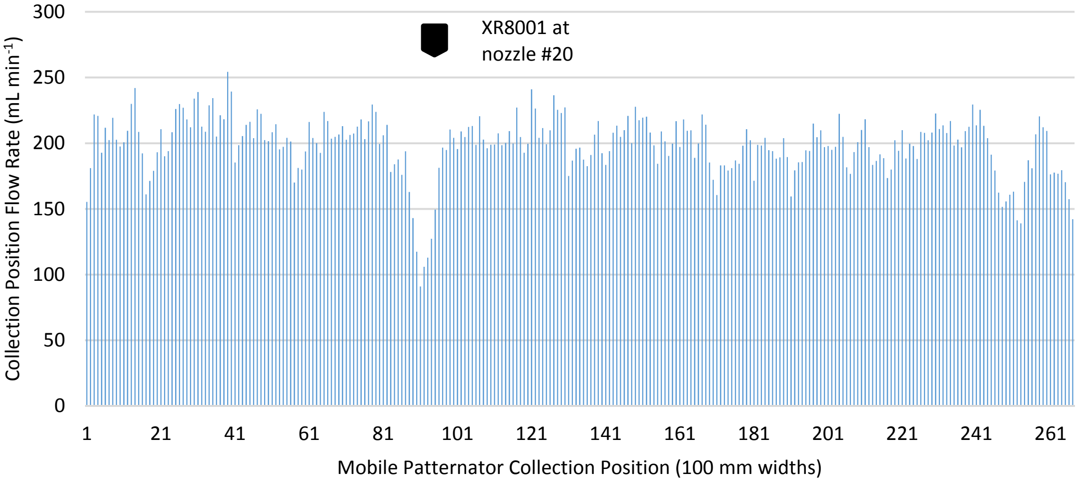

Figure 16. Spray pattern data from Sprayertest 1000 with XR8001 replacement nozzle at position #20 (CV 13.3%).

simulation shown in figure 14. The full boom spray pattern distribution results from the Sprayertest 1000 with the one nozzle at position #20 replaced with an XR8001 nozzle is shown in figure 16.

A second simulation was created using the indoor patternator XR8005 replacement test which was inserted into the modified reference dataset (fig. 14). The resulting simulated boom distribution with the XR8005 nozzle is shown in figure 17. The full boom spray pattern distribution results from the Sprayertest 1000 with one nozzle at nozzle #20 replaced with an XR8005 nozzle is shown in figure 18.

Table 7 summarizes the comparisons of the nozzle replacement tests from the Sprayertest 1000 with the simulations using data from the indoor patternator tests grouped into similar collection widths. While absolute CV values were different between the actual and simulated full boom tests, it was interesting to note the differences in CV from baseline within the actual and simulated tests were similar, yielding a difference of only 1.6%. In a previous study, Chapple et al. (1993) noted comparable differences of 1.1% between CV values from a three-nozzle boom simulation (based on pattern measurements from one nozzle) and actual pattern measurements from a three-nozzle boom. Thus, extrapolation to full-boom situations based on boom subsection measurements may provide acceptable estimates if boom setup errors can be accounted for.

CONCLUSIONS

The nozzle lateral angle test showed the potential for substantial increase in spray pattern CV at low angle changes depending on the nozzle type. Spray pattern CVs exceeded 10% as nozzle lateral angles for the 80° nozzles were adjusted 4° or beyond; the 110° nozzle pattern CVs did not exceed 8.5% when the lateral angle was set up to 8°. The nozzle spacing test showed that pattern CVs for the 80° and 110° nozzles tested were not highly sensitive to spacing deviations. An offset of 125 mm was necessary for pattern CVs to

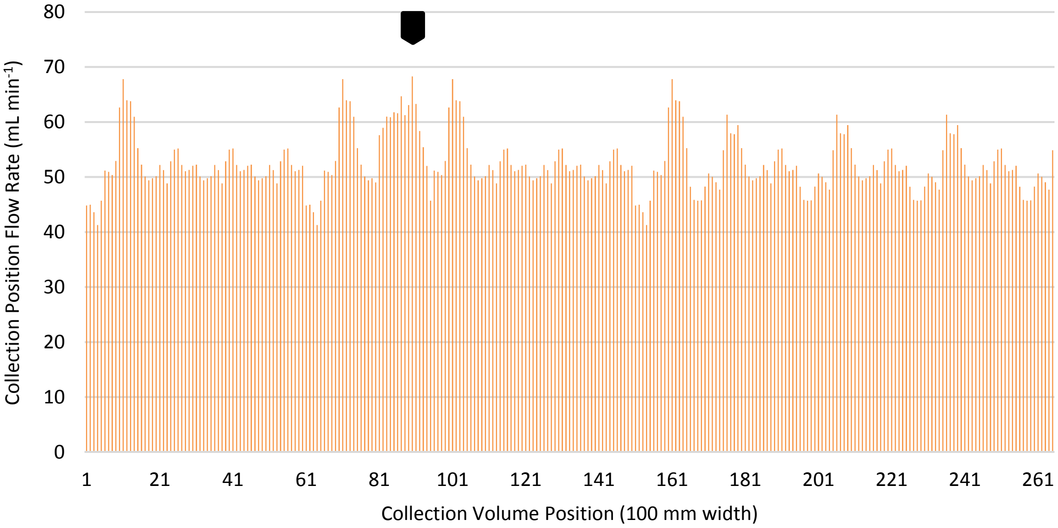

Figure 17. Simulated 27.4 m full boom scenario (CV 10.1%) created from patternator for XR8003 nozzles with one subsection of XR8005 spray pattern data inserted.

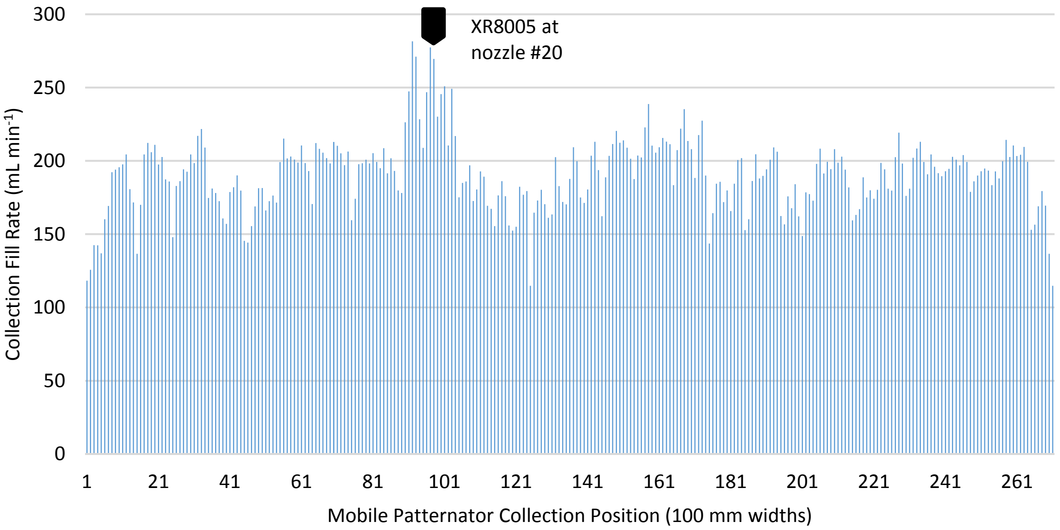

Figure 18. Spray pattern distribution data from Sprayertest 1000 with XR8005 replacement nozzle #20 (CV 12.3%).

Table 7. Summary of comparison data between actual outdoor full boom tests with simulated data from indoor spray patternator nozzle replacement tests (100 mm groupings).

Test Setup	Average CV from Actual Full Boom Test (%)	CV Deviation from Baseline Actual Full Boom Test (%)	Average CV from Modified Simulated Full Boom Test (%)	CV Deviation from Baseline Simulated Full Boom Test (%)
Baseline	11.0	-	9.4	-
w/ XR 8001	13.3	2.3	12.0	2.6
w/ XR 8005	12.3	1.3	10.1	0.6

exceed 10% compared to the initial baseline tests at the manufacturer-specified spacing of 50 cm. The nozzle replacement test with the XR8001 and XR8005 nozzles yielded pattern CV increases of 14.8% and 4.3%, respectively, compared to the baseline data consisting of all XR8003 nozzles. The variability in this difference was not expected due to the fact that flow rate changes, as a% decrease or increase, were comparable for the XR8001 (-66%) and XR8005 (+70%) nozzles. The nozzle pitch angle test had low sensitivity to pitch angle changes. The spray pattern CV remained below the 10% threshold of a good pattern even with 24° of rotation both in the fore and aft direction.

Results from simulating full boom changes on laboratory based patternator data were a reasonable representation of the changes setup factors may have had on a full boom sprayer. The modified simulated full boom CV (9.4%) was comparable to the measured full boom sprayer CV (11%) after the nozzle angle variation was accounted for. Differences in simulated and actual CV values after an error was introduced into the boom (i.e., one XRC8003 nozzle replaced with XR8001 or XR8005) were low (0.3% and 0.7%, respectively) and were likely within the detection limits of the patternator systems used.

A comparison among error detection in the full boom indicated that quantifying the CV for nozzle flow rate changes would be most noticed from a change compared to pressure or spray pattern. Among those parameters measured after errors were introduced into the full boom setup, nozzle flow rate CVs deviated by the greatest amount, followed by spray pattern (measured in 100 mm widths), individual nozzle pressure, and boom subsection pressure, with average deviations in CV of 7.4%, 1.8%, 1.2%, and -0.2%, respectively.

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