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COMPARISON OF 2-WAY VERSUS METERED 3-WAY BOOM SHUT-OFF VALVES FOR AUTOMATIC SECTION CONTROL ON AGRICULTURAL SPRAYERS

A. Sharda, J. D. Luck, J. P. Fulton, T. P. McDonald, S. A. Shearer, D. K. Mullenix

ABSTRACT. *Modern spray rate controllers along with technologies such as automatic section control (ASC) provide benefits such as overlap reduction on agricultural sprayers. However, product (liquid) dynamics within the boom plumbing affect off-rate errors and application uniformity during rate changes and ASC actuation. Therefore, this study was conducted to compare nozzle flow stability and uniformity across the boom when using two different boom shut-off valves (2-way and metered 3-way) on an 18.3-m sprayer boom. Pressure transducers were mounted at 1) the boom manifold, 2) randomly at 12 nozzle bodies across the spray boom, and 3) upstream and downstream of the flow regulating valve. Effective system flow rate was measured using two flow meter(s), one located upstream of the boom control valves (2-way or metered 3-way) and another mounted to measure the tank return flow for the metered 3-way boom valve. Measured nozzle pressure was converted to nozzle flow using the manufacturer's pressure-flow data. Results indicated that the 2-way boom versus metered 3-way valve response was significantly different. Significant differences in damping ratios were found when exiting (under-damped) and reentering (over-damped) of spray zones. For the metered 3-way boom valve configuration, nozzle flow settled faster (0.1 to 4.2 s) virtually eliminating off-rate errors whereas the 2-way boom valve configuration took up to 34.3 s to settle with off-rate errors ranging from 3.3% to 11.5%. The delayed nozzle flow settling times were associated with pressure settling (0.7 to 31.4 s) downstream of the regulating valve for the 2-way configuration. Ground speed and point row angle impacted nozzle flow settling times and off-rate errors. The increase in ground speed and point row angle increased nozzle flow settling time for the 2-way valve setup, except that acceleration decreased settling times when exiting spray zones. The delayed response contributed to off-rate time which decreased as the sprayer accelerated and point row angle decreased for both the 2-way (1.7 to 19.3 s) and metered 3-way (2.1 to 4.4 s) boom shut-off valve setups.*

Keywords. *Liquid application, Precision agriculture, Distribution, Pressure, Variable-rate technology.*

Crop production costs have increased drastically in recent years due to rising input prices including nutrients and pesticides. These escalating input costs along with global competitiveness in food prices require producers to not only utilize equipment with higher productivity rates and efficiency, but also to integrate control systems to accurately meter and apply crop inputs. Recently, self-propelled agriculture sprayers have grown in size with nominal boom widths of 27 or 39 m being popular and potential operating ground speeds nearing 32 km h^{-1}. These large sprayers are being adopted by farmers to cover more area in less time to complete spraying activities in a timely fashion.

Presently, a typical agricultural sprayer used for crop production has two basic components; hardware and a rate control system. The sprayer hardware consists of a tank, pump, hoses, possibly tubing, nozzles, fittings, and other required plumbing. The rate control system includes flow control hardware such as boom shut-off valves, a regulating valve, feedback mechanisms [e.g. flow meter(s) and ground speed sensor], microprocessor based controller and software which contains the control algorithm(s). These spray controllers typically utilize either a ground speed radar or a global positioning system (GPS) receiver to provide ground speed feedback and then regulate system flow accordingly. Therefore, as ground speed changes, the rate controller adjusts the system flow to maintain the set target application rate. System flow rate is controlled using hardware including a flow meter, regulating valve, and boom shut-off valves. Today, a control system utilizing GPS and section control capabilities can automatically actuate boom section valves and thereby directly managing flow to these sections as required. The flow control system

Submitted for review in November 2011 as manuscript number IET 9431; approved for publication by the Information & Electrical Technologies Division of ASABE in June 2012. Presented at the 2011 ASABE Annual Meeting as Paper No. 1111791.

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utilizing automatic section control (ASC) capabilities promptly turns sections on in areas designated for spraying and off in previously sprayed regions or regions requiring no application. In this case, application overlap is reduced. Luck et al. (2010a) reported that the use of ASC instead of manual control of boom sections has helped producers reduce the over-application area from 12.4% down to 6.2%. Further, use of ASC technology to efficiently manage boom sections can potentially result in 15.2% to 17.5% reduction in overlapped area (Luck et al., 2010b) thereby providing savings on inputs.

However, during field operation, the accuracy of an agricultural sprayer is inversely proportional to the reaction time of a flow control configuration to dynamically adjust to the target system flow (Anglund and Ayers, 2003). Therefore, intended application accuracy of a sprayer depends on the timely response of all the feedback (e.g. flow meter) and control hardware and software. Rietz et al. (1997) reported that control systems tend to over-spray when turning sections on and off while one boom section remains on. A control system using a regulating valve and 2-way boom valves for implementing ASC can also impact boom dynamics and nozzle pressure response during ASC actuation. Sharda et al. (2010a) reported nozzle pressure variations ranging from 6.7% to 20.0% during ASC actuation which equated to an increase of 3.7% to 10.6% in nozzle flow. Additionally, they found nozzle pressure stabilization times approached 25.2 s for an automatic boom-section control system using 2-way boom valves. Bennur and Taylor (2010) reported that the control system can have a unique minimum response time for each flow configuration to maintain optimum performance. Further, during field operation the demand on the flow control configuration can be unexpectedly high, especially in an irregularly shaped field due to frequent ground speed and ASC actuations. For these field conditions, nozzle off-rate errors beyond ±10% can occur for approximately 60% of the time (Sharda et al., 2010b). However, according to the guide for commercial applicators (USEPA and USDA, 1975) and Rietz et al. (1997), sprayers are expected to be within ±5% of the recommended target rate.

Among the flow control hardware, the boom shut-off valve is of particular importance for sprayers. Two general types of boom shut-off valves exist; 2-way (on/off) or 3-way which include a return line back to tank. These boom valves perform the simple function of turning boom sections on and off but handle liquid flow in different ways. Two-way boom valves are the most popular in the United States on self-propelled sprayers. This valve has one inlet and one outlet, i.e. product flows to the boom section in the on-state whereas it stops in the off-state. Since the excess flow has no outlet for the off-state, the product intended for the section turned off can be momentarily transferred to those sections still on (Sharda et al., 2010a). During this transient time, the controller adjusts the system flow rate, normally through an inline regulating valve or varying the pump speed via a hydraulic valve to the desired target rate. Therefore, system flow rate management during ASC actuation using the 2-way boom valve configuration will largely depend on the interaction between flow meter feedback, the regulating valve, and controller response.

On the contrary, a 3-way boom shut-off valve has one inlet but two outlets. One outlet permits flow to the boom section while the second is connected to return flow back to tank. When the 3-way boom valve is in the on-state, product flows from the pump to the boom section whereas in the off-state product is redirected back to tank. Since this flow configuration does not require a flow meter and regulating valve for flow rate management when actuating ASC, the 3-way boom valve should return the equivalent flow from the off boom sections back to the tank without affecting pressure in the remaining sections. A metered 3-way boom valve is a specific type of 3-way valve. A metered 3-way boom valve has an integrated user adjustable bypass dial for calibrating and controlling the amount of product returned back to tank when off (Teejet, 2011). During calibration, the return flow is adjusted so that it equals the flow to the boom section under the expected operating conditions. Therefore, during ASC actuation the 3-way boom-valves permit maintaining a constant pressure regardless if the boom valve is in the on- or off-state. However, a metered 3-way boom valve setup still requires flowmeter feedback to the controller to properly manage system flow for sprayer acceleration or deceleration.

With projected U.S. expenditures of $11.9 billion on pesticides in 2011 (USDA, 2010), the use of modern spray technology can provide tremendous input savings while increasing operators' productivity. However, response time to quickly manage system flow rate is critical for application accuracy. Therefore, the overarching goal of this study was to compare and contrast nozzle flow response of 2-way and metered 3-way boom shut-off valve configurations when implementing automatic section control technology. Specific objectives were to: 1) specify and compare damping ratios and settling times for single nozzle discharge rates between 2-way and metered 3-way boom shut-off valve configurations, and 2) quantify and compare off-rate errors from the boom sprayer configured with the 2-way and metered 3-way valve using three simulated ground speeds and point row angles.

Materials and Methods

Sprayer and Flow Control System

A 3-point hitch mounted agricultural sprayer (Schaben Industries, Columbus, Neb.) with an 18.3-m wide boom served as the platform for conducting this study. The sprayer was operated in a static position using water as the test liquid (ISO, 1997). It utilized a centrifugal pump (FMC-150-HYD-206, ACE Pumps Corp., Memphis, Tenn.) that was hydraulically driven by a John Deere 6420 tractor (Deere and Company, Moline, Ill.). The dry-boom setup was divided into three sections with the plumbing and identification provided in figure 1. Turbo Teejet wide angle, flat spray nozzles (TT11003, Teejet Technologies, Wheaton, Ill.) were used for these experiments (Teejet, 2008).

Flow control configuration-1 used a Raven Viper-II controller (Raven Ind., Sioux Falls, S. Dak.); turbine-type

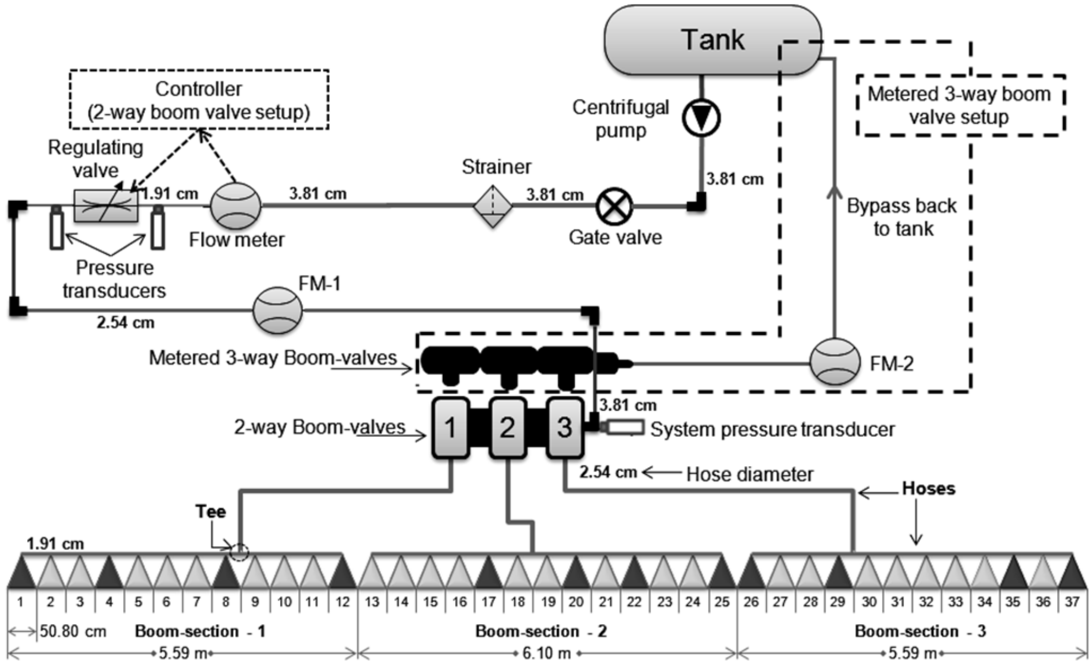

Figure 1. Sprayer configuration and plumbing for the 2-way and metered 3-way boom valve configuration. Each nozzle location, represented by triangles, was numbered between 1 and 37 from left to right. Four pressure transducers were mounted within each boom section as represented by the solid black triangles. Note the addition of the bypass line and second flow meter (FM-2) in the metered 3-way boom valve setup (within the dashed line).

flow meter (Model No. RFM-60P, Raven Ind., Sioux Falls, S. Dak.); 2.54-cm butterfly type regulating valve (Model No. 063-0171-120, Raven Ind., Sioux Falls, S. Dak.) to adjust overall system flow rate; and 2-way boom valves (Model No. 1-063-0172-330, Raven Ind., Sioux Falls, S. Dak.) to turn on or off flow to each of the three boom sections (fig. 1). The setup used a valve calibration number (VCN) of 2123 for the regulating valve as suggested in the manufacturer's product literature. An auxiliary flow meter (FM-1) (Model FT-16-NEXW-LEG-5, Flow Technology Inc., Tempe, Ariz.) with 3-4 ms response time, ±0.05% accuracy and 0 to 227 L min^{-1} measurement range was installed downstream of the regulating valve. The auxiliary flow meter was used to measure overall system flow rate.

Flow control configuration-2 consisted of replacing the 2-way boom valves with metered 3-way boom shut-off valves (Model DS-430EC-3, Teejet Technologies, Wheaton, Ill.; fig. 1). The metered 3-way boom shut-off valves utilized an adjustable bypass mechanism which can be adjusted to ensure equivalent flow is returned to the tank when in the off state. Since this setup does not require rate adjustment when turning sections on and off, the flow regulating valve and flow meter were not used for flow control configuration-2 tests. A pre-determined target pressure was set prior to testing. Proper setup procedures for these boom valves required initially adjusting the dials to the "zero" position when all sections were turned on to achieve the desired target system pressure. One section was then turned off and the bypass dial of the corresponding section adjusted until the intended target system pressure was achieved again. The same procedure was followed for the other two boom valves as outlined in the manufacturer's literature. To measure the bypass flow during these tests, a second flow meter (FM-2) (same as FM-1) was placed in the bypass line between the metered 3-way boom valves and tank (fig. 1). The difference in flow between FM-1 and FM-2 was then used to determine the effective system flow rate at any point in time during a test.

Data Acquisition

Thin film pressure transducers (Model No. 1502 B81 EZ 100 PSI G, PCB Piezotronics Inc., Depew, N.Y.) were used to measure nozzle pressure at 12 locations across the spray boom (fig. 1). Stated specifications of the pressure transducers were a measurement range of 0 to 689.5 kPa with a reported accuracy of ≤0.25% full scale and a response time of ≤1 ms. Another pressure transducer was mounted at the boom valves to monitor system pressure. The sensor was located coincident with the gauge providing visual operator feedback. Additional pressure transducers were mounted immediately upstream and downstream of the regulating valve to measure the pressure drop (fig. 1). The analog signals from the pressure transducers, three boom valves, and flow meters were sampled using two National Instrument (NI, National Instruments, Austin, Tex.) 9221 analog input modules. The boom sections were turned off and on using an input signal from NI-9475 digital output modules. The digital output signals controlling each boom valve (on and off state) were generated using input/output modules (Model 70G-ODC15, Grayhill Inc., La Grange, Ill.). A program developed in LabVIEW (version 8.6) facilitated the control and data acquisition functions which included logging all data to a *.TXT file at a 40-Hz sampling frequency.

EXPERIMENTAL DESIGN

Boom-Valve Tests

Flow control configuration-1 and -2 were used to evaluate nozzle flow stability and response across the boom when using ASC (boom section) during typical field scenarios. Tests were conducted simulating sprayer ASC actuation when exiting and reentering point rows at three angles; 20°, 45°, and 70°. The three angles were selected to represent high, moderate and low point row incidence angles typically encountered within Alabama fields. Different ground speeds of 9.6, 12.1, and 16.1 km h^{-1} were also selected as treatments while a uniform target rate of 112.1 L ha^{-1} was programmed into the controller. For these tests, the term "exit" was used to signify the sprayer transitioning from a spray zone to a no-spray zone (e.g., entering the headland) while "reentry" defined moving back into the spray zone. All tests were replicated three times generating 27 total tests for each configuration. The self-test feature available in the rate controller was used to simulate the desired ground speed. All tests for flow control configuration-1 were conducted with the controller setup in the flow compensation mode. The system was initially set to spray 112.1 L ha^{-1} at 16.1 km h^{-1} and for all subsequent tests only ground speed in the self-test option adjusted. For flow control configuration-2, the target system pressure corresponding to each speed and application rate during flow control configuration-1 was calculated and set for the sprayer before each test (table 1). The theoretical time required to shut-off and on each boom section when exiting and reentering spray zones was calculated based on ground speed, boom section width and point row angle (table 1). A LabVIEW program (v. 8.6) was used to automatically control the on and off state of the boom valves thereby simulating exiting and reentering point rows. The program used suitable time delays to allow the spray system to stabilize before initiating and terminating a test (fig. 2).

DATA ANALYSES

Measured nozzle pressure was converted to flow by fitting a second order polynomial regression line (eq. 1) to the manufacturer's reported nozzle pressure-flow data (Teejet, 2008). Nozzle flow rates were estimated only for boom sections operating in the on-state during a test. MATLAB (R2011b, The MathWorks, Inc., Natick, Mass.) was used to compute the initial nozzle pressure, lag time, peak nozzle pressure, final nozzle pressure, percent nozzle pressure overshoot, damping ratio (ζ), nozzle flow settling time (NFST), system flow settling time (SF-ST), nozzle pressure drain time, boom valve input signal off/on time, and pressure drop across the butterfly regulating valve.

$$\textit{Nozzle flow} = -2 * 10^{-5} * \textit{pressure}^2 + 0.0059 * \textit{pressure} + 0.1003 \quad (1)$$

The percent difference between actual accumulated nozzle flow and target system flow was calculated and termed, nozzle off-rate. Damping ratio represents the decay of an oscillation. In this study, the damping ratio was computed after a step input of turning on or off sections and provided an indication of overall system performance. Thus, the damping ratio was used to describe how the nozzle pressure oscillated as the response decays towards steady state after a boom section was turned on or off. The nozzle and system flow settling times represented the time difference between a change in flow rate (±2%) from the initial steady-state value to the time when the rate settled to within ±2% of final flow rate after the boom section(s) was

Table 1. Computed timing and target rate (system flow) for 112.1 L ha^{-1} application rate to simulate exiting and reentering 20°, 45°, and 70° point row angles for flow control configurations using the 2-way and metered 3-way boom valves.

			Sections 1 and 3		Section 2[a]	
Point Row Angle	Ground Speed (km h^{-1})	System Pressure (kPa)	Time (s)	Rate (L min^{-1})	Time (s)	Rate (L min^{-1})
20°	9.6	180.0	0.8	11.0	0.9	12.1
	12.1	275.0	0.7	13.7	0.7	14.9
	16.1	450.0	0.5	18.4	0.5	20.0
45°	9.6	180.0	2.3	11.0	2.5	12.1
	12.1	275.0	1.8	13.7	2.0	14.9
	16.1	450.0	1.4	18.4	1.5	20.0
70°	9.6	180.0	6.2	11.0	6.8	12.1
	12.1	275.0	5.0	13.7	5.4	14.9
	16.1	450.0	3.8	18.4	4.1	20.0

[a] Section 2 has one additional nozzle versus sections 1 and 3 therefore required different timing and rate for these point row scenarios.

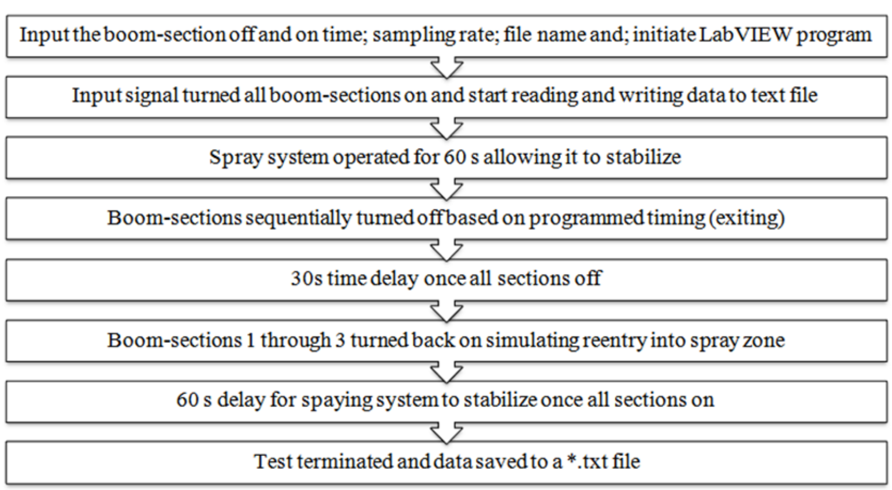

Figure 2. Data collection procedure for the LabVIEW program.

turned off or on. These tests were conducted under controlled conditions with spray boom level and in static position. Typically, during any dynamic change in the system, a ±2% error band is used to analyze response of control system; therefore the same was selected to quantify settling time for this study. For the boom-valve tests, off-rate time (ORT) was calculated for exiting and reentering the spray zones. The ORT characterized the total time for which the nozzle off-rate was beyond ±5% of the target. For illustrations in the results and discussion section, flow data from one nozzle within a boom section was plotted.

An ANOVA was conducted in SAS (SAS Institute, Inc., N.C.) using Proc GLM to determine if statistical differences existed between the boom and regulating valves based on the mean values of nozzle off-rate and flow settling time. A 95% confidence interval was used for these comparisons. Means for different parameters were calculated using the GLM procedure and multiple comparisons of NFST, damping ratio, ORT, and total ORT for all tests were conducted using the Tukey-Kramer procedure.

RESULTS AND DISCUSSION

BOOM VALVE TESTS

The nozzle flow response for the 2-way (flow control configuration-1) and metered 3-way (flow control configuration-2) boom valve tests are presented in and figure 3. Nozzle flow did not stabilize for flow control configuration-1 at 20° point row with nozzle off-rate errors beyond ±5% when exiting the spray zone at all three ground speeds (table 2). For 45° and 70° point row angles, nozzle flow settling time for the 2-way valve varied between 0.7 and 1.7 s when exiting spray zones (table 2). For reentry, the nozzle flow settled between 13.4 and 34.3 s after the 3rd boom section was in the spray zone (table 3). The NFSTs decreased as the ground speed increased when exiting spray zones. During reentry, NFSTs increased with ground speed (thereby target system flow) and point row angle. The longer settling times for reentering spray zones suggests slow response while pressurizing the system and adjusting to the target nozzle flow (fig. 4). These extended nozzle flow settling time using the 2-way valves was associated with pressure stabilization downstream of the regulating valve which varied from 0.7 to 31.4 s for the various tests. The pressure stabilization downstream of the regulating valve demonstrated that the valve response time is critical when managing nozzle flow.

The ζ varied from 0.5 to 0.8 exhibiting a second order under-damped system when exiting the spray zone (table 2). Higher values of ζ correspond to smaller oscillations within the system plumbing and faster system stabilization. The lower ζ values (0.5) therefore explained the higher settling time (1.3 s) for the 9.6 km h^{-1} test. The ζ changed in direct proportion with increases in ground speed but the point row angle did not impact the ζ when exiting. The system response was a second order over-damped response (ζ >1) while reentering spray zone since the nozzle pressure did not oscillate during transient response.

The nozzle flow for the 2-way boom valve setup settled relatively quickly but generated off-rate errors between 3.3% and 11.5% when exiting spray zones. The nozzle off-rate increased when switching between one and two boom sections (ASC actuation) off when exiting. Also, for both 45° and 70° point row angles, the two higher speeds 12.1 and 16.1 km h^{-1} generated off-rate errors exceeding 10%. During reentry of spray zones, the nozzle off-rate error was within ±5% after all three boom sections were within the spray zones. The ORT (0.6 to 5.0 s) for the 2-way boom valve increased with speed, except that the ORT was

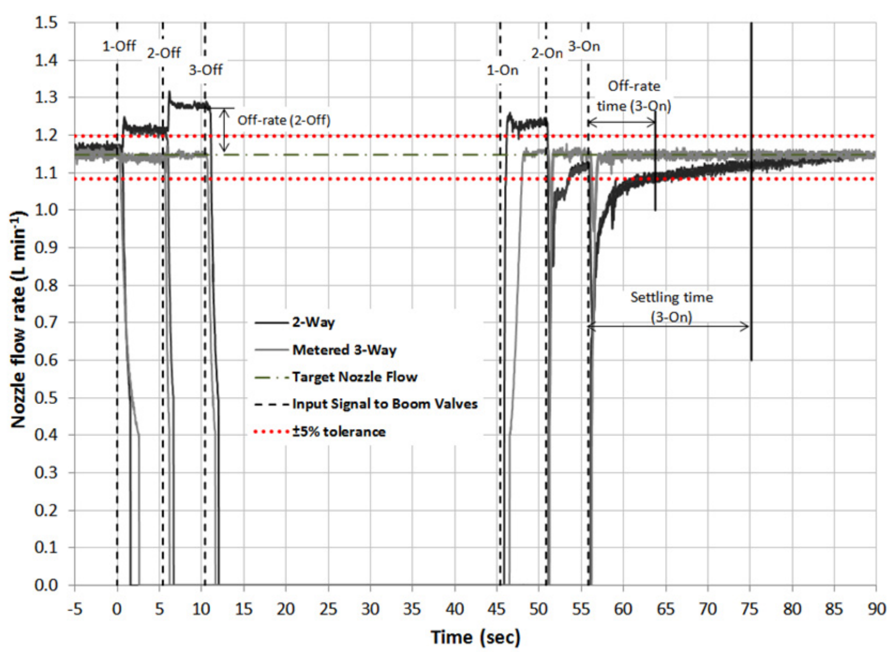

Figure 3. Nozzle flow response for the 2-way and metered 3-way boom valves when exiting and reentering 70° point rows at 12.1 km h^{-1} ground speed and 112.1 L ha^{-1} application rate.

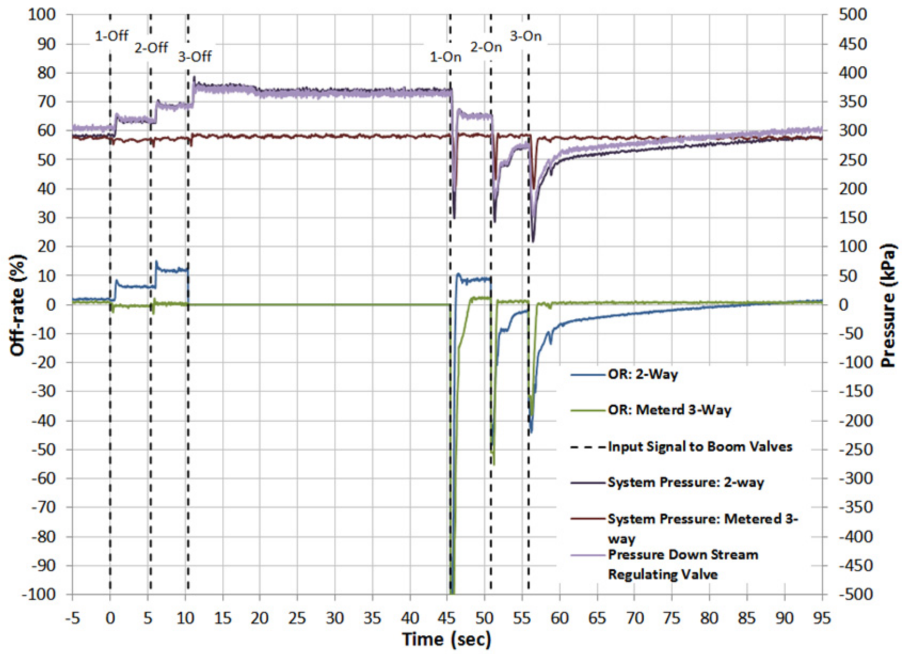

Figure 4. Pressure downstream of the regulating valve and nozzle off-rate for the 2-way and metered 3-way boom valve configurations when exiting and reentering 70° point rows at 12.1 km h^{-1} ground speed and 112.1 L ha^{-1} application rate.

highest at 12.1 km h^{-1}, when exiting the spray zone (fig. 4). The total ORT when exiting varied from 1.7 to 9.6 s and was highest (9.6 s) at 12.1 km h^{-1} and the 70° angle of incidence (fig. 5). The total ORT for reentry highlighted that nozzle off-rate error occurred from 1.8 to 19.3 s, which increased with both ground speed and point row angle (fig. 6).

The nozzle flow failed to settle for the 20° point row when exiting a spray zone, whereas for 45° and 70° point rows nozzle flow settled within 0.5 s (tables 2 and 3) for the metered 3-way valve (fig. 3). Nozzle pressure spikes were observed when boom sections were turned off but lasted for a short duration (<0.04 s). The nozzle off-rate error was negligible with nozzle flow always within ±5% of the target rate. Therefore, the metered 3-way valve did not generate an ORT when exiting spray zones (figs. 3 and 4). During spray zone reentry, nozzle flow settled between 0.9 and 4.2 s but only after all three boom sections were within the spray zone and all sections were on. The nozzle ORT for the metered 3-way valve was estimated between 0.5 and 1.5 s and the total ORT from 2.1 to 4.4 s when reentering. The NFST was comparable when exiting but it decreased with ground speed and point row angle for reentry. The total ORT for reentry decreased with increase in ground speed but increased at higher point row angles, except that it was highest at the 12.1 km h^{-1} ground speed for all three point row angles (figs. 5 and 6).

Table 2. Summary of nozzle flow response and pressure damping ratio (ζ) when exiting a spray zone.

			Booms Off[a][b]								
			1				1 and 2				
Angle	Valve	Speed (km h^{-1})	OR (%)	NFST (s)	ζ	ORT| (s)	OR (%)	NFST (s)	ζ	ORT (s)	
20°	2-way	9.6	-	#	-	-	-	#	-	0.8[c]	0.8
		12.1	-	#	-	-	-	#	-	0.6[c]	0.6
		16.1	-	#	-	-	-	#	-	0.3[c]	0.3
	3-way	9.6	-	#	-	-	-	#	-	-	-
		12.1	-	#	-	-	-	#	-	-	-
		16.1	-	#	-	-	-	#	-	-	-
45°	2-way	9.6	3.3[b]	1.3[a]	0.6[b]	0.6[d]	4.3[b]	1.6[a]	0.5[b]	1.1[c]	1.7
		12.1	6.3[a]	0.8[b]	0.7[a]	1.2[c]	11.5[a]	0.9[b]	0.7[a]	1.8[bc]	3.0
		16.1	6.1[a]	0.7[bc]	0.8[a]	0.7[b]	10.3[a]	0.7[bc]	0.8[a]	1.4[c]	2.1
	3-way	9.6	-0.6[c]	0.5[cd]	-	-	0.1[c]	0.5[d]	-	-	-
		12.1	-1.0[c]	0.1[d]	-	-	0.2[c]	0.5[d]	-	-	-
		16.1	-1.3[c]	0.0[d]	-	-	-0.7[c]	0.5[d]	-	-	-
70°	2-way	9.6	3.5[b]	1.3[a]	0.6[b]	0.6[d]	5.2[b]	1.7[a]	0.5[b]	4.0[ab]	4.6
		12.1	6.2[a]	0.8[b]	0.7[a]	4.7[a]	11.5[a]	0.9[b]	0.7[a]	5.0[a]	9.6
		16.1	6.2[a]	0.7[bc]	0.8[a]	3.3[b]	10.1[a]	0.8[b]	0.7[a]	3.7[ab]	7.0
	3-way	9.6	-0.9[c]	0.4[d]	-	-	0.0[c]	0.6[d]	-	-	-
		12.1	-1.3[c]	0.2[d]	-	-	-0.2[c]	0.5[d]	-	-	-
		16.1	-1.3[c]	0.0[d]	-	-	-0.6[c]	0.5[d]	-	-	-

[a] OR=off-rate, NFST=nozzle flow rate settling time, ORT=off-rate time, and Total ORT=total off-rate time (ORT: 1boom off + ORT: 1&2 boom off).
[b] Within columns, means followed by the same letter are not statistically different at the 95% confidence level.

Table 3. Summary of mean nozzle flow response when reentering a spray zone.

			Booms On[a][b]				
			1	1 & 2	1, 2, and 3		
Angle	Valve	Speed (km h^{-1})	ORT (s)	ORT (s)	NFST (s)	ORT (s)	Total ORT (s)
20°	2-way	9.6	0.9^{e}	0.8^{cd}	13.9^{e}	10.1^{ab}	11.8
		12.1	0.7^{e}	0.6^{cd}	23.4^{c}	7.2^{c}	8.5
		16.1	0.5^{e}	0.4^{d}	18.7^{d}	0.9^{e}	1.8
	3-way	9.6	0.8^{e}	0.8^{cd}	4.2^{f}	1.2^{e}	2.8
		12.1	0.7^{e}	0.7^{cd}	3.2^{fg}	1.6^{e}	3.0
		16.1	0.5^{e}	0.5^{cd}	1.2^{g}	1.1^{e}	2.1
45°	2-way	9.6	2.4^{c}	2.3^{b}	13.4^{e}	9.8^{ab}	15.1
		12.1	2.0^{cd}	1.5^{bc}	28.0^{b}	8.9^{abc}	12.3
		16.1	1.5^{d}	0.6^{cd}	31.8^{a}	4.3^{d}	6.3
	3-way	9.6	0.9^{e}	0.9^{cd}	3.2^{fg}	1.2^{e}	3.0
		12.1	1.9^{cd}	0.8^{cd}	2.7^{fg}	1.3^{e}	4.0
		16.1	0.8^{e}	0.8^{cd}	1.0^{g}	1.1^{e}	2.7
70°	2-way	9.6	3.7^{b}	5.3^{a}	14.6^{e}	10.3^{a}	19.3
		12.1	5.4^{a}	2.3^{b}	28.3^{b}	8.2^{bc}	15.8
		16.1	4.0^{b}	0.5^{cd}	34.3^{a}	4.4^{d}	9.0
	3-way	9.6	0.9^{e}	1.0^{cd}	3.5^{f}	1.4^{e}	3.3
		12.1	2.4^{c}	0.8^{cd}	1.1^{g}	1.2^{e}	4.4
		16.1	0.9^{e}	0.8^{cd}	0.9^{g}	1.1^{e}	2.8

[a] ORT=off-rate time ; NFST=nozzle flow settling time; and Total ORT=Total off-rate time (ORT:1 boom on +ORT 1&2 boom on + ORT: 1, 2 & 3 boom on).

[b] Within columns, means followed by the same letter are not statistically different at the 95% confidence level.

Overall, results indicated there were distinct differences in system response when using ASC for plumbing configurations that utilized either 2-way and metered 3-way valves (table 4). The time for consecutive boom sections to exit and reenter a spray zone was less than 1 s for the 20° point row tests. Therefore, very short on or off times highlighted response time limitations of the control system for particular operating conditions to manage nozzle flow within acceptable limits. For 45° and 70° point rows, nozzle flow remained stable and settled more quickly (tables 2 and 3) resulting in short ORTs when using the metered 3-way valve setup (fig. 4). These results suggested that energy transfer during ASC actuation for the boom sections remaining on was much lower when using metered 3-way valves as compared to a 2-way valve setup. Although the metered 3-way valve improved nozzle stability during ASC, it is suitable for tank mix applications only. The boom-valves on many contemporary agricultural sprayers are plumbed close to the respective boom sections. Therefore, installing a 3-way will require additional hoses and plumbing to handle return flow to the tank. The additional plumbing can thereby add weight to existing spray booms. Also, bypass dials on each boom valve must be calibrated to achieve the target system pressure. The difference in nozzle flow response between these 2-way and metered 3-way boom valves was anticipated as the typical rate controller was unaffected. Interestingly, both flow control configurations generated distinct nozzle flow response with changes in ground speed and/or point row angles (tables 2 and 3).

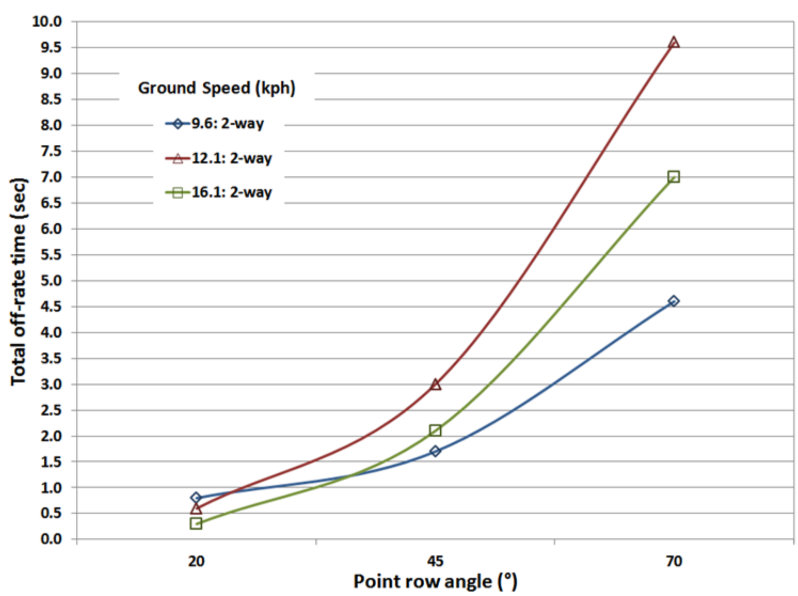

Figure 5. Total nozzle off-rate time at different ground speeds and point row angles for the 2-way boom valve configurations when exiting a spray zone.

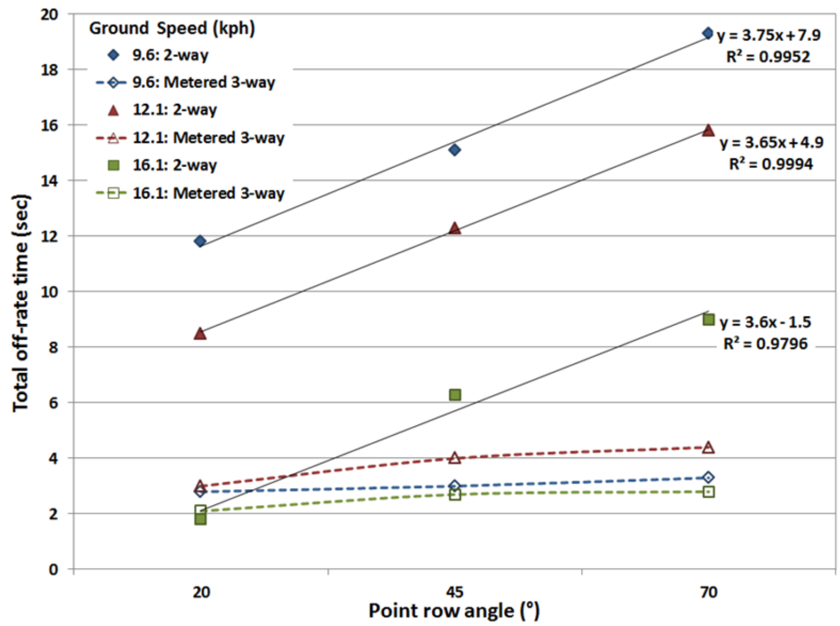

Figure 6. Total nozzle off-rate time at different ground speeds and point row angles for the two different boom valve configurations when reentering a spray zone.

CONCLUSIONS

Conclusions for this study are as follows:

- The 2-way and metered 3-way boom valves impacted nozzle response significantly differently. For the 2-way boom valve setup, damping ratios increased with ground speed and were different between exiting (under-damped) and reentering (over-damped) a spray zone at every incident angle whereas the metered 3-way valve did not exhibit any transient change in nozzle pressure.
- The metered 3-way boom valve configuration generated quicker nozzle flow settling time (0.1 to 4.2 s) as compared to the 2-way boom valve setup which took up to 34.3 s to settle nozzle flow. The delayed nozzle flow settling times for the 2-way boom valve setup were associated with pressure settling (0.7 to 31.4 s) downstream of the regulating valve for the 2-way tests.

Table 4. ANOVA results for nozzle flow settling time and off-rate during 2-way and metered 3-way tests at 45° and 70° point row angles.

Source[a]	Degrees of Freedom	Sum of Squares	P-value
NFST 1-boom off	11	6.58	<0.0001
OR 1-boom off	11	396.18	<0.0001
NFST 2-booms off	11	5.89	<0.0001
OR 2-booms off	11	889.81	<0.0001
ζ 1-boom off	5	0.08	<0.0001
ζ 2-booms off	5	0.25	<0.0001
ORT 1-boom on	17	98.45	<0.0001
ORT 2-booms on	17	69.35	<0.0001
NFST 3-booms on	17	7312.80	<0.0001
ORT 3-booms on	17	721.77	<0.0001

[a] OR=off-rate; ST=settling time; NFST 1Off=nozzle flow rate settling time for one boom off; OR 1Off=off-rate for one boom off; NFST 2Off=nozzle flow settling time for two booms off; OR 2Off=off-rate for two booms off; NFST 3On=nozzle flow settling time for three booms on; OR 3On=off-rate for three booms on.

- The nozzle flow settling time for the 2-way boom valve decreased as ground speed increased while exiting a spray zone whereas it increased with ground speed when reentering a spray zone; except for a ground speed increase from 12.1 to 16.1 kph at a 20° point row. For the metered 3-way boom valve, ground speed did not impact nozzle flow settling when exiting but decreased as ground speed increased while reentering spray zones. For 20° point rows, nozzle flow did not settle when exiting a spray zone for both the 2-way and metered 3-way boom valve configurations because of control system response time limitations.
- The nozzle flow settling time also increased with increase in point row angle when exiting and reentering (e.g. 18.7 to 34.3 s at 16.1 km h^{-1}) a spray zone for the 2-way boom valve. Conversely, the metered 3-way boom valve configuration decreased the nozzle flow settling time with increase in point row angle when reentering whereas point row angle did not impact the settling time while exiting a spray zone.
- There was negligible nozzle off-rate for metered 3-way boom valve configuration, whereas the 2-way boom valve resulted in off-rate errors between 3.3% and 11.5%. The nozzle off-rate increased at the two higher speeds for the 2-way boom valves whereas speed did not impact off-rate for the 3-way boom valve setup.
- Total off-rate time decreased as the sprayer accelerated and also with decrease in point row angle for both the 2-way and metered 3-way boom shut-off valves when exiting and reentering spray zones. An exception was observed at a 12.1 km h^{-1} forward speed for the metered 3-way boom valve for which total off-rate time was higher than the other two forward speeds for all point row angles.

ACKNOWLEDGEMENTS

The authors would like to thank Christian Brodbeck for his assistance during this study. Partial funding for this project was provided through a special grant from CSREES-USDA entitled, "Precision Agriculture Technologies for Improved Crop Production in the Tennessee Valley of Alabama," Alabama Cotton Commission and Alabama Soybean Producers. Mention of trade names and commercial products is for informational purposes and does not imply endorsement by Auburn University or the Alabama Agricultural Experiment Station.

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